An Evaluation of Lift Engines in Tactical VTOL Aircraft

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The key to the attainment of efficient operational VTOL aircraft is the successful optimization of the propulsion system for discrete mission requirements. One of the more challenging problems facing the designer of VTOL aircraft is the mismatch in thrust that exists between takeoff and cruise flight conditions. VTOL aircraft normally require three to four times as much thrust for vertical flight as needed for cruise. When turbine engines are throttled back to meet cruise requirements, the fuel consumption characteristics suffer markedly. The system tradeoffs narrow down to the weight of an engine sized for cruise plus the additional weight of lift engines, as compared to a main propulsion engine sized for takeoff plus the weight and volume of excessive amounts of fuel. The results of a detailed analysis evaluating several lift systems installed in both VTOL fighter and transport aircraft indicate that engines must be uncompromisingly designed for cruise, and the available thrust also be utilized for vertical flight. The thrust needed above this amount, to account for the difference in takeoff weight and aircraft control, should then be provided by separate lift engines. The ultimate selection of the lift engine configuration will be established primarily by the aircraft hover and control requirements.

Introduction

AFTER evaluating the results of military air operations that took place during World War II and the Korean conflict, it has become increasingly evident that the major vulnerability of a fixed site air arm is the location of the airbase itself. Therefore, a method to implement the over-all dispersal and survivability of combat aircraft appears to be an absolute necessity. V/STOL aircraft provide a potential solution for this serious problem, and military strategists are currently advocating the development of three VTOL aircraft concepts: 1) an aircraft for close support missions, 2) a Mach 2.0 strike fighter, and 3) a short to medium haul transport.

The goal of achieving effective V/STOL aircraft in these mission categories confronts both the aircraft and engine designers with a most challenging task. In fact, they face one of the most complex problems since the introduction of jet aircraft in the 1945–1950 time period.

We recognize that VTOL is not basically a new phenomenon since helicopters have been accomplishing this for many years. However, the VTOL airplane does constitute a new class of aircraft and is not a replacement for helicopters. They combine a unique blend of capabilities, i.e., long range flight at high cruising speed coupled with the ability to take off and land on short unprepared fields located in remote and dispersed areas. This freedom from dependence upon fixed runways has long been considered a major tactical advantage by military planners. It is only an advantage if the penalty associated with VTOL does not limit the performance, range, and payload of the aircraft. Until recently this penalty has been considered too great to provide an effective aircraft and much of this penalty has been associated with the poor ratio of lifting thrust to aircraft empty weight, leaving little room for payload and fuel. Together with improvements in airframe design, we as engine manufacturers have accepted the challenge of improving thrust/weight ratio of the lift/propulsion system and through the use of new design techniques and advanced engine technology have developed a lift engine concept that can assure the successful achievement of operational tactical VTOL aircraft.

Presented as Preprint 64-767 at the Military Aircraft Systems and Technology Meeting (Secret), Washington, D. C., September 21–23, 1964; revision received March 15, 1965.

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V/STOL Aircraft Programs

Over the past ten years practically all of the major aviation companies in the world have set about designing, and in many cases building, new experimental VTOL aircraft. Many of these aircraft have had a thorough flight evaluation and the results of this testing have produced an abundance of new information affecting the entire philosophy of VTOL technology. Principally, it is the thrust required for vertical takeoff and landing without ground roll that poses a novel set of problems with regard to propulsion systems. In the design of jet VTOL aircraft there is a considerable mismatch, as shown in Fig. 1, between the thrust required for the typical cruise flight condition and that necessary for offsetting the weight of the aircraft during vertical flight. Normally, VTOL aircraft require three to four times as much thrust for vertical flight as required for cruise. The mismatch decreases in

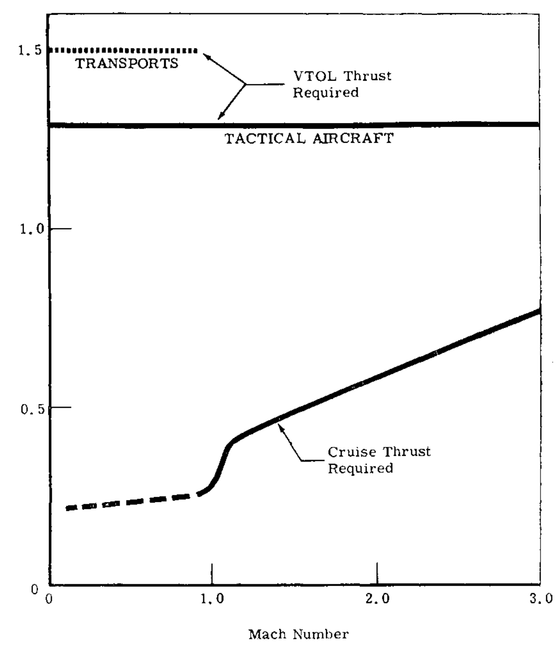

Fig. 1 Comparison of takeoff and cruise thrust for fixed wing turbine aircraft.

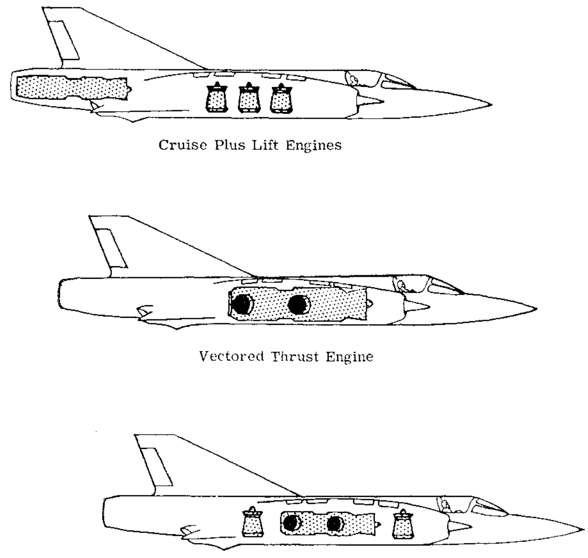

Fig. 2 VTOL system comparisons for tactical aircraft.

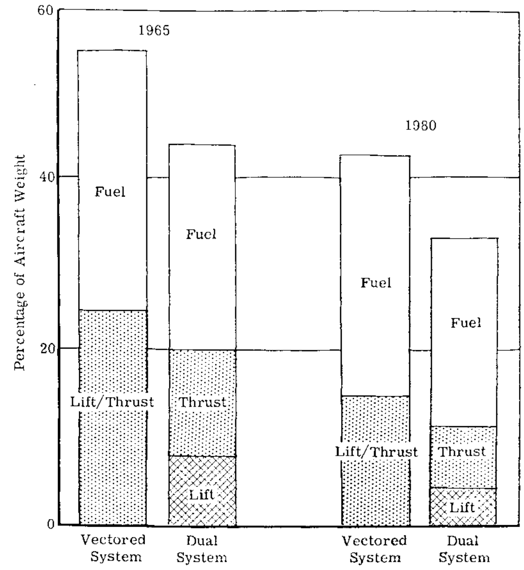

Fig. 3 Powerplant and fuel weight comparisons.

magnitude as the air speed and appropriate cruise thrust increase. Unfortunately, when turbine engines are throttled back to meet cruise requirements, their fuel consumption characteristics suffer markedly. The effect in many cases amounts to doubling the fuel consumption of the throttled engine as compared to the fuel consumption of a smaller unthrottled engine sized for cruise thrust. The system tradeoffs then narrow down to the weight of supplemental lift engines vs the weight and volume of excessive amounts of fuel. The selection of the lift/thrust system that can most effectively accommodate this mismatch in thrust should result in the lowest gross weight aircraft to meet specific mission profiles.

VTOL Propulsion System

There are presently four basically successful lift/thrust systems to provide VTOL capability. They are tilt thrust, augmented thrust, vectored thrust, and dual propulsion.

This paper is primarily concerned with the combination of short hover time and high cruise speed requirements. Therefore, we shall confine our discussions to the latter two systems, examples of which are shown in Fig. 2. Dual propulsion combines vertical lift engines for takeoff and landing and separate propulsion engines for cruise. The vectored thrust system incorporates one or more engines whose thrust is diverted vertically for takeoff and landing and redirected horizontally for forward flight.

The gross weight of an airplane is largely dependent upon the weight of the propulsion system and fuel for a fixed payload and range. The results of a comparative study evaluating these parameters for both dual and vectored thrust propulsion systems have established a decided advantage in favor of the dual propulsion system as shown in Fig. 3. The vectored thrust system is limited to thrust/weight ratios associated with main propulsion technology. The dual propulsion system that combines the low weight of lift engines with the reduced weight of small cruise engines results in a lower specific propulsion system weight. Additional benefits due to the improvements in cruise SFC also contribute heavily to the weight advantage shown for the dual system. The system comparisons were also extended to account for the technological improvements in engine design through 1980.

The results of a detailed study to evaluate the effectiveness of the two VTOL propulsion systems are shown in Figs. 4–7. The aircraft comparisons were made at 0.8 Mach number at 36,000 ft, 0.9 Mach number at sea level, 1.2 Mach number at sea level, and Mach 2.0 at 50,000 ft, respectively. All aircraft had Mach 2.0 capability. The installation of a singular propulsion system (vectored thrust engine), when compared to a combined propulsion system (main propulsion plus lift engines) installed in a Mach 2.0 plus airplane flying a subsonic mission, resulted in a considerably larger aircraft. The initial examination (as shown in Figs. 4–7) was based upon current state-of-the-art technology. Anticipating general improvements in engine technology in terms of higher thrust/weight ratio powerplants, this same type of analysis was extended through the year 1980 with very similar results. The lift engines still provided the tool to consistently account for the mismatch in takeoff-cruise thrust. All main propulsion engines were optimized for the climb-cruise flight conditions.

In the analysis for Mach 1.2, the combined lift-propulsion system continued to maintain its system superiority for both the current state of the art and the advanced design technology. For the Mach 2 flight condition at 50,000 ft where the cruise thrust levels were more compatible with takeoff requirements, the singular VTOL system began to show a favorable comparison with the combined system. This did not

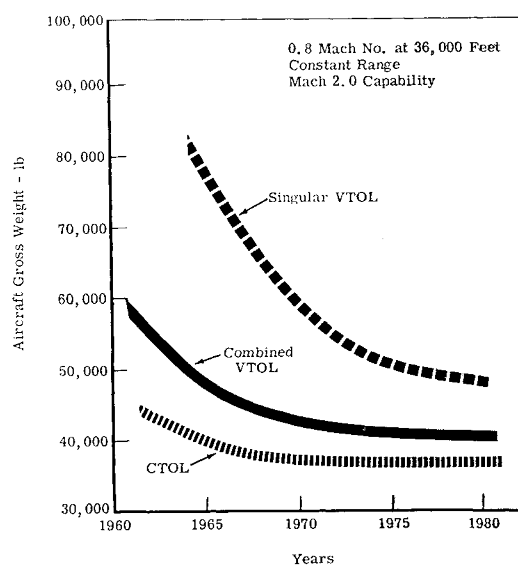

Fig. 4 Effect of propulsion/lift system on aircraft gross weight.

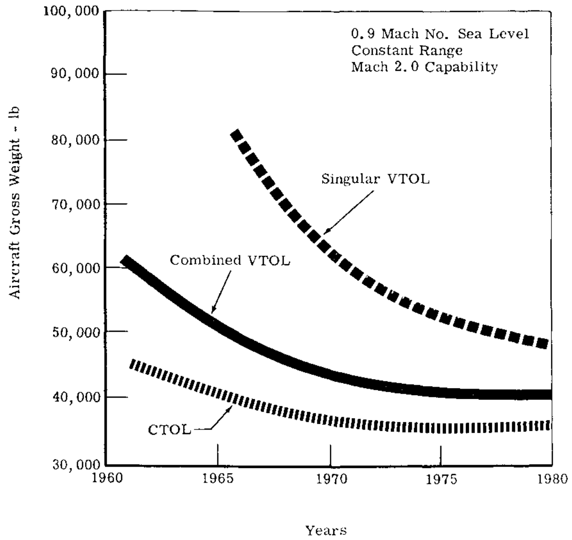

Fig. 5 Effect of propulsion/lift system on aircraft gross weight.

occur, however, until the 1970–1975 time frame when the 15:1 thrust/weight cruise engines should be available.

Since the singular propulsion system appears to offer a satisfactory solution only at the extremely high-speed portion of the spectrum, we must examine the over-all operating profile. Predicated upon current operating practices, approximately 75% of the mission is performed subsonically and only the dash segments are conducted at supersonic speeds. With the mission profile heavily weighted in the direction of the lower operating speeds, the combined VTOL propulsion system should still provide the optimum arrangement and result in the lowest gross weight airplane. In all these studies, equal values of drag and installation penalties were assumed for both propulsion systems.

In this same study, a comparison of the vertical takeoff with a conventional takeoff aircraft was also made to establish the magnitude of the so-called "penalty" for VTOL capability. In all cases it amounted to less than 20% of the aircraft gross weight and as the thrust/weight ratios of the lift engines improved, the VTOL penalty almost disappeared.

Basic Aircraft and Engine Costs

Enlightened by advanced technology and resulting VTOL potential, a whole new approach to mission analysis and

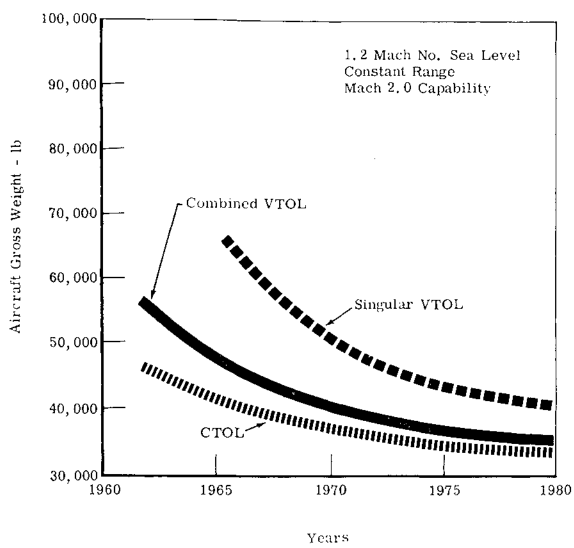

Fig. 6 Effect of propulsion/lift system on aircraft gross weight.

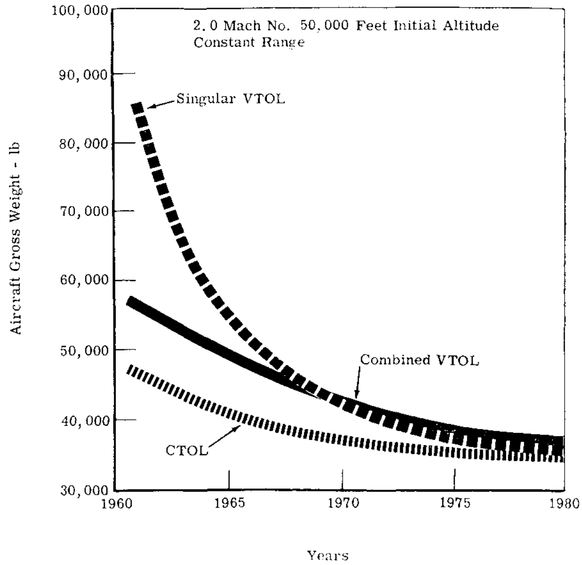

Fig. 7 Effect of propulsion/lift system on aircraft gross weight.

system evaluations can be followed. The improved flexibility and shorter mission times involved in dispersing VTOL aircraft nearer the front lines than conventional aircraft bring out two favorable factors: 1) VTOL aircraft can be lighter than conventional aircraft for the same mission; and 2) VTOL aircraft can also be more economical than conventional aircraft for the same mission.

Figure 8 illustrates how the radius of action affects the gross weight of a typical fighter aircraft with different thrust to weight ratio lift engines. The conventional aircraft (CTOL) must be operated from a fixed base located far behind the lines. This is imperative in order to reduce the vulnerability of a fixed base to enemy attack. The VTOL aircraft can be dispersed from highly mobile and flexible bases nearer the front lines with even less vulnerability and a lighter gross weight. To illustrate, a conventional aircraft ($T/W = 5.5$) requiring 650 naut mile radius of action weighs 50,000 lb, as compared to a VTOL aircraft ($T/W = 20:1$) requiring 200 naut miles which weighs only 41,000 lb. Thus, the increased flexibility of VTOL aircraft can give a definite gross weight advantage.

From an economics standpoint, the cost per pound of thrust for a lift engine is only 50% of that of the main propulsion engine. This is basically due to the simplicity and short operating times involved for lift engines. Figure 9 illustrates

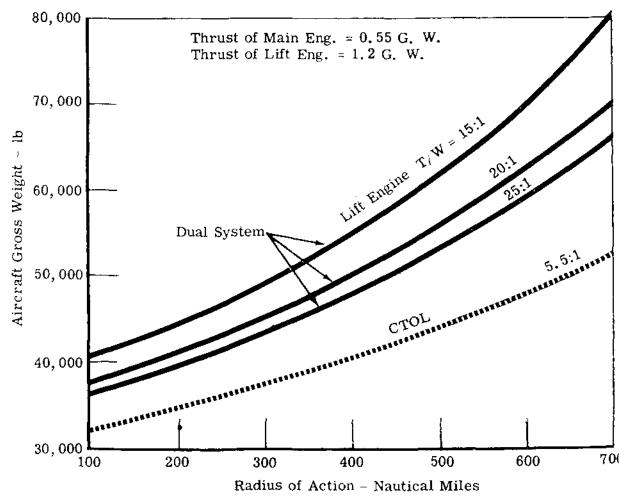

Fig. 8 Effect of mission radius on aircraft gross weight.

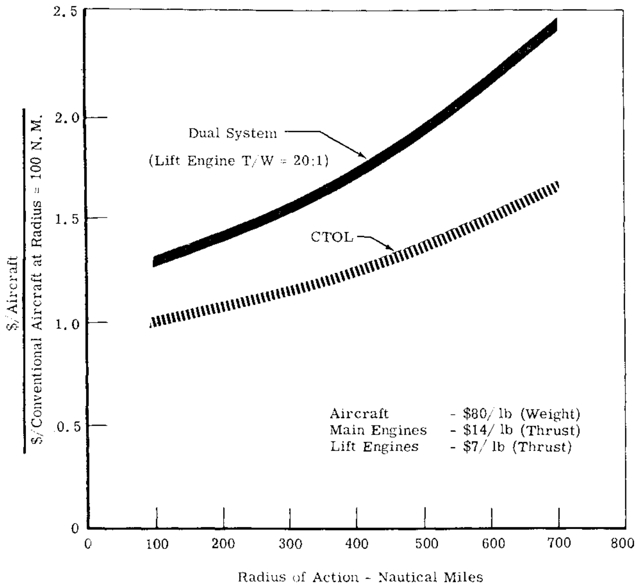

Fig. 9 Effect of VTOL on relative aircraft cost.

how this affects the economics associated with VTOL capability. The cost of a conventional aircraft with a 100-naut mile radius of action is considered as unity for this comparison. On this basis, the conventional aircraft with a 650-naut mile radius has a cost ratio of 1.58 as compared to a VTOL aircraft with a 200-naut mile radius and a cost ratio of 1.4. Thus, the VTOL fighter is not only more flexibile and lighter, but it also can be more economical.

Lift Engine Technology

The key to the attainment of efficient operational VTOL aircraft is the successful optimization of the propulsion system for specific military missions. There are many factors that have a strong influence upon the selection of a lift system for V/STOL aircraft, such as performance, weight, size, safety, and cost. The three parameters, however, that most significantly affect the ultimate selection of a lift system is the installed thrust/weight ratio, fuel consumption, and hover requirements. Figure 10 presents an historical projection of the thrust/weight ratios for both main propulsion and lift engines for the period between 1950 and 1970. A review of this projection indicates that utilizing main propulsion design techniques could only extend the thrust/weight ratio to a maximum of 12:1 in the 1970 time frame. This apparently would not be adequate as aircraft designers claim an efficient VTOL vehicle requires a minimum of 15 lb of thrust per pound engine weight from the lift system. Improvements beyond this value would greatly enhance the effectiveness of the aircraft. By adapting new engine design techniques encompassing lightweight technology, it is possible to forecast 30:1 thrust/weight ratios for lift engines in the 1970–1975 time period.

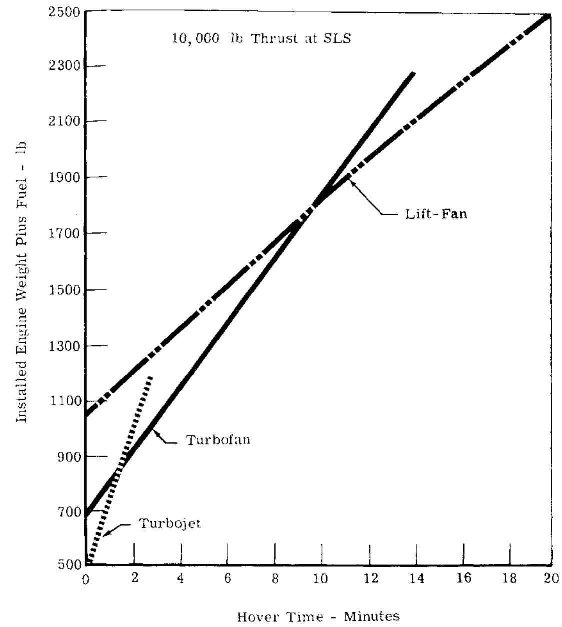

Fig. 11 Comparison of lift systems.

The large weight advantage forecasted for the lift engine is primarily associated with the operating environment and is reflected in the basic design. A lift engine is essentially simple as compared with a large single engine designed for both lift and propulsion. The lift engine is normally a low pressure ratio engine, namely, a few stages of compressor and a single stage of turbine. It does not have mechanical drives for auxiliaries, has a starting system impinging directly

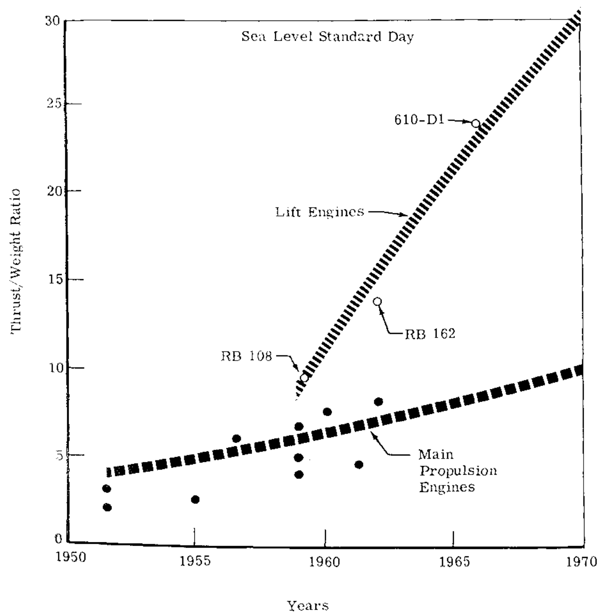

Fig. 10 Thrust/weight ratio trend for turbine engines.

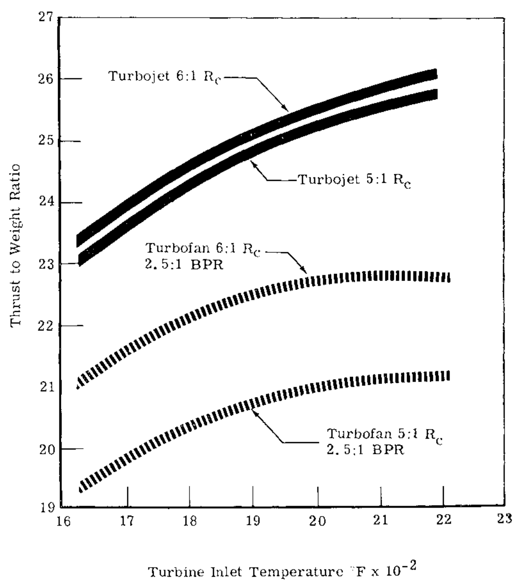

Fig. 12 Effect of turbine inlet temperature on engine thrust/weight ratio.

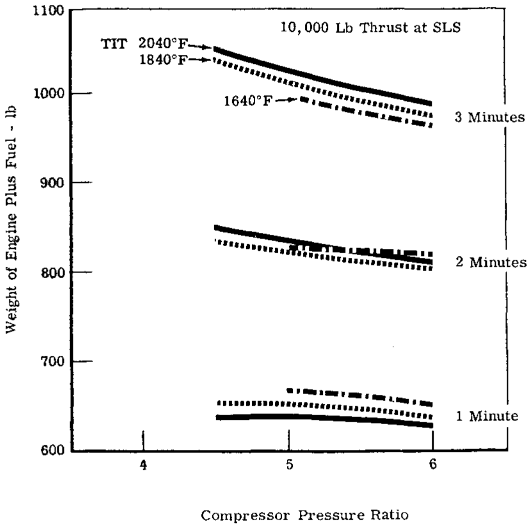

Fig. 13 Effect of turbine inlet temperature and hover time on weight of engine plus fuel for turbojet lift engine configurations.

into the turbine, and a simple fuel system that only has to operate near sea level. The attractiveness of a main propulsion engine for tactical aircraft is measured normally in terms of performance over a broad speed and altitude spectrum. The lift engine operational requirements are limited to low forward speeds, altitude, and time. This comparison can be defined best as a tradeoff of SFC for engine weight.

There are several direct lift systems that meet these criteria and the final selection will depend upon which system will result in the lowest weight in terms of installed engine weight plus fuel for preselected hovering time periods. Included in Fig. 11 is a comparison of three direct lift systems. The turbojet appears to offer the best solution for the extremely short hovering requirements (less than 2 min at maximum thrust) and the tip turbine or geared fan is optimum at extremely long hovering time periods (in excess of 8 min at maximum thrust). The turbofan lift engine falls somewhere in between and is optimum for installations that require hovering capability between 2 and 8 min. As in all aircraft designs, the selection of the lift system also will be modulated by other factors such as aircraft frontal area, volume, and control.

Within the framework of each lift system the hover requirement will affect also the choice of engine cycle parameters. The proper selection of engine cycle is quite critical in the optimization of lift engine thrust/weight ratio. The turbojet is highly sensitive to turbine inlet temperature as shown in Fig. 12. The highest turbine inlet temperature results in the highest thrust/weight ratio for the turbojet. The turbofan lift engine displays no apparent improvement in thrust/weight ratio above 2000°F. However, the turbofan is highly sensitive to pressure ratio and therefore the highest value of pressure ratio should be considered in the design of a turbofan system compatible with compressor distortion phenomena, complexity, and light weight.

The thrust/weight ratio alone is not the answer. We must assess also the attractiveness of an engine in terms of system weight, engine plus fuel. The highest turbine inlet temperature, although providing the smallest and therefore the lightest turbojet lift engine, does not always result in the lowest system weight. Since the fuel consumption is considerably higher with increased turbine inlet temperatures, it is necessary to trade fuel weight with engine weight in order to optimize the over-all system. Here again, the hover requirements cannot be treated lightly. As presented in Fig. 13, considering only 1 min of hover at maximum thrust, the weight of the turbojet engine is the most important factor and therefore the highest turbine inlet temperature would result in the lowest system weight. At 2 min of operation at maximum thrust, there appears to be a crossover with equal emphasis being assigned to both engine weight and fuel consumption. Above 2 min of operation, fuel weight becomes the discriminating factor, and, therefore, turbine inlet temperature may be reduced. Although the cooler engine may result in the lowest propulsion system weight, engine volume may be one of the overriding parameters in the ultimate selection.

Another consideration in the selection of a lift system for VTOL is the amount of bleed air required for aircraft reaction control. Engine bleed for aircraft control imposes penalties in lift engine performance, weight, and volume. Recent results from several aircraft flight test programs have indicated that the control requirements are becoming more severe and therefore a definitive evaluation of control requirements must be established before the final optimization of the propulsion system can be made. Compressor bleed penalties as shown

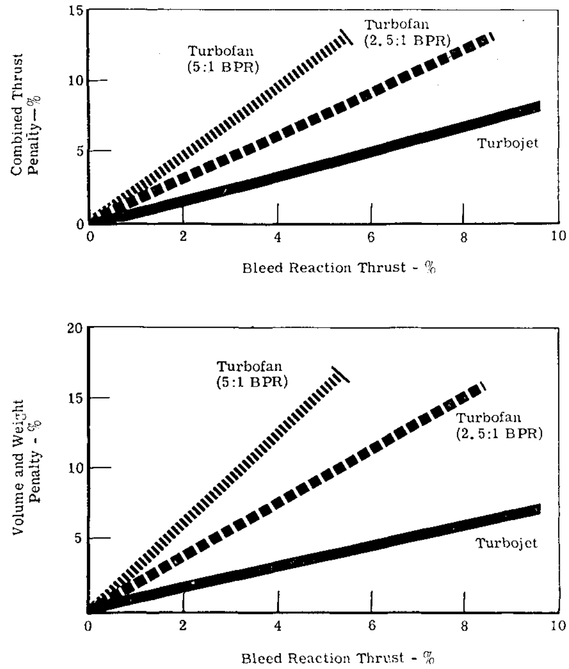

Fig. 14 Engine compressor bleed penalties for aircraft control.

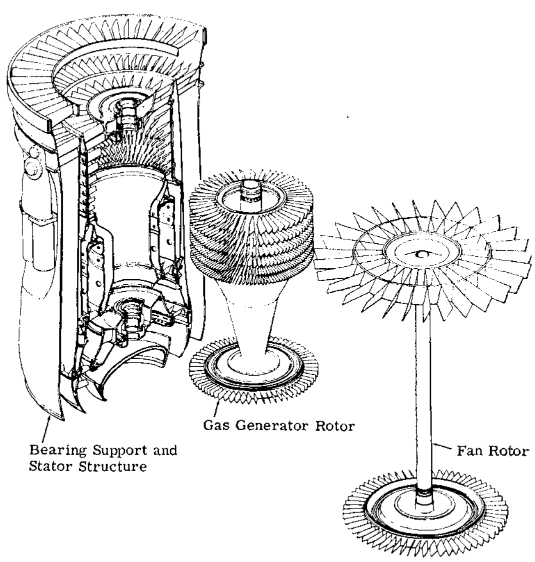

Fig. 15 Allison 610-D1 lift fan engine.

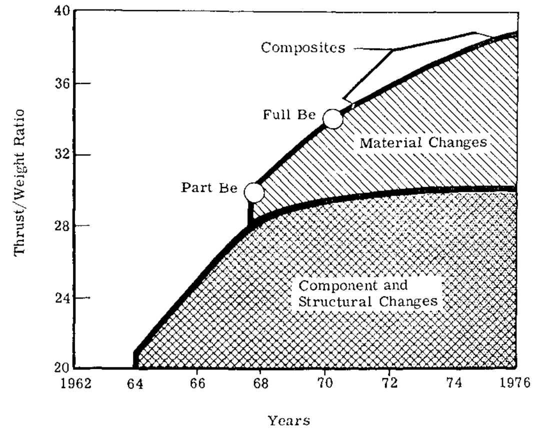

Fig. 16 Projection of lift engine thrust/weight ratio through 1975.

in Fig. 14 are smallest for a turbojet and greatest for the high bypass ratio turbofan. The combined thrust penalty is that portion of the engine thrust lost by bleeding and not fully recovered by expanding the bleed air through the aircraft control nozzles. The volume and weight penalties correspond to the increase in size and weight needed for engine thrust plus bleed reaction thrust to match the thrust of a nonbleed engine.

Lift Engine Design Features

Having reviewed the parameters that affect the design and ultimate selection of a lift engine, let us now examine the results of incorporating this technology into the physical design of a lift engine. The Allison model 610-D1 is typical of the lift fan and lift jets that are currently being considered in aircraft installations to provide VTOL capability. It represents the culmination of a maximum effort to produce a lift engine of simple design, low specific weight, relatively good fuel economy, and a high degree of reliability.

The engine employs two spool rotor systems in which the free turbine drives a forward fan. It is a simple axial-flow type with fixed inlet and jet nozzle geometry. The extensive use of titanium and aluminum, coupled with an effort to maintain a minimum volume and frontal area, has resulted in an engine with a thrust/weight ratio of approximately 22:1. Rated takeoff thrust is 10,000 lb and an SFC of 0.634. Figure 15 is an exploded view of the stationary and rotor sections of the engine.

Considering that lift engines are not required to provide any forward propulsion and need only a 50 hr time between overhaul, a new set of design criteria has been used in establishing the mechanical arrangement. Compactness has been a keynote throughout the design. The combustion section incorporates a high heat release annular burner, selected because of its well documented efficient use of space. Because of the compactness, the rotor is capable of being supported by only two bearings. The relatively limited range of altitudes and speeds during transition is reflected in the simple fuel pump and fuel control system. Engine starting on the ground is provided by air impingement from the main propulsion compressor bleed air or any other external source directed to the turbine blades. In-flight starts may also be made by windmilling the compressor, depending upon the mode of engine installation and aircraft mission flight speed.

The overhaul life of a lift engine is more dependent upon number of starts than the number of hours of running tie. Two minutes of operation at maximum thrust have been used in establishing the time between overhauls (TBO) for lift engines. An engine designed with a TBO of between 50 and

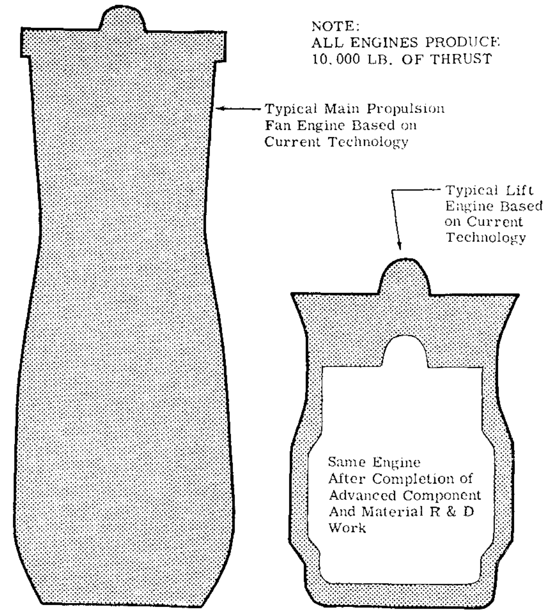

Fig. 17 Combined effect of component research and development.

100 hr of operation implies that the lift engine will only require scheduled overhauls after an accumulation of 1000 hr of aircraft flight time.

Advanced Technology

The performance and weight of the engine designs have been discussed in the context of current technology. However, studies incorporating advanced ideas indicate that the thrust/weight ratios can be greatly extended. Figure 16 presents a forecast of the areas in which improvement in thrust/weight ratios can be made and the levels that can be attained. The forecast of improvements in thrust/weight ratio is generated by two primary factors: component and structural design improvements and basic material changes. The component and structural improvements would provide thrust/weight ratios of approximately 30:1 in 1972 using conventional materials. However, through the inclusion of advanced materials, such as beryllium, Marage steels, and metallic fiber composites, it appears possibile to achieve thrust/weight ratios in the order of 40:1 in the 1980 time frame. A comparison of the relative sizes is shown in Fig. 17.

To accomplish this objective requires technological advancements in the area of high stage loadings for fans and compressors, thermodynamic improvements associated with high heat release combustion, improvement in performance of turbines and nozzles, and all of this coupled with advanced material development. Results of this effort could then produce the next generation of lift engines which would be smaller in diameter, shorter in length, lighter in weight, and even better in performance. A strong research program encompassing these activities has been generated by both the military services and engine contractors, and continuation of this extensive effort is strongly urged in order to assure the ultimate success of future lightweight propulsion systems.

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