A Concise Approach to V/STOL Propulsion

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The goal of the article is to present a broad-based analysis of the aircraft design requirements imposed by the capability for V/STOL. The cost in terms of aircraft gross weight to provide this capability is the basic theme. The method of approach capitalizes upon simple and traditional concepts to develop fundamental notions concerning V/STOL technology. Although the basic discussion is centered about propulsion system aspects, a broad perspective of the interrelationships among propulsive, aerodynamic, and mission requirements is provided. In addition to introducing a generalized approach to V/STOL propulsion technology, the results of several comparison studies showing the relative effects of various propulsion system concepts are discussed. A logical result of the discussion, after having indicated the present state of the art, is an outline of the areas that most significantly affect the size of V/STOL aircraft. The most significant point is the importance of evaluating the relative merit of V/STOL concepts under a fair and consistent set of ground rules. Examples of how the balance of relative superiority can be upset by slight modifications to mission requirements are shown to emphasize this point.

Introduction

DURING the last few years, many prototype versions of V/STOL aircraft have been appearing within the European and American aerospace industries. The great array of aircraft configurations, which represent an equally great spectrum of propulsion system concepts, is an indication of the diversity of opinion about how to "go" V/STOL. The incentive to provide this capability in modern aircraft is the result of an increasing demand for operational flexibility. For example, the utility of military vehicles such as direct support fighters and surveillance aircraft could be expanded significantly through the capability for V/STOL. Another possibility would be the reduction of passenger travel time to and from commercial airports, by locating terminals in relatively urban locations which could accommodate V/STOL transports.

For whatever the application, however, the price of V/STOL capability in terms of aircraft weight (size), which recent studies have shown could be inordinately high, must be held down. The fact that operation in the vertical mode occupies a small fraction of the total operational span emphasizes the requirement of insuring that the weight penalty is in fair proportion to the increased utility afforded by the V/STOL capability.

The requirement of providing V/STOL capability affects all of the basic disciplines involved in aircraft design. A clear understanding of the over-all picture can be obtained by adopting a broad perspective that highlights the interrelationships among the engine, propulsion system, and aerodynamic configuration. Fundamental parameters that describe gross effects such as aircraft lift/drag ratio; propulsion system thrust/weight ratio; and the relative engine size, total rated cruise engine thrust/VTO gross weight, provide adequate tools for a comprehensive and straightforward discussion. Since the propulsion system represents the most radical departure from conventional aircraft concepts, it is desirable to start here to develop the over-all picture.

Propulsion System Requirements

A well-designed propulsion system provides the most efficient use of hardware and fuel weight. Criteria that characterize efficiency are the ratios of thrust/hardware weight, and fuel weight flow/thrust, generally known as the thrust/weight ratio (T/W) and specific fuel consumption (SFC). It is clear that T/W should be maximized and SFC minimized. For presently available engines, the latter requirement calls for operation at or near maximum unaugmented power. Operation at lower (or higher) power settings corresponds to less efficient use of fuel.

Relatively high thrust demands resulting from extreme performance requirements such as acceleration, V_{max}, combat ceiling, etc., dictate larger engine sizes for the same basic engine cycle than from cruising flight considerations alone. To satisfy these higher power demands, a relatively higher SFC must be tolerated during the low-thrust but long-duration cruise flight. This results in heavier fuel loads that, in turn, dictate heavier airplanes and/or compromised performance. One standard way of getting around this obstacle is to provide the ability for changing the basic engine cycle in flight, e.g., add an after-burner.

The provisions for vertical takeoff capability may be considered as a high-thrust demand extension of a basic set of mission requirements. In this case, however, the maximum thrust requirements are on the order of the gross take-off weight, which is vastly greater than any inflight requirement. In addition, the added weight of devices for providing vertical thrust tends to compound the problem. Two limiting methods for providing VTO capability may be generalized as follows.

If the cruise engines are used to provide all of the vertical thrust, then the takeoff condition sizes, the engine, and the propulsion system will be poorly matched to the aircraft during cruise operation. It might be suggested that aircraft that must satisfy high inflight thrust requirements tend to remove or share the "blame" for the mismatch, with the VTO requirement. However, even the highly thrust-loaded century series aircraft (Mach 2.0) have a total takeoff thrust rating of only some 70% of the gross takeoff weight, and this includes thrust augmentation caused by afterburning.

On the other hand, if the cruise engines are not used at all for providing lift, and if a number of vertically oriented lifting devices, such as lift engines or lift fans are being used, then the cruise engine and fuel load size are still affected. The incremental system weight and poorer aerodynamic efficiency (lift/drag), which must be tolerated throughout the mission, seriously can affect propulsion system performance. Therefore, since the cruise engine size is related intimately to the aircraft weight, it is reasonable to speak of the relative engine

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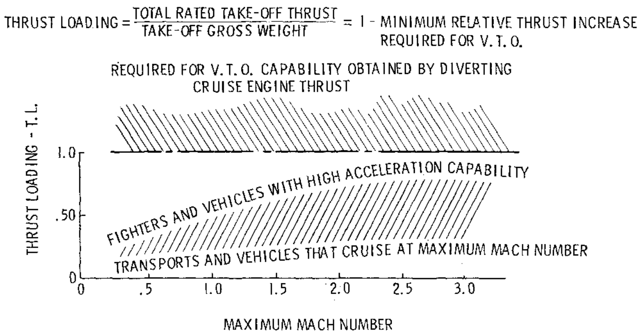


Fig. 1 VTO thrust deficiency of jet aircraft.

size as the ratio of the total rated cruise engine thrust to takeoff gross weight. This ratio is denoted as thrust loading.

Thrust loading = relative cruise engine size $N_H \times F_{N*}/W_0$

where N_H = number of cruise engines
F_{N*} = rated cruise engine thrust (maximum, horizontal, sea level, static)
W_0 = aircraft takeoff gross weight

In general, high values of thrust loading correspond to relatively "peppy" aircraft with strong acceleration capability. Fighters have thrust loading values on the order of 0.50–0.70 and transports range between 0.20–0.35. This is shown in Fig. 1, which points out that high maximum speed requirements alone provide little or no improvement toward reducing the cruise thrust mismatch that results from providing VTO with diverted cruise engine thrust. The high-thrust loadings of military aircraft stem from relatively stringent requirements, such as acceleration and combat ceiling criteria. Now, using the notion of a relative cruise engine size, or thrust loading, the relative effect of any propulsion system concept upon aircraft size may be clearly shown. But first it is necessary to define the required bookkeeping methods.

Propulsion System Weight Fraction

It is convenient to consider the cruise engine gas generator as the fundamental building block of the propulsion system. In addition to the weight of the hardware required to make it an engine (nozzle, afterburner, accessories, etc.), the weight required to install the engine in the aircraft (ducts, controls supports, closures, etc.) must be included in the total propulsion system weight. The primary objective is to relate fundamental gas generator characteristics to the aircraft VTO gross weight.

First, it must be recognized that the fraction of the VTO weight, which is required by the propulsion system hardware, is slightly greater than the reciprocal of the installed propulsion system thrust/weight ratio. This reasoning may be applied to relate the propulsion system weight fraction to the gas generator thrust/weight ratio using installation factors, as follows:

$$\frac{\text{propulsion system weight}}{\text{VTO gross weight}} = \frac{L/W}{(T/W)_{\text{installed}}} = \frac{L/W}{(T/W)_{\text{gas generator}}(R_T/R_W)} \tag{1}$$

where L/W = ratio of installed lift to VTO gross weight
R_T = Ratio of installed lift to gas generator thrust
R_W = Ratio of installed weight to gas generator weight

The right-hand side of Eq. (1) is strictly true only for diverted cruise engine thrust propulsion systems. However, it is instructive to examine the general nature of this relationship, as shown in Fig. 2. Also shown is the growth of the propulsion system weight fraction of a lift-cruise engine concept as various components are added to the gas generator. The major point to be made by the general curve is the rapid improvement in weight fraction as relatively low thrust/weight ratios are increased, and the less spectacular weight reductions stemming from improvements in high thrust/weight ratios.

It is interesting to consider that this diminishing return type of relationship might be somewhat representative of the course of VTOL propulsion system development. It is important to bear in mind that improvements stem from both the engine and the airframe manufacturer's efforts.

This relationship also shows the relative effects of mixing high thrust/weight lifting devices with low thrust-to-weight diverted thrust cruise engines to achieve efficient V/STOL propulsion systems. For instance, an improvement of 33% in weight fraction could be achieved by mixing equal parts of 15:1 lift engines with 5:1 lift-cruise engines. The resultant system lift-thrust/weight would be

$$T/W = 2/(+ \tfrac{1}{15}\ \tfrac{1}{5}) = 7.5.$$

In addition, the cruise engine size may be made more compatible with the relatively low in-flight thrust requirements, thus providing more efficient use of mission fuel.

The format of Fig. 2, although useful in general context, is not the most practical means of viewing the V/STOL propulsion system weight fraction picture. By considering the relative size of the cruise engine (the thrust loading), a more practical view point may be obtained. For instance, V/STOL propulsion systems that provide all of the lift by diverting cruise engine thrust can have only one value of thrust loading, which is equal to the lift/weight ratio L/W for an ideal installation. If we now consider that the cruise engine size is continuously reduced and that the supplemental

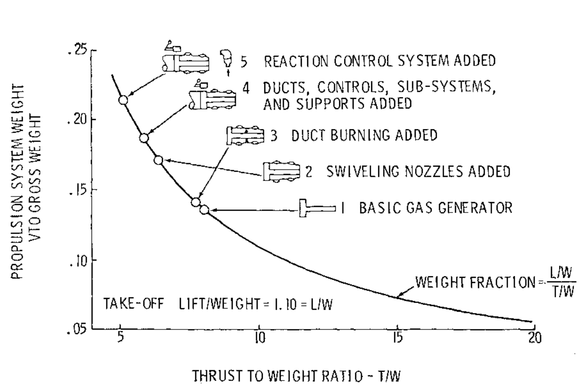


Fig. 2 Weight fractions of V/STOL propulsion systems.

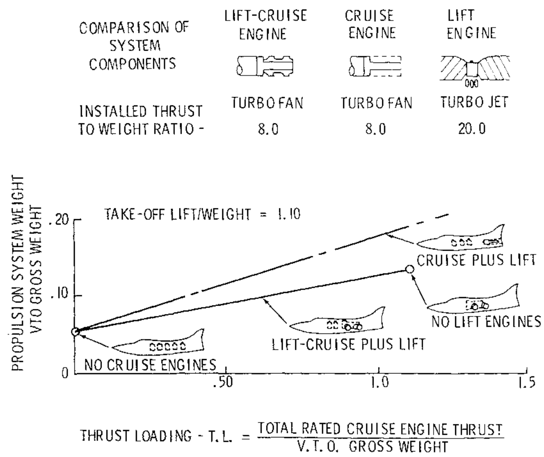


Fig. 3 Mixed V/STOL propulsion systems with low installation penalties.

lift is provided by relatively high thrust/weight ratio lifting devices, then the propulsion system weight fraction and the thrust loading also are reduced continuously. As a thrust loading of zero is approached, the weight fraction approaches a lower limit corresponding to the high thrust/weight of the lifting devices. The vehicle takes on the aspects of an elevator. This is described in Fig. 3, which also shows the case corresponding to deriving all of the lift from vertically oriented lifting devices.

It is interesting to note that the relative effects of various V/STOL propulsion concepts may be compared in Fig. 3 without consideration of the absolute size of any of the engines or the aircraft. However, sizing any one of these items immediately determines the required size of the others. An important point stems from the fact that the engine thrust-to-weight ratios have been assumed constant throughout the range of permissible engine scaling. Experience has shown that a maximum variation of only 2% in weight fraction results from this simplification.

The lift engine plus cruise engine concept is heavier relatively at any cruise engine size, based upon the ground rules of Fig. 3. If we consider a thrust loading requirement of 0.70 based upon some stringent inflight criterior, then the cost in propulsion system weight fraction for not utilizing cruise engine thrust to provide lift is about 3.5%.

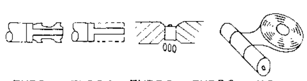
The thrust/weight ratios of Fig. 3 correspond closely to presently quoted values for advanced gas generators. The effects of moderate installation penalties upon thrust and weight are shown in Fig. 4, which includes the lift-fan plus cruise engine concept. The available range in thrust loading for this type of system is limited by the range in fan augmentation ratio, hence the fan pressure ratio limitations shown in the figure. A greater range of thrust loading may be provided by employing larger afterburning augmentation ratios and/or by adding a number of isolated cruise engines. In addition to the weight fraction of propulsion system hardware, the weight fraction of fuel required to meet mission demands also reflects the relative merit of propulsion system concepts and will be discussed next.

Fuel Weight Fraction

A significant fraction of the total fuel load may result from the lift-off and hovering requirements of VTOL aircraft. During hovering operation, the power requirements are continually diminished as fuel is consumed and radically differ between the takeoff and landing modes. Figure 5 shows the effect of duration of hover for several typical systems. As the duration grows above 2 min, the low *SFC* of the highly augmented lift-fans provides a significant advantage. It is important to remember, however, that a meaningful comparison must be based upon the sum total of all of the mission leg requirements.

In order to examine the relative merit of various propulsion system concepts with regard to the efficient use of fuel, it must be understood that an engine's *SFC* characteristics cannot tell the complete story. The fuel used during a mission leg reflects not only the engine's cycle efficiency in terms of *SFC*, but also the complete vehicle's aerodynamic efficiency in terms of the lift/drag ratio. The methodology shown in Fig. 6 indicates the engine-aircraft matching procedure and shows the relative effects of the key factors.

	LIFT-CRUISE ENGINE	CRUISE ENGINE	LIFT ENGINE	CRUISE ENGINE PLUS LIFT FAN			
COMPARISON OF SYSTEM COMPONENTS							
	TURBO FAN	TURBO FAN	TURBO JET	TURBO JET	TIP FAN	TURBINE PRESSURE	FAN RATIO
THRUST AUGMENTATION OF GAS GENERATOR -	30%	30%	0	40%	1.10	1.20	1.30
THRUST TO WEIGHT RATIO OF GAS GENERATOR OR LIFT FAN -	8.0	8.0	20.0	8.0	14.0	23.0	30.0
INSTALLED THRUST TO WEIGHT RATIO -	5.2	6.8	11.0	-	5.6	6.2	6.1



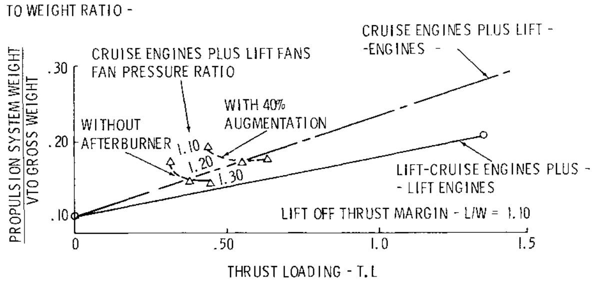


Fig. 4 Mixed V/STOL propulsion systems with moderate installation penalties

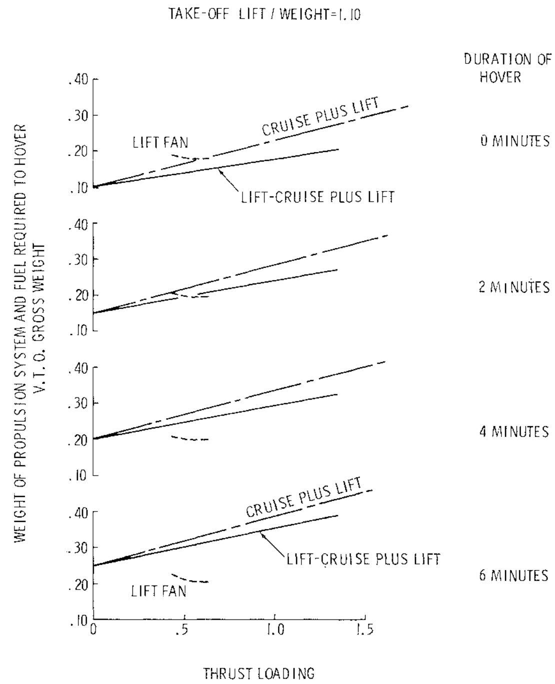


Fig. 5 Comparison of hovering fuel requirements.

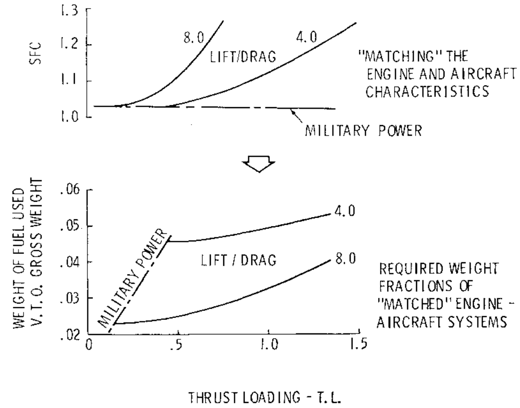


Fig. 6 Development of fuel weight requirements for rubberized engine-aircraft systems.

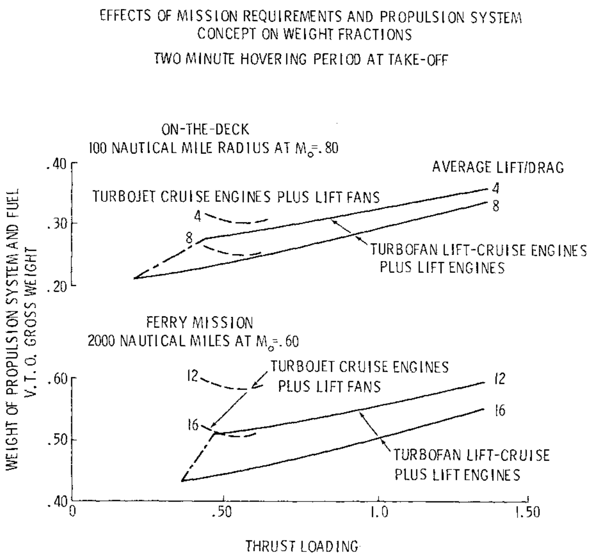


Fig. 7 Effects of mission requirements and propulsion system concept on weight fractions.

Figure 7 presents a comparison of the propulsion system plus fuel weight fraction requirements for two typical V/STOL concepts, corresponding to an on-the-deck mission and a ferry mission. The following points are emphasized.

1) The relative merits of several propulsion systems must be examined under a set of ground rules which distinguishes the various configuration factors such as L/W, L/D, etc.; no attempt has been made to do this in Fig. 7.

2) The comparison shown basically reflects the fact that turbofans have better *SFC* characteristics than turbojets at the given flight conditions. If a midmission hover requirement were considered, such as a rescue mission, or if the take-off hover period were extended, the relatively low hovering *SFC's* of the lift-fan might change the picture significantly.

3) Nonperformance considerations such as ground erosion, noise, safety, and cost effectiveness criteria may dictate a strongly controlling influence upon propulsion system selection.

The most significant point to be made by the curves of Fig. 7 is that the minimum weight fractions occur at military power, which corresponds to the lowest values of thrust loading (relative cruise engine size). This characteristic underscores the serious consequences resulting from sizing the cruise engine to provide all or even large portions of the total VTO lift. The picture provided by Fig. 7, although it includes the aspects of matching the engine to the aircraft and the aircraft to the missions, does not provide the final answers.

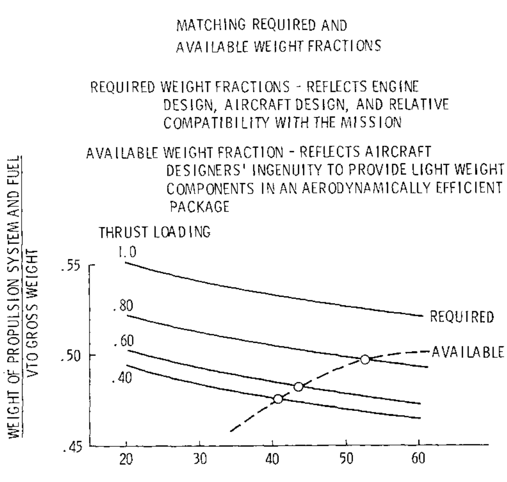


Fig. 8 Matching required and available weight fractions.

Aircraft Sizing

Although the required total weight fractions are known, it is not possible to know the aircraft and engine sizes until the available total weight fractions have been determined. The availability of propulsion system plus fuel weight is determined by subtracting the weight of all the other aircraft components from the aircraft gross weight. The available weight fraction may be expressed as follows:

$$\begin{array}{l}\text{Available weight fraction of} \\ \text{propulsion system and fuel}\end{array} = 1 - \left\{ \begin{array}{l} \dfrac{\text{fuselage weight}}{\text{aircraft gross weight}} + \\ \dfrac{\text{wing weight}}{\text{aircraft gross weight}} + \\ \dfrac{\text{control system weight}}{\text{aircraft gross weight}} + \\ \dfrac{\text{empennage weight}}{\text{aircraft gross weight}} + \\ \dfrac{\text{fixed weight items}}{\text{aircraft gross weight}} \end{array} \right.$$

The component weight fractions must be minimal and consistent with the lift/drag characteristics that already have influenced the required propulsion system plus fuel weight fractions. This is the crux of the matter. The airframe manufacturer's experience and ingenuity are put to the test when he is asked to minimize component weight fractions and to maximize aircraft lift/drag characteristics. Figure 8 compares the required and available weight fractions of the propulsion system and fuel. The rapidly increasing penalty in aircraft size with relative cruise engine size (thrust loading) indicates that the state of the art is being taxed.

It is interesting to note that the required weight fractions of Fig. 8 have been transcribed from Fig. 7 by taking account of a small but significant variation of lift/drag ratio with gross weight. If this relationship had been ignored, and the lift/drag ratio considered to be strictly a function of Mach Number, then the required curves of Fig. 8 would be horizontal lines resulting in larger matched aircraft gross weights. The basic point to be made here is the relatively large effect upon gross weight of small changes in aerodynamic efficiency, lift/drag.

Therefore, we can see how important it is not only to insure high lift/drag ratios and low component weight fractions, but also to be able to predict these values accurately. Now, it has been shown that the required fuel weight is strongly dependent upon the lift/drag ratios attainable, which, in turn, reflect the efficiency with which the components have been integrated. This interplay of technology is a fundamental factor in establishing the state of the art for all types of aircraft.

It is interesting to consider the available and required curves of Fig. 8 as supply and demand characteristics. In this view, the age-old addage holds, i.e., the more available the supply or the less exacting the demand, the less expensive the cost.

Nonperformance Considerations

The cost in aircraft weight to design into the vehicle the capability to meet stringent mission requirements appears to be an extremely sensitive factor. Improvements or inaccuracies in design parameters or component weights which reflect weight fraction changes on the order of 1% can mean as much as 10% in aircraft gross weight. Furthermore, heavier aircraft are required to accommodate the relatively high thrust loadings demanded by combat ceiling and V_{max} criteria (Fig. 9).

All of the considerations involved in determining the fair price of V/STOL, or any other stringent mission requirement, are not confined to performance characteristics. An important and possibly controlling consideration is that of safety. For VTOL aircraft, this might mean the ability to recover a hovering vehicle after it has lost an engine. The ramifications of such a requirement tend to limit the possible propulsion system concepts. For instance, the single diverted cruise engine case is eliminated, and the twin diverted cruise engine case would require that the basic engines, which are sized to lift the vehicle, be capable of emergency thrust augmentation on the order of 70–100%. In addition, the latter case would be limited to arrangements that require little or no trim correction caused by one engine operation.

As we consider propulsion system concepts that employ more and more engines to provide lift, whether diverted thrust cruise engines or pure lift engines, the requirement for basic lift thrust augmentation for a one-engine-out contingency is reduced. However, since operating and maintenance considerations will limit the number of engines allowable in a practical aircraft, some significant emergency augmentation capability or basic engine oversize will be required to satisfy safety requirements. The excess propulsion system hardware resulting exclusively from safety considerations will be manifested in larger required weight fractions and, thus, greater aircraft gross weights. It is interesting to note that, owing to the turbomachinery characteristics of lift-fans driven by cruise engines, these systems incur a loss of only 35% of the total lift with half of the cruise engines inoperative.

Just as safety considerations dictate propulsion system weight penalties through the requirement for excess thrust during emergencies, so do stability control criteria dictate similar penalties. The control forces required to maintain the stability of hovering aircraft are strongly dependent upon the propulsion system arrangement and the aircraft gross weight, because these two factors significantly affect the vehicles' inertial characteristics, e.g., mass and distribution of mass. The price, in terms of aircraft gross weight, which must be paid to provide the control forces, primarily is dependent upon the same factors. The weight and volume penalty for reaction control ducting is minimal generally when the control fluid is made available at high pressures and low temperatures. However, the performance penalty of a gas generator is relatively large when bleed flow is tapped at high cycle pressures. These fundamental considerations must be weighed in conjunction with the complexities of employing burning, ejectors, lift-fans, etc., to arrive at the solution that provides adequate control forces and incurs the smallest penalty in aircraft gross weight.

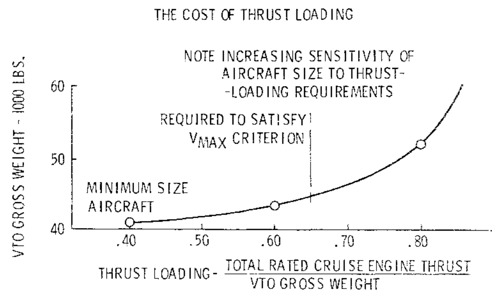


Fig. 9 Cost of thrust loading.

Conclusions

The fundamental point that may be drawn from the preceding discussion is not a very startling one, but a very important one. This is, that the best propulsion system concept for any V/STOL aircraft is related intimately to the mission requirements, safety and stability criteria, and ingenuity of the designer.

Each of the V/STOL concepts that comprise the total spectrum now before the industry will probably fill a role that has yet to be defined. The selection of the proper propulsion system concept for any set of design requirements, however, is beyond intuitive approach, owing to the inordinately large array of candidate engines and concepts. The approach presented herein can provide the basis for an effective method of attacking the problems.