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PRELIMINARY STUDY OF PROPULSION SYSTEMS AND AIRPLANE WING PARAMETERS FOR A U. S. NAVY SUBSONIC V/STOL AIRCRAFT

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16. Abstract

Two V/STOL propulsion concepts are evaluated in a common aircraft configuration. One propulsion system consists of cross-coupled turboshaft engines driving variable-pitch fans. The other system is a gas-coupled combination of turbojet gas generators and tip-turbine fixed pitch fans. Evaluations are made of endurance at low altitude, low speed loiter with equal takeoff fuel loads. Effects of propulsion system sizing, bypass ratio, and aircraft wing planform parameters are investigated and compared. Shaft-driven propulsion systems appear to result in better overall performance, although at higher installed weight, than gas systems.

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Preliminary Study of Propulsion Systems and Airplane Wing Parameters for a U.S. Navy Subsonic V/STOL Aircraft

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SUMMARY

Performance is evaluated for two V/STOL propulsion concepts in a common aircraft configuration. One propulsion system consists of cross- coupled turboshaft engines driving variable- pitch fans. The other system is a gas- coupled combination of turbojet gas generators and tip- turbine fixed pitch fans. The systems are evaluated primarily for endurance at low altitude, low speed loiter with equal takeoff fuel loads. Effects of propulsion system sizing, bypass ratio, and aircraft wing planform parameters are investigated and compared. Results show reasons for preferring low bypass ratio in either gas- or shaft- driven propulsion systems. Shaft- driven propulsion systems appear to result in better overall performance, although at higher installed weight, than gas systems. At gross weights and wingspans of interest for the aircraft, low wing areas appear preferable. Increased wingspan appears desirable, but may exceed practical limits for the type of aircraft studied.

INTRODUCTION

This study presents preliminary results of an evaluation of propulsion systems for a subsonic V/STOL type of U.S. Navy aircraft intended to operate from small ship facilities. Projected use of the aircraft emphasizes V/STOL capability along with long endurance, making the choice of propulsion system critical in terms of performance and weight.

The background of this study lies in original proposals for such V/STOL aircraft made by The Boeing Company and McDonnell Douglas Aircraft (references 1 and 2). The Boeing airplane used a propulsion system, proposed by Detroit-Diesel Allison (DDA), consisting of cross- coupled turboshaft engines driving variable- pitch fans. The McDonnell proposed airplane was to be powered by a General Electric (GE) propulsion system which is a gas- coupled combination of turbojet gas generators and tip- turbine fixed- pitch fans. These studies were complete preliminary designs which included airplane aerodynamics, aircraft weight schedules, and propulsion system weight breakdowns. The propulsion system bypass ratios, component efficiencies, and operating characteristics were outlined and specified. Thus, comparisons of the two propulsion systems, such as reference 3, were based only on these particular proposals.

The purpose of this study is to compare performance for the two basically different V/STOL propulsion systems over a wide range of bypass ratios and system sizes. Propulsion system variations are to be derivatives of the basic systems described in references 1 and 2. In this study, to allow greater focus on the propulsion system comparisons, the two systems are installed in a common aircraft configuration with equal fuel load. A brief examination is also made of the effect of aircraft wing area and wingspan. Other topics such as life cycle costs, reliability, maintainability, and vulnerability are also important but are not considered here.

The discussion and study results are presented in four main parts. The first part covers cycle performance and weight of the shaft- coupled and gas- coupled systems at different bypass ratios. This part of the study makes use of the NNEP and WATE-1 engine cycle and engine weight computer codes described in references 4 and 5. The next part of the study evaluates and compares the performance of the baseline propulsion systems on a baseline aircraft. For the same baseline aircraft, the third part of the results shows the effect on performance of propulsion system size, bypass ratio, and mission constraints. The final part of the results investigates the combined effects of the aircraft wing area and span, mission requirements, and propulsion system bypass ratio on selecting the total system.

ANALYSIS AND PROCEDURE

Aircraft Configurations

For comparability, the gas- and shaft- driven propulsion systems are assumed installed in similar aircraft with equal mission objectives. The nominal configuration shown in figure 1 is a medium- gross- weight, low- wing aircraft with three high- airflow fans and two gas generators or turboshaft cores installed as the propulsion system. The shaft- driven aircraft in figure 1(a), and the gas- driven aircraft in figure 1(b) have one fan installed in the nose section of the fuselage which is remotely driven for V/STOL maneuvers, but is inoperative during cruise. The remaining two fans are located on or near the fuselage, aft of the wing leading edge. The cores are in the nacelles, as in the shaft system, or are located in the fuselage, as in the gas-driven system of figure 1(b).

The two aircraft are assumed, as much as possible, to have common design features in the wings, tail section, and fuselage. Specific differences in configuration are intended to provide a more suitable match for each propulsion system. Hence, in this study, the shaft- coupled system uses body-mounted tilting nacelles aft of the wing whereas the gas-coupled system has over-the-wing partially-blended fixed nacelles with lobster- tail type deflecting nozzles.

The shaft- driven aircraft in part(a) of figure 1 shows the cross- shafted tilting nacelles containing the turboshaft cores and geared, variable pitch fans. The necessary combiner-box/transmission with forward shafting to the nose fan is also shown. The gas- driven aircraft shown in figure 1(b) illustrates the assumed placement of the gas generator cores, their inlets, and necessary ducting. The lift/ cruise nacelles containing the tip- turbine fans are shown cross-ducted through the fuselage.

An airframe weight model is used in this study which reflects the higher internal fuselage requirements of the gas- driven system suggested by the schematic. On the other hand, wing weight for a given span is lower in the gas aircraft than the shaft aircraft due to structural support given by the partially blended nacelles.

Mission Definition

The baseline mission is shown schematically in figure 2. This mission is not intended to correspond to any specific military requirement but rather has been set up as a reasonable framework for system performance comparisons in the present study. In the following performance evaluations, segment (A), takeoff, is either vertical (VTO) or short takeoff (STO). The ground rule used in the present study specifies that a vertical takeoff is only possible when the ratio of vertical thrust to airplane gross weight equals or exceeds 1.08 . This value allows for a 3 or 4 percent thrust loss due to suckdown effects at VTO initiation. The alternative takeoff mode, STO, is assumed possible as long as the thrust to weight ratio is 0.80 or greater. As noted in the figure, both STO and VTO are assumed to require 2.5 minutes at maximum power.

Operating radius, defined as the distance from takeoff to the loiter area, is 150 n.mi. in the baseline mission. For conservative purposes, no distance credit is given for climb to cruise, descent to loiter, or climb to return cruise. Hence the outbound and return cruise distances are equal to the operating radius. Each cruise leg allows selection of the best cruise altitude and velocity (BCAV) to minimize fuel usage on that leg but in all cases, the loiter altitude is 10 000 feet. Loiter Mach number is optimized to yield maximum time on station (TOS) at the loiter altitude. However, in any case, loiter Mach number is restricted to lie between 0.30 and 0.60 .

The baseline mission emphasizes endurance at the loiter conditions of low altitude and Mach number. Hence, for contrast, an alternate "all cruise" mission is noted at the bottom of figure 2. The purpose of this mission is to place more emphasis on sustained cruise capability by evaluating the maximum operating radius (RMAX) of a given aircraft when no low altitude loiter is required. This mission will be used later in this study to evaluate the alternate mission role of aircraft designed to meet the specific objectives of the primary low altitude loiter mission. In addition, regardless of the mission, a possible one-engine-out (OEO) emergency situation must also be satisfied in that the aircraft must land vertically with a thrust/ weight of at least 1.03 with the three fans powered by the one remaining core engine. The impact of this emergency vertical landing (EVL) requirement will be discussed later.

Aerodynamics

For both gas and shaft propulsion systems, the present study assumes that aerodynamic drag characteristics of the general aircraft configuration of figure 1 are the same. Examples of the total drag coefficient, C_D , as a function of lift coefficient, C_L , and flight Mach number are shown in figure 3. As noted in the figure, the aircraft for this example has a body fineness ratio of 6 and a wing planform with aspect ratio (AR) of 5, taper ratio of 0.33, and a mean thickness/ chord of 0.18 . In this figure the baseline aircraft has a zero- lift drag coefficient (C_{Do}) of 0.035 . It is assumed that external stores are already mounted on the aircraft, contributing a drag coefficient increment of about 0.0030 . The curves in the figure are based on the drag relation

$$C_D = C_{Do} + \frac{(C_L - C_{Lo})^2}{\pi \epsilon AR}$$

where the Oswald efficiency, ϵ, of the wing planform is a function of both C_L and Mach number. The effect of ϵ produces a sharp drag rise at Mach numbers above 0.7 and alters the parabolic nature of the C_D versus C_L curves at C_L values above 0.3 .

Engine Calculations

Propulsion system variations for the present study are assumed to be derivatives using, as a baseline, the cores, fans, and other parts of the gas and shaft systems proposed in references 1 and 2. To simulate the two baseline propulsion systems (an advanced DDA T701 with Ham. Std. Fan for the shaft system and advanced GE J97 with LF459 Fan for the gas system - both unscaled), it was necessary to have component performance maps. These were obtained from the appropriate company (DDA or GE) and incorporated into the NNEP computer code (ref. 4) to calculate the engine performance. The computer simulation was matched to baseline engine performance supplied by GE and DDA for the gas and shaft systems, respectively. The cycle simulations adhered to component limits, such as on speeds and temperatures, imposed by the manufacturers. The optimization capability of NNEP was also employed to adjust fan pitch setting and bypass nozzle area for the shaft system and nozzle area for the gas system to maximize vertical thrust ratings or to minimize SFC at part-power operation. Engine component weights were also calculated using the WATE-1 computer code (ref. 5) for later inclusion in estimates of the weights of the installed propulsion systems. These system weights will be discussed later.

The shaft system was modeled to have a water injector between the fan and the advanced T701. When water was used, an amount equal to that required to saturate the airflow at the compressor face was assumed in calculating basic engine performance. For conservatism, later mission studies for the shaft system assumed less thrust augmentation for water injection, corresponding to 80 percent of the saturation water flow rate. For the gas system, 4 percent water injection before the combustor was used in calculating the performance data base. Later mission studies indicated that 6 percent water was required.

In the present study, the term water injection actually refers to water-alcohol mixtures to avoid freezing. Water injection thrust augmentation is often considered objectionable on the basis of adverse effects on engine operation such as vibration and material problems. However, the use of water injection as applied here is restricted to emergency conditions, making the question of reduced engine life academic.

Tropical day (std.+31°F) sea level static performance for 2 fans on (i.e. driven by) 2 cores, 3 fan- 2 core, and 3 fan- 1 core modes with and without water injection are shown in Tables I thru V for the shaft and gas systems at different nominal bypass ratios (BPR). Each system has a baseline or originally suggested BPR in references 1 and 2. The gas system was proposed at a BPR of 8.02 and the shaft system at 12.2 .

Table I shows thermodynamic cycle data for the gas and shaft systems in the 2 fan- 2 core cruise configuration where no power is supplied to the nose fan. Fan size (airflow) is varied to reflect different BPR while the core sizes are held constant by keeping the core corrected airflow, $W\sqrt{\theta}/\delta$, a constant in each system. Bypass ratios of 6.0, 8.02 (baseline), 10.0, and 12.0 are shown for the gas system. In the last three columns of Table I, the shaft system data is listed for BPR of 8.0, 10.0, and the baseline value of 12.2 . Similar data is given in Tables II and III for normal vertical (3-on- 2) operation, and in Tables IV and V for the emergency thrust (3-on- 1) mode. The nose, or third, fan at each system BPR is assumed the same size as the lift/cruise fans. The data of Table III for water injection during normal VTO (3-on- 2) is not used in the present study but is included for general interest and to indicate the thrust augmentation possibilities of water injection in this mode.

In generating the data of Tables I thru V for the gas system, combustor exit temperature (CET) is limited to 2700°R for both 2-on- 2 and 3-on- 2 operation. A CET limit of 2875°R is allowed in the emergency (3 fan- 1 core) mode of Tables IV and V. Compressor relative speed ($N/\sqrt{\theta}$) is limitted to less than 101.4 percent in 3- on- 2 operation and to less than 105 percent during emergency operation, as seen in Tables III and V.

For the shaft system, CET is restricted to 2880°R or less for 2-on- 2 operation, 3000°R for 3-on- 2, and 3200°R for the 3 fan- 1 core mode. Such higher CET limits for the shaft system relative to the gas system are, for the most part, due to temperature limits of the duct material of the gas system, which must carry hot gas to other parts of the airplane. Some differences in technology level assumed by GE and DDA may also exist, but these are beyond the scope of this study. Compressor relative speed is limitted to 105 percent in 2 fan- 2 core or 3-on- 2 operation and 10 percent overspeed is allowed in the emergency mode. The geared fan in the shaft system is allowed no more than 13 percent overspeed, occuring most often in cruise mode, as seen in Table I. The variable pitch angle (β) of the fan is limitted to -6 to +5 degrees.

As seen in Table I, the gas system produces 5000 to 7000 lb. more thrust than the shaft system at equal bypass ratios in the 2-on- 2 mode. However, in the normal VTO 3-on- 2 mode of Table II, the thrust advantage of the gas system is much smaller. This relative improvement of the shaft system thrust is principally due to the increase of allowable CET to 3000°R. In the emergency 3-on- 1 mode of Tables IV and V the shaft system thrust exceeds that of the gas system in both dry and water injected operation by 6 to 12 percent. As can be seen in the Tables, the shaft system benefits in this mode from a combination of higher allowed CET and core overspeed, and variable fan pitch. Note that fan pitch and core speed optimums are at or near their allowable limits in the water injected cycle data of Table V. Special note should be given to the operating fan pressure ratios (FPR) of both systems in the 3-on- 1 emergency mode of Tables IV and V. Data for FPR, especially at higher BPR, are given as 1.13 or less. Such low values of FPR expose the systems to high thrust- loss sensitivity.

Other tables (not shown here) were generated for 2 fan- 2 core cruise operation of each system at each BPR. These tables contain cruise thrust and specific fuel consumption (SFC) for full and part- power operation for a range of flight altitudes and subsonic Mach numbers. The cruise data, along with the vertical thrust data of Tables I thru V were used in evaluating the performance of the propulsion systems in a computerized flight model of the mission.

Figure 4 shows typical thrust and SFC curves for the gas and shaft systems operating in the 2 fan- 2 core cruise mode. Examples are given for two flight conditions; loiter at an altitude of 10000 ft. and cruise at 36000 ft. For comparison purposes, the data for each system is shown at a BPR of 8 and the propulsion system sizes are scaled for equal thrust (35000 lb.) in the normal VTO mode (3 fan- 2 core) of Table II. If the systems were compared in figure 4 at a BPR of 12 instead of 8 the general levels of SFC would be slightly lower, but the relative differences would still apply.

As seen in the figure, the major difference in SFC for the two systems is at the loiter condition. The shaft system has a 3 to 8 percent lower SFC than the gas system over a wide range of thrust level. Maximum thrust for each system at cruise and loiter is identified in figure 4 by a circle symbol. The high level of installed thrust required for these V/STOL aircraft result in extremely low- power operation, relative to the maximum thrust available, during loiter.

At the typical cruise altitude, the maximum thrust of each system is noticeably lower than at the loiter condition. However, typical cruise thrust requirements still result in part- power operation. The cruise SFC of the gas and shaft systems are comparable in the required thrust range and signifigantly lower than the loiter values.

For typical levels of required loiter thrust, the SFC of the shaft system is 8 percent lower than that of the gas system. The better fuel economy of the shaft system is probably due to higher component efficiencies and the optimization of fan pitch angle at part- power points. This performance advantage for the shaft system appears in the comparisons made throughout this study.

Propulsion System Weight

As mentioned earlier, component weights of the engine cycles covered by Table I for both gas and shaft systems were also estimated with the computer code of reference 5. These component weights were added to simple models of other parts of the propulsion system installations such as nacelles, transmissions, shafting, and ducts to result in a total installed weight for the gas and shaft systems. Figure 5 shows the installed weights of each propulsion system as relative core size factor (CSF) and nominal bypass ratio vary. For the range of variables in this figure, system weights appear to have a very linear behavior.

For simplicity, in the present study, the propulsion system weights of figure 5 have been fitted with the following relations:

$$W = 1855 + 4830*CSF + 230*BPR*CSF \qquad \text{(SHAFT)}$$

$$W = 1700 + 3370*CSF + 390*BPR*CSF \qquad \text{(GAS)}$$

Core size factor (CSF) is a measure of the corrected airflow of the turboshaft or gas generator core relative to the core size used in the reference engine data of Table I . Note that CSF is a factor on corrected airflow, hence physical size, of each core. Physical airflow of the shaft system core changes with BPR, due to changing pressure ratio of the fan located in front of it, even when CSF (corrected airflow) is held constant.

RESULTS AND DISCUSSION

Baseline Aircraft

Weight schedules and descriptions for the gas- driven and shaft- driven baseline aircraft of this study are presented in Table VI. Wing area and aspect ratios are the same for each aircraft in the Table, and are not necessarily to be regarded as "optimum" results. Individual weight items in the breakdown are derived from previous studies of similar aircraft in references 1 and 2. These reference studies generally allow a slightly higher design fuel load for the gas aircraft since, as discussed earlier, fuel usage of the baseline gas system is higher than that of the shaft system. However, for comparison purposes in this study, the design fuel loads have been made equal. The present study uses an airframe weight model sensitive to wing planform, fuselage size, and propulsion system size. The weight model is calibrated by the weights shown here and by the earlier references. These weights should be considered as only representative since they are subject to refinement as more detailed structure and component studies are made.

Table VI divides the aircraft weight into three major groups; Airframe, Propulsion, and Other Systems. The Airframe weight consists of wing, tail, fuselage, landing gear, and a part of the weight associated with installation of the propulsion system. The Propulsion weight group is assumed here to include the major part of the nacelle and installation-related weight. This grouping is to allow for studies of other fan and core sizes with attendant changes in installed weight. The Table shows the weight of the baseline shaft system as heavier than the baseline gas system. Note that the crew and equipment weight is included in the schedule at the outset. This allows the sum of the three major weight groups, along with expendable payload, to be termed as unfueled takeoff weight (UTOW). Takeoff gross weight (TOGW) for any mission is then simply the sum of UTOW and the takeoff fuel load. Any water carried for possible maneuvers with water injection is considered chargable to the fuel load.

The emergency landing weight (ELW) of the aircraft is assumed to consist of the UTOW, minus the payload, plus an 800 pound allowance for emergency landing fuel and water. Emergency landing weights are shown here as 23810 lb. for the shaft-driven aircraft and 22250 lb. for the gas aircraft. Since the largest part of the ELW is UTOW, this value, along with the OEO thrust of the propulsion system, determines whether the aircraft can safely land in an emergency.

Table VII summarizes the vertical thrust capabilities, including OEO emergency landing, of the systems presented in Tables I thru V. If a thrust/ weight of 1.03 is assumed to allow for a safe EVL, it can be seen that the baseline (BPR=12.2) shaft system, without water injection, could safely land the baseline shaft aircraft of Table VI with one core engine out (OEO). In this case the shaft-driven aircraft could perform the EVL with a thrust/ weight of 25388/23810 or 1.066. The water injected cases for the shaft systems shown in Table V assume that 100 percent saturation is achieved at the compressor face. These thrust values are repeated in Table VII for the shaft system during OEO emergency. For conservatism, however, it is assumed in this study that if water injection is used only 80 percent of saturation is achievable. The corresponding thrust of 27040 lb. is also shown in Table VII for the baseline BPR of 12.2. In this case, the thrust/ weight of the baseline shaft aircraft in "wet" EVL is 1.135 .

Data for the gas-driven system shown in Table VII at the baseline nominal BPR of 8.02 points to the fact that the baseline aircraft in Table VI cannot safely land during EVL without water injection. The OEO emergency wet ratings for the gas systems shown in Table V are based on 4 percent combustor water injection. Table VII, however, shows that 4 percent water injection at the baseline BPR of 8.02 is still too low in emergency thrust, giving a value of 22026 lb., which is lower than the ELW of the baseline aircraft of 22250 lb. Hence, in the present study water injection is assumed used during EVL by all gas-driven systems at a rate of 6 percent. This water rate may not be needed in some of the higher-than-baseline values of BPR, but only requires the carrying of less than 140 extra pounds of water. In this case the baseline gas propulsion system, at a 6 percent water rate, in the baseline aircraft of Table VI is capable of EVL with a thrust / weight of 22916/22250 or 1.03 .

Baseline System Endurance

Figure 6 shows the variation of Time On Station (TOS) as fuel load (hence TOGW) is changed for both the baseline shaft and gas-driven aircraft. Water injection is not used for takeoff thrust augmentation but is assumed to be carried for one-engine-out emergency vertical landing (EVL). The radius of action for all cases in this figure is 150 n.mi. The mission in figure 6 is the baseline mission of figure 2 where TOS is evaluated for loiter at a fixed low altitude of 10000 ft. with optimized loiter Mach number. The values of TOS shown include the effects of a 5 percent SFC degradation penalty assumed for each propulsion system. Figure 6 is based on the baseline aircraft and propulsion system weight schedules of Table VI. Increased takeoff fuel load in both aircraft increases the TOS and TOGW until the maximum design value of internal fuel load of 15000 lb. is reached , with UTOW constant for both aircraft.

The takeoff fuel load is greater than the mission fuel actually used, since in every case 5 percent of the takeoff fuel must be held in reserve. The variation of TOS with TOGW is not linear because increased loiter time and, hence, fuel requirement tend to increase the fuel needed on the outbound climb and cruise legs of the mission. A vertical line is shown at a TOGW of 32540 lb. for the shaft airplane and a TOGW of 30830 lb. for the gas-driven airplane. These are the maximum allowable TOGW for vertical takeoff at a thrust to weight ratio of 1.08 or greater. Each value of maximum TOGW for VTO is derived from the dry VTO (3 fans on 2 cores) thrust listed in Tables II and VII for each baseline propulsion system. Takeoff at higher TOGW must be assumed to be a STO maneuver with varying takeoff distance. Note that, as shown in figure 2, both VTO and STO takeoff fuel are assessed the same (2.5 minutes at full power). For either the gas or shaft systems, maximum VTO fuel load is far less than the design fuel load and depends on the VTO thrust. For the baseline shaft system BPR of 12.2, VTO thrust is 35142 lb. and the maximum VTO fuel load is 6380 lb. The resulting TOS for the baseline 150 n.mi. mission is 72 minutes. The baseline gas propulsion system, at a BPR of 8.02, has a VTO thrust of 33234 lb. and, hence, a lower allowable TOGW which limits VTO fuel to 6230 lb. . Lower takeoff fuel and slightly higher fuel consumption rate combine to give the gas system a TOS of 56 minutes, or 16 minutes less than the capability of the baseline shaft-driven system.

At the STO point on each curve with maximum internal fuel of 15000 lb., it is noted that the TOGW of the shaft aircraft is higher than that of the gas aircraft (41160 versus 39600 lb.). These differences in TOGW are mostly due to differences in UTOW caused by the heavier propulsion system installation of the shaft-driven system. Nevertheless, the better fuel economy of the shaft system results in a maximum STO-TOS of 220 minutes. The gas system has a maximum STO-TOS of 204 minutes at the same maximum fuel condition.

Note also, as mentioned earlier, the baseline gas aircraft with its baseline propulsion system is just marginally capable of an emergency vertical landing (EVL) if 6 percent water injection is assumed. The shaft aircraft, however, is capable of EVL without water injection and, in fact, exceeds this requirement.

Effect of Fan and Core Size

The preceding section compared the gas and shaft systems in a common airplane. However, the engine sizes and BPR were held to their baseline, unequal values. Such comparisons, therefore, shed little light on the individual or relative merits of the two propulsion systems. This section expands on the previous one by examining the effect of engine size and BPR while keeping the systems in a common airplane.

The gas and shaft baseline systems have certain nominal values of sea- level corrected airflow for the fans and cores. These values were seen in Table I under the baseline nominal propulsion system bypass ratios of 8.02 for the gas system and 12.2 for the shaft system. Effects of fan and core size variations relative to the baseline propulsion systems are examined in figures 7 and 8 by using a fan size factor (FSF) and core size factor (CSF) to express corrected airflow relative to the baseline gas and shaft fans and cores shown in Table I. Note again that physical airflow of the shaft system core changes with BPR, due to changing pressure ratio of the fan located in front of it, even when CSF (corrected airflow) is held constant. For the gas system, FSF and CSF relate fan and core corrected airflows to 627.75 and 79.17 lb./sec, respectively, shown for the baseline BPR of 8.02 in Table I. Similarly, in the shaft-driven propulsion system, FSF and CSF relate fan and core corrected airflows to 690.69 and 42.83 lb./sec, respectively, which are noted at the baseline nominal BPR of 12.2. Hence, the non-baseline gas system shown in Table I at a BPR of 12, but with the baseline core size, is defined as having a CSF of 1.0 and a FSF of about 1.50. This implies a fan diameter about 22 percent larger than the baseline fan.

Figure 7 shows the effect of FSF and CSF on TOS for the baseline mission and baseline gas-driven aircraft of Table VI. The solid-line curves in the figure show the variation of TOS with design BPR of the system at various values of CSF. Each combination of CSF and BPR implies a value of FSF. Dashed lines of constant FSF are shown overlaid on each figure. The right-hand side of figure 7 shows the maximum STO-TOS of the aircraft when taking off with the full design internal fuel load of 15000 lb. The circled point at FSF and CSF of 1.0 and BPR of 8.02 has a STO-TOS of 204 minutes and corresponds to the maximum STO-TOS shown in figure 6. The left side of figure 7 shows the effect of the same propulsion system variables on the VTO-TOS capability where in each case the aircraft fuel has been off-loaded to allow VTO with a thrust / weight of 1.08. The circled point in the left-hand part of figure 7 at a VTO-TOS of 56 minutes with CSF=1.0, BPR=8.02, and FSF=1.0 is the same case shown in figure 6 for VTO with 6230 lb. of fuel.

An emergency vertical landing (EVL) limit line is shown cutting across the curves in figure 7 for STO-TOS and VTO-TOS at each BPR. The OEO vertical thrust of the gas-driven system was shown in Table VII to depend on BPR. This thrust is also proportional to CSF at each BPR. The emergency landing weight (ELW) of the aircraft is strongly affected by the propulsion system weight which, in turn, is a function of CSF and FSF. Hence, for a given aircraft such as in figure 7, there is a minimum allowable CSF at each BPR for a safe OEO emergency vertical landing with a thrust/ weight of 1.03. It can be seen in figure 7 that the baseline gas aircraft with the baseline propulsion system installed is on the EVL limit at a BPR of 8.02. There is no margin for EVL in this case if unforeseen thrust losses or increases in ELW occur. Note that at BPR=6, the minimum CSF for EVL is about 1.1, but with a corresponding value of FSF of less than 0.9.

Since STO-TOS tends to increase at each BPR as CSF decreases, the effect of the EVL limit line sets an upper limit on STO-TOS at each BPR. Along each EVL limit line, changes in BPR produce relatively small changes in TOS for both STO and VTO.

Figure 7 also serves to show the effect of fixing the fan size at baseline (FSF=1) while larger core sizes are used or, conversely, fixing the core at baseline size (CSF=1) while FSF is increased. Either approach tends to increase VTO-TOS (while STO-TOS decreases) and provide wider margins in the system for safe EVL. However, it should be pointed out that lower BPR by increasing CSF and holding FSF produces more rapid payoff in increased VTO-TOS. Furthermore, holding or slightly decreasing FSF avoids nacelle size growth and increases the operating fan pressure ratio of the propulsion system in all modes.

Figure 8 shows both STO-TOS and VTO-TOS for the shaft-driven baseline aircraft as BPR, CSF, and FSF are varied. The EVL limit lines establishing minimum CSF and maximum STO-TOS at each BPR are also shown in both parts of figure 8. The circled point for the baseline shaft propulsion system at BPR=12.2 and CSF=1.0 in both parts of the figure identifies the TOS capability of the baseline aircraft. In this case the STO-TOS is 220 minutes and the VTO-TOS is 72 minutes, corresponding to results given for the shaft aircraft in figure 6. Note that in the shaft system, the baseline aircraft and engine combination shows a considerable margin from the minimum CSF for the EVL limit line at a BPR of 12.2. If CSF is held fixed at 1.0 the shaft system results in figure 8 approach the EVL limit at a BPR near 8, where FSF has reduced to less than 0.8. Performance of the shaft system in figure 8 is generally better than the gas system in figure 7 since, for any selected VTO-TOS, the corresponding STO-TOS capability of the shaft system is greater. Therefore the shaft system is exhibiting better cruise and loiter fuel economy along with generally greater margins for safe EVL.

Figures 7 and 8 also serve to illustrate that if CSF is considered variable, a desired or "design" value of TOS for the vertical takeoff mode can be specified at each BPR. The relative fan size, FSF, would still depend on the CSF required at each BPR to meet the design value of VTO-TOS. A value of VTO-TOS less than that of the EVL limit line could be specified at any BPR. However, if the EVL constraint is also to be observed, the CSF and also the FSF of the propulsion system would then be sized by the EVL criteria of thrust/ ELW of 1.03, disregarding the value of VTO-TOS. Hence, at each BPR, it is possible to find the required CSF to meet the higher values of specified VTO-TOS, or, to find the minimum CSF needed to meet only the EVL requirement.

Effect of BPR and Specified VTO-TOS

Fixing the design value of VTO-TOS by floating the scale size of the propulsion system allows more consistent comparisons to be made between different system types and different bypass ratios. Figure 9 is presented in six parts to illustrate the effect of BPR and design VTO-TOS on the performance of the gas-driven V/STOL aircraft. Results are shown for fixed values of VTO-TOS of 90 and 120 minutes at each BPR. Also included in the figure are results that would apply to minimum size propulsion systems intended to just meet the EVL criteria at each BPR.

The six items shown in figure 9 are the required core and fan relative sizes (CSF and FSF); the TOS capability of the aircraft and TOGW for STO with the full internal fuel load of 15000 lb.; the VTO-TOS capability of the minimum CSF system designed by the EVL constraint; and the maximum operating radius (RMAX) achievable with the aircraft by using STO takeoff at full fuel load and maintaining a high -altitude cruise at an optimum Mach number. Maximum operating radius stresses cruise efficiency at high altitude and Mach number of about 0.7, whereas the TOS figure of merit gives more importance to fuel efficiency at a relatively low altitude of 10000 ft. and a loiter Mach number of about 0.4.

In each part of figure 9 a solid symbol has been spotted to locate data pertaining to the baseline propulsion system. In this case, as mentioned earlier, the baseline gas- driven system and baseline aircraft fall on the EVL limit line at the baseline BPR of 8.02. Note that CSF and FSF are 1.0 for this case, and that STO-TOS and RMAX are greater than those for gas- driven systems with design values of VTO-TOS of 90 or 120 minutes.

It can be seen in figure 9 that, at each BPR, designing for 90 minutes VTO-TOS calls for larger CSF, FSF, and TOGW than the EVL-designed system. However, the VTO-TOS of the EVL system only exceeds 60 minutes for bypass ratios higher than about 9. Furthermore, the STO-TOS of the EVL-designed cases generally exceed those of the 90 minute designs by less than 20 minutes and differ in TOGW by less than 1000 lb. Hence, minimum sizing of propulsion systems can too easily result in poor VTO mission performance for only slight gains in STO mission performance.

The best choice of BPR for STO-TOS or RMAX appears to fall in the range of 8 to 10 for either fixed VTO-TOS designs or for EVL designs. However, a choice of BPR in the 6 to 8 range may be preferable since performance is only slightly compromised while avoiding large diameter fans (high FSF) and high values of TOGW. As seen in Table II, normal VTO

(3 fan-2 core) fan pressure ratio of the gas propulsion systems in the BPR range of 6 to 8 is also higher (1.2 to 1.3) than for BPR of 10 and 12. Such fan pressure ratios may be preferred since operating fan pressure ratios in the emergency (3 fan- 1 core) vertical thrust modes are always less than those at normal VTO, which increases the thrust loss sensitivities of the propulsion system during these critical maneuvers.

Figure 10 is a six part composite illustration of the effect of design BPR and design VTO-TOS for the shaft- driven propulsion system. As in figure 9 for the gas system, the baseline aircraft parameters are used with aspect ratio of 6 and wing area of 300 sq. ft.. Results for RMAX, STO-TOS, STO-TOGW, FSF, CSF, and VTO-TOS for the EVL-designed propulsion system are shown for BPR in the range of 8 to 12.2.

The baseline BPR of the shaft system is 12.2 as noted in Table VII. The data for the baseline BPR and baseline size shaft system are noted in each part of figure 10 by the dark solid symbol. Note that the baseline system, at BPR=12.2, CSF=1.0, and FSF=1.0 shows a considerable margin in size over that of the EVL-designed minimum size propulsion system. This reflects the fact that the OEI vertical thrust of the shaft system is substantially larger than required for EVL when the baseline propulsion system is used. At BPR=12.2 the EVL minimum system requires core and fan size factors of only 0.86 . As BPR is reduced along the EVL limit line, the required fan size decreases even further to 0.76 at BPR=8, while the minimum required core size rises to nearly match that of the baseline system at 1.0 .

Each aspect of the STO performance of an EVL-designed shaft system in figure 10 appears superior to that of the gas system in figure 9, mostly due to the better fuel efficiency of the shaft system and the ability to meet the EVL criteria with a relatively small propulsion system. However, the normal 3 fan- 2 core VTO thrust of the shaft system is not large enough in the EVL- designed system to allow enough takeoff fuel load for good VTO mission performance. At the baseline BPR of 12.2, the maximum VTO- TOS for the EVL-designed system is less than 10 minutes. This VTO- TOS rises to 45 minutes as BPR deceases to 8, due to increased VTO thrust accompanying the increased core scale factor. In any event, the shaft system results of figure 10 show the risk of poor VTO mission performance when propulsion systems are sized for minimum EVL requirements.

As in the gas system results of figure 9, figure 10 shows that considerably larger CSF and FSF than the baseline are required for specified VTO- TOS designed systems of 90 and 120 minutes at the baseline BPR of 12.2 . Also, as with the gas system, changes in STO-TOGW, STO-TOS, and PMAX are relatively small as BPR is varied at constant VTO-TOS. For the shaft system, the best value of BPR would seem to be about 10 on the basis of STO performance for specified VTO-TOS. However, it is possible that BPR=8 would be perferred since FSF would be kept smaller than baseline (0.85 to 0.90) and normal VTO fan pressure ratios are in the neighborhood of 1.3 . These advantages are obtained with small compromises in STO performance compared to results for BPR=10.

An overall comparison of figures 9 and 10 shows that lower-than- baseline bypass ratio versions of either the gas or shaft propulsion systems can result in good VTO and STO performance by proper matching of the core size to the aircraft and mission. Comparison of the STO- TOGW in these figures shows that in general, for the same baseline aircraft, BPR, design VTO- TOS, and the same 15000 lb. fuel load, the shaft- driven aircraft must weigh about 1000 lb. more than the gas- driven aircraft. This TOGW difference is mostly due to heavier propulsion system weight in the shaft system. On the other hand, due to better fuel efficiency, under the same conditions the shaft aircraft is capable of about 50 n.mi. greater operating radius and about 20 minutes greater STO- TOS than a gas aircraft.

Effect of Wing Parameters

In figures 6 through 10, the aircraft has been fixed at its baseline parameters including a wing area of 300 sq.ft. and aspect ratio of 6. Airframe weights in those figures primarily depended on the propulsion system weight which is a function of type of system, size factors, and bypass ratio. Fixing the aircraft parameters provided a convenient method of examining the effects of CSF, BPR, EVL constraints, and specified VTO-TOS.

Based on the results shown in figures 9 and 10, figures 11 and 12 show the effect of wing area and wing span on both the gas- and shaft- driven aircraft for specified VTO- TOS designs at a reduced bypass ratio. Aspect ratio could have been used in figures 11 and 12 instead of wingspan. Wingspan is used since it may be a more important deciding factor in aircraft selection. It can affect takeoff clearances and/or folded span for stowage considerations.

Figure 11, for the gas aircraft, consists of five parts showing the effect of wing area, span, and design VTO- TOS on STO values of TOS, TOGW, and PMAX, along with required propulsion system size (CSF) and fan size (FSF) at each point. In figure 11 the gas system has a nominal BPR of 6, so that the FSF is always a fixed fraction of CSF (about

0.75). Results are shown for two fixed values of specified VTO- TOS, 90 and 120 minutes. Limits for EVL are not shown in figures 11 and 12 because for the stated values of VTO-TOS, EVL thrust / weight ratios are above the minimum required level of 1.03 . Data for the baseline aircraft are noted at a span of 42.4 feet and a wing area of 300 sq.ft. on the 90 minute VTO-TOS curve of each figure by means of a solid symbol.

As seen in the earlier figures, designing for a 120 minute VTO- TOS requires a larger propulsion system and larger TOGW, with slightly reduced STO mission performance when compared to the 90 minute TOS. In figure 11, TOS and RMAX results tend to favor aircraft of smaller wing area and, hence, higher wing loading. Performance for the higher wing area of 400 sq.ft. only exceeds that of the 300 sq.ft. wing at spans well above 50 feet, and in the direction of growing TOGW. The effect of wingspan is a general increase in STO-TOS or RMAX. The shape of the curves suggest optimum values of span for each wing area. But in the present study these must be considered as "theoretical" since they occur at high aspect ratio where estimated wing weight and performance may be unreliable. The advantage of increased span on STO- TOS and STO-RMAX are seen in the other parts of figure 11. Each curve, however, tends to diminish performance gains at higher wingspans due to the persistent growth of airframe weight with span as seen in the figure. Practical limits on wingspan will probably limit span selection to the lower or mid-range values.

For each fixed value of VTO-TOS, it can be seen that wingspan has little effect on required CSF (and FSF), and that the effect of wing area on engine size is even smaller. Since required engine size varies only slightly, once VTO-TOS is set, the variations seen in TOGW along each curve are principally due to increased airframe weight with increased span. On the other hand, most of the difference in TOGW for different VTO- TOS at the same span and wing area is due to the difference of about 0.10 in engine size (CSF).

The required fan size in figure 11, since BPR is 6, ranges between 0.92 and 1.03 of the proposed baseline fan size. This contrasts with figure 9, where the baseline BPR of 8.02 needed an FSF of 1.1 to 1.2 for similar mission performance. The differences in FSF for the two values of BPR represent an 8 inch difference in fan diameter with a corresponding reduction in nacelle size. Furthermore, as noted in Table II, the normal VTO fan pressure ratio for BPR=6 is 1.29, whereas for the baseline BPR of 8.02 it is 1.22 .

Figure 12 presents results for the shaft- driven aircraft showing the effect of wing area, wingspan, and design VTO-TOS on STO performance and on the required engine size.

Results are shown for a shaft system with a reduced BPR of 8.0 and design VTO- TOS of 90 and 120 minutes. In general, the effects seen in figure 12 and the trends in STO- TOS and STO- TOGW are similar to those of the gas system shown in figure 11. Also, as before, data points for the baseline aircraft with wing area of 300 sq.ft. and wingspan of 42.4 ft. are identified in figure 12 with a solid symbol.

In figure 12, the shaft system with BPR=8 is seen to require an FSF between 0.85 and 0.93, depending on VTO- TOS. This is considerably smaller than the baseline fan. Also, comparing STO performance and TOGW in figure 12 with the baseline shaft sytem results in figure 10 shows that the lower BPR system gives equivalent performance.

To summarize figures 11 and 12, it is apparent that longer wingspan increases both STO- RMAX and STO- TOS, although with a penalty in the form of increased airframe weight which is evident in the increased TOGW. For a given design value of VTO- TOS, changes in wingspan or area appear to have little effect on the required CSF or FSF.

Selected Aircraft

Table VIII summarizes the weight breakdown and performance of gas- driven and shaft- driven aircraft with lower- than-baseline bypass ratio propulsion systems as discussed in the previous section. The aircraft in the table meet a specific goal VTO- TOS of 90 minutes on the baseline 150 n.mi. mission. Two combinations of wing area and aspect ratio are shown for each system to illustrate the effect of wingspan. The two aircraft tabulated here have wing areas of 300 and 350 sq.ft. with aspect ratios of 7 and 8, respectively. The wingspans of each are about 46 and 53 feet. The 53 foot span cases could have also been based on results for an aspect ratio of 7 and wing area of 400 sq.ft., with slight differences in weight and performance. Weight items in the airframe, propulsion systems, emergency landing weight, and STO takeoff gross weight are presented as in Table VI where the baseline aircraft were described. However, additional design and performance data are included at the bottom of Table VIII as an aid in comparing the gas and shaft aircraft and to show the effect of increased wingspan for each.

The relative core sizes for the selected bypass ratio systems in Table VIII are those required to meet the specified VTO- TOS of 90 minutes in each case. Cores must be oversized 12 to 14 percent for the selected shaft system and 22 to 24 percent for the gas system. In these cases, however, the fan sizes are less than the baseline due to the lower bypass ratios. The propulsion system weights show the effects of BPR and CSF, as in figure 5. For the cases in

Table VIII, the shaft system is slightly lighter than its baseline system and the gas system is about 500 lb. heavier than its baseline. The wing portion of each aircraft weight shows the greatest sensitivity to changing wingspan.

The last two lines of Table VIII show that, with water injection, either system has an emergency one- engine- out thrust / weight capability in excess of the minimum requirement of 1.03 . However, as mentioned earlier, only the shaft system shows a safe EVL margin when operating "dry" without water injection thrust augmentation during emergency.

CONCLUDING REMARKS

For the common configuration subsonic V/STOL aircraft of this study, the shaft-driven propulsion systems appear to result in better overall performance, although at higher installed weight, than the gas-driven systems. This brief study was made with the condition that maximum internal fuel load of both the shaft and gas aircraft be equal. It is, however, possible that a higher design fuel allowance for the gas aircraft would result in more equal performance for the two systems. Increased design fuel would tend to scale up the required weights of the airframe and propulsion system in the gas aircraft. Thus, the TOGW of the shaft and gas airplanes would also become more equal.

In any event, results for both systems show that the choice of system bypass ratio in the low range may be preferred, allowing relatively smaller fans operating at higher fan pressure ratio and, in addition, at little or no loss of typical mission performance. Such results are obtained by better matching of propulsion system size with the aircraft at each bypass ratio.

For the aircraft, low wing areas (or high wing loadings) appear preferable, except for a tendency toward higher areas as span is increased beyond 50 feet. The effect of wing span is to generally improve performance as span increases. Aircraft weight growth may produce theoretical optimums in wingspan at high values of span an TOGW. However, limits on wingspan in the mid-range would probably be dominated by practical or physical limits on aircraft stowage and wing folding considerations.

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TABLE I

Engine Performance on +31 deg F Day - 2 Cores & 2 Fans No Water Injection

	GAS				SHAFT		
NOMINAL BPR	6	8.02 baseline	10	12	8	10	12.2 baseline
FAN INLET							
AIRFLOW lb/sec	451.41	600.74	749.57	899.18	498.35	576.93	665.58
RECOVERY	0.985	0.985	0.985	0.985	0.992	0.992	0.992
FAN							
$W\sqrt{\theta}/\delta$ lb/sec	471.55	627.75	783.38	939.74	513.02	598.70	690.69
PR	1.402	1.307	1.251	1.194	1.419	1.330	1.269
η	0.859	0.862	0.862	0.863	0.885	0.885	0.885
$N/\sqrt{\theta}$ % relative	96.60	96.55	96.56	96.67	113.0	113.0	113.0
β relative angle	-	-	-	-	0	0	0
COMPRESSOR							
$W\sqrt{\theta}/\delta$ lb/sec	79.17	79.17	79.17	79.17	42.83	42.83	42.83
PR	16.34	16.34	16.34	16.34	11.88	11.88	11.88
η	0.838	0.838	0.838	0.838	0.828	0.828	0.828
$N/\sqrt{\theta}$ % relative	99.19	99.19	99.19	99.19	95.38	95.38	95.38
COMBUSTOR- Exit T, deg R	2700	2700	2700	2700	2880	2880	2880
HIGH PRESS. TURBINE							
PR	4.262	4.262	4.262	4.262	3.825	3.710	3.631
η	0.911	0.911	0.911	0.911	0.879	0.879	0.879
LOW PRESS. TURBINE							
PR	2.472	2.577	2.677	2.722	3.741	3.638	3.590
η	0.861	0.862	0.862	0.861	0.887	0.887	0.887
BYPASS NOZZLE							
AREA sq.in.	1550	2200	2930	3810	1150	1530	1990
C_s	1.0	1.0	1.0	1.0	0.951	0.947	0.943
C_v	0.94	0.94	0.94	0.94	0.985	0.984	0.983
CORE NOZZLE							
AREA sq.in.					550	535	530
C_s					0.796	0.829	0.849
C_v					0.982	0.982	0.982
THRUST - lb.	26776	29678	32172	33806	24716	25776	26954

TABLE II

Engine Performance on +31 deg F Day - 2 Cores & 3 Fans No Water Injection

	GAS				SHAFT		
NOMINAL BPR	6	8.02 baseline	10	12	8	10	12.2 baseline
FAN INLET							
AIRFLOW lb/sec	437.36	583.65	728.62	867.75	486.27	566.35	653.23
RECOVERY	0.985	0.985	0.985	0.985	0.992	0.992	0.992
FAN							
$W\sqrt{\theta}/\delta$ lb/sec	457.25	610.16	761.76	906.89	504.63	587.73	677.87
PR	1.292	1.221	1.179	1.145	1.318	1.252	1.207
η	0.857	0.857	0.857	0.860	0.881	0.879	0.879
$N/\sqrt{\theta}$ % relative	89.53	89.50	89.46	89.56	100.6	100.6	94.4
β relative angle	-	-	-	-	0.805	1.17	4.77
COMPRESSOR							
$W\sqrt{\theta}/\delta$ lb/sec	79.22	79.22	79.22	79.22	47.24	46.94	46.75
PR	16.36	16.36	16.36	16.36	13.54	13.43	13.35
η	0.838	0.838	0.838	0.838	0.833	0.833	0.833
$N/\sqrt{\theta}$ % relative	99.27	99.27	99.27	99.27	97.62	97.47	97.36
COMBUSTOR- Exit T, deg R	2700	2700	2700	2700	3000	3000	3000
HIGH PRESS. TURBINE							
PR	4.266	4.266	4.266	4.266	3.821	3.708	3.630
η	0.911	0.911	0.911	0.911	0.878	0.878	0.879
LOW PRESS. TURBINE							
PR	2.840	2.951	3.042	3.122	3.961	3.862	3.822
η	0.827	0.828	0.829	0.824	0.906	0.906	0.905
BYPASS NOZZLE							
AREA sq.in.	1685	2465	3350	4310	1335	1775	2290
C_ς	1.0	1.0	1.0	1.0	0.946	0.942	0.939
C_v	0.94	0.94	0.94	0.94	0.985	0.984	0.983
CORE NOZZLE							
AREA sq.in.					554	525	530
C_ς					0.836	0.860	0.875
C_v					0.983	0.983	0.982
THRUST - lb.	29976	33294	36024	38277	32192	33530	35142

TABLE III

Engine Performance on +31 deg F Day - 2 Cores & 3 Fans WITH Water Injection

	GAS , 4% Combustor Water				SHAFT, 100% Saturation at Compressor Face		
NOMINAL BPR	6	8.02 baseline	10	12	8	10	12.2 baseline
FAN INLET							
AIRFLOW lb/sec	440.33	587.65	732.22	882.29	528.09	597.41	709.80
RECOVERY	0.985	0.985	0.985	0.985	0.992	0.992	0.992
FAN							
$W\sqrt{\theta}/\delta$ lb/sec	460.15	614.09	765.18	922.09	548.02	619.95	736.53
PR	1.327	1.249	1.202	1.161	1.423	1.358	1.271
η	0.860	0.860	0.860	0.860	0.882	0.883	0.881
$N/\sqrt{\theta}$ % relative	91.70	91.68	91.45	92.28	109.5	109.8	110.0
β relative angle	-	-	-	-	4.77	4.33	4.91
COMPRESSOR							
$W\sqrt{\theta}/\delta$ lb/sec	80.62	80.62	80.62	80.62	53.45	53.53	53.23
PR	17.38	17.38	17.38	17.38	15.95	15.99	15.85
η	0.825	0.825	0.825	0.825	0.825	0.825	0.827
$N/\sqrt{\theta}$ % relative	101.4	101.4	101.4	101.4	103.4	103.6	103.0
COMBUSTOR- Exit T, deg R	2700	2700	2700	2700	2894	2938	2938
HIGH PRESS. TURBINE							
PR	4.234	4.234	4.234	4.234	3.852	3.739	3.658
η	0.911	0.911	0.911	0.911	0.880	0.880	0.879
LOW PRESS. TURBINE							
PR	2.928	3.059	3.161	3.076	4.716	4.651	4.535
η	0.825	0.825	0.826	0.822	0.914	0.915	0.915
BYPASS NOZZLE							
AREA sq.in.	1615	2350	3170	4370	1240	1550	2150
C_{ς}	1.0	1.0	1.0	1.0	0.952	0.948	0.943
C_v	0.94	0.94	0.94	0.94	0.985	0.984	0.983
CORE NOZZLE							
AREA sq.in.					554	525	530
C_{ς}					0.819	0.840	0.862
C_v					0.983	0.983	0.983
THRUST - lb.	32730	36345	39369	41727	41448	42176	43696

TABLE IV

Engine Performance on +31 deg F Day - 1 Core & 3 Fans No Water Injection

	GAS				SHAFT		
NOMINAL BPR	6	8.02 baseline	10	12	8	10	12 [2] baseline
FAN INLET							
AIRFLOW lb/sec	382.26	504.74	632.64	754.14	446.80	519.93	605.57
RECOVERY	0.985	0.985	0.985	0.985	0.992	0.992	0.992
FAN							
$W\sqrt{\theta}/\delta$ lb/sec	399.18	527.31	660.94	788.16	463.63	539.57	628.43
PR	1.176	1.135	1.108	1.090	1.183	1.152	1.127
η	0.845	0.848	0.846	0.854	0.855	0.858	0.857
$N/\sqrt{\theta}$ % relative	74.58	74.13	74.14	74.83	87.62	88.71	89.33
β relative angle	-	-	-	-	-1.53	-1.49	-1.20
COMPRESSOR							
$W\sqrt{\theta}/\delta$ lb/sec	81.16	81.16	81.16	81.16	53.56	53.19	52.97
PR	17.34	17.34	17.34	17.34	16.16	15.95	15.83
η	0.808	0.808	0.808	0.808	0.824	0.827	0.829
$N/\sqrt{\theta}$ % relative	103.3	103.3	103.3	103.3	103.8	103.0	102.5
COMBUSTOR- Exit T, deg R	2875	2875	2875	2875	3190	3190	3195
HIGH PRESS. TURBINE							
PR	4.267	4.267	4.267	4.267	3.848	3.734	3.656
η	0.911	0.911	0.911	0.911	0.879	0.879	0.879
LOW PRESS. TURBINE							
PR	3.355	3.429	3.497	3.475	4.211	4.158	4.158
η	0.735	0.737	0.742	0.734	0.895	0.897	0.897
BYPASS NOZZLE							
AREA sq.in.	1837	2725	3835	4370	1690	2190	2830
C_s	1.0	1.0	1.0	1.0	0.938	0.936	0.935
C_v	0.94	0.94	0.94	0.94	0.983	0.983	0.983
CORE NOZZLE							
AREA sq.in.					554	525	530
C_s					0.888	0.900	0.908
C_v					0.983	0.983	0.982
THRUST - lb.	18309	20247	21741	22962	22720	23973	25388

TABLE V

Engine Performance on +31 deg F Day - 1 Core & 3 Fans WITH Water Injection

	GAS 4% Combustor Water				SHAFT, 100% Saturation at Compressor Face		
NOMINAL BPR	6	8.02 baseline	10	12	8	10	12.2 baseline
FAN INLET							
AIRFLOW lb/sec	395.97	522.67	641.10	747.05	421.02	505.50	633.40
RECOVERY	0.985	0.985	0.985	0.985	0.992	0.992	0.992
FAN							
$W\sqrt{\theta}/\delta$ lb/sec	413.95	546.32	669.80	780.75	437.07	524.57	657.30
PR	1.191	1.146	1.120	1.101	1.223	1.184	1.133
η	0.843	0.847	0.852	0.862	0.872	0.868	0.844
$N/\sqrt{\theta}$ % relative	77.53	76.96	76.08	76.26	94.75	98.44	109.0
β relative angle	-	-	-	-	- 5.98	- 5.88	- 5.65
COMPRESSOR							
$W\sqrt{\theta}/\delta$ lb/sec	81.47	81.47	81.47	81.47	55.41	55.81	55.32
PR	18.18	18.18	18.18	18.18	17.03	17.21	16.98
η	0.789	0.789	0.789	0.789	0.809	0.807	0.810
$N/\sqrt{\theta}$ % relative	104.9	104.9	104.9	104.9	108.7	109.9	108.5
COMBUSTOR- Exit T, deg R	2875	2875	2875	2875	2987	3050	3050
HIGH PRESS. TURBINE							
PR	4.233	4.233	4.233	4.233	3.854	3.744	3.661
η	0.911	0.911	0.911	0.911	0.881	0.881	0.881
LOW PRESS. TURBINE							
PR	3.524	3.606	3.655	3.608	4.495	4.501	4.419
η	0.737	0.740	0.740	0.732	0.907	0.909	0.914
BYPASS NOZZLE							
AREA sq.in.	1840	2720	3655	4370	1425	1910	2880
C_δ	1.0	1.0	1.0	1.0	0.940	0.938	0.935
C_v	0.94	0.94	0.94	0.94	0.983	0.983	0.983
CORE NOZZLE							
AREA sq.in.					554	525	530
C_δ					0.877	0.892	0.908
C_v					0.983	0.983	0.983
THRUST - lb.	19896	22056	23703	25104	23416	25559	27452

TABLE VI

Typical Weight Schedules - Baseline Aircraft and Engines

	Shaft	Gas
Propulsion System Nominal BPR	12.2	8.02
Design Internal Fuel - lbs.	15000	15000
Wing Area sq.ft.	300	300
Aspect Ratio	6.0	6.0
Span ft.	42.4	42.4
Note	Pivot Nacelles	Over-Wing Part.Blended
Airframe	5920	5650
Wing	1670	1430
Fuselage & Tail	2700	2800
Landing Gear	1000	970
Nacelle Rotation	350	-
Air Induction	-	250
Installation Penalties	200	200
Propulsion	9490	8200
Nacelles	1400	1000
Gas Generators (cores)	3000	1600
Fans	1040	2100
Nozzles & Thrust Vectoring	550	1300
Valves & Ducting	-	1200
Transmissions & Shafts	2500	-
Controls & Starting	400	400
Fuels & Water Systems	600	600
Other Systems	7600	7600
Controls,electronics,etc.	1700	1700
Avionics	2700	2700
Air Cond.,Anti-ice,etc.	1700	1700
Crew and Survival gear	1000	1000
Trapped liquids,oil,etc.	500	500
TOTAL of Airframe+Propulsion+ Other Systems	23010	21450
Expendable Payload	3150	3150
Unfueled Takeoff Weight (UTOW)	26160	24600
Emergency Landing Fuel & Water	800	800
Emergency Landing Weight (ELW)	23810	22250
TOGW with Max. Internal Fuel	41160	39600
Vertical Takeoff Thrust	35142	33294

TABLE VII

Vertical Thrust Summaries

Shaft Systems

Condition		Nominal Bypass Ratio		
		8	10	12.2 baseline
Normal VTO, 3 Fans on 2 Cores Dry, No Water Injection		32192	33530	35142
Emergency Vertical Thrust 3 Fans 1 Core	Dry	22720	23973	25388
	Full Wet 100% Saturation at Compressor Entrance	23416	25559	27452
	Wet 80% Saturation at Compressor Entrance	23277	25242	27040

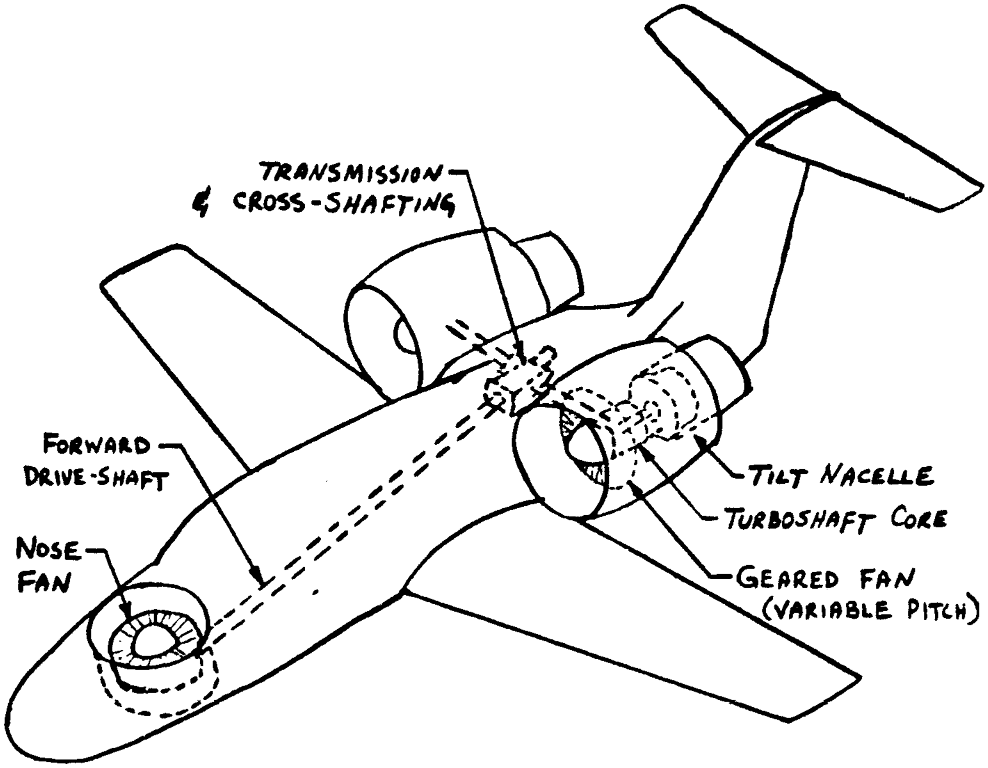
Gas Systems

Condition		Nominal Bypass Ratio			
		6	8.02 baseline	10	12
Normal VTO, 3 Fans on 2 Cores Dry, No Water Injection		29976	33294	36024	38277
Emergency Vertical Thrust 3 Fans 1 Core	Dry	18309	20247	21741	22962
	Wet 4% Combustor Water	19896	22026	23073	25104
	Wet 6% Combustor Water	20689	22916	24684	26175

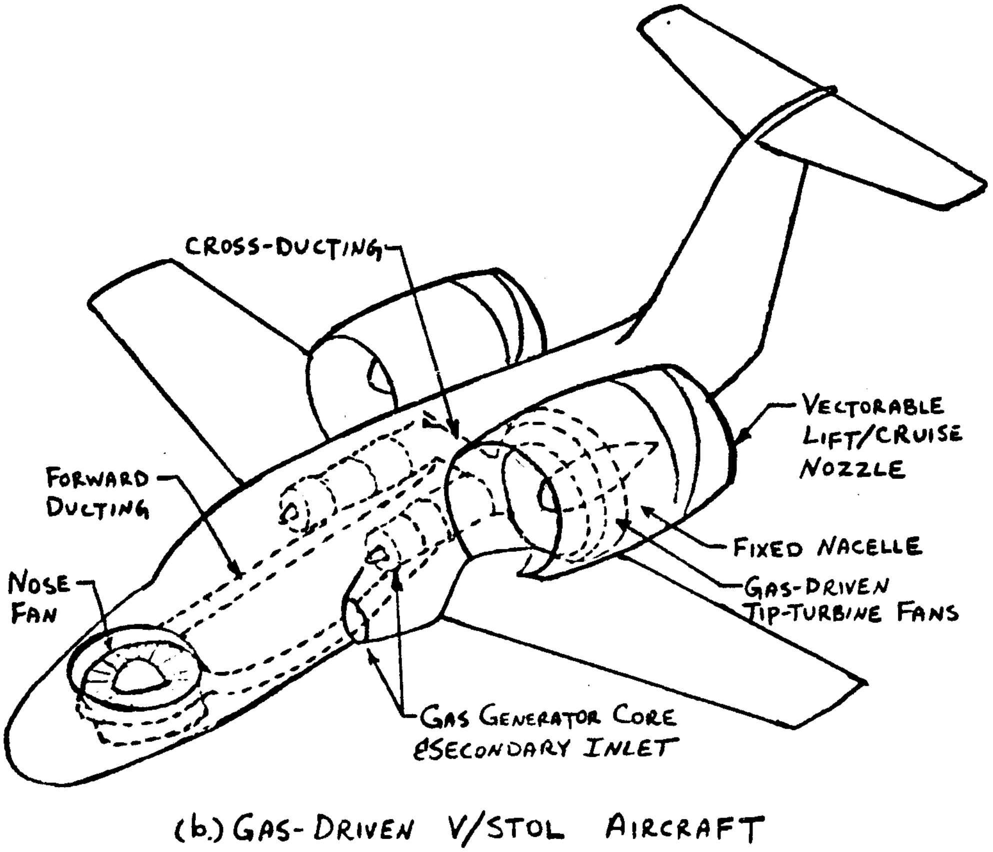
TABLE VIII

Weight and Performance Summary - Mission Designed Aircraft

	Shaft		Gas	
Propulsion System Nominal BPR	8.0	8.0	6.0	6.0
Design Internal Fuel - lbs.	15000	15000	15000	15000
Wing Area sq.ft.	300	350	300	350
Aspect Ratio	7	8	7	8
Span ft.	46	53	46	53
Airframe	6130	6780	5920	6550
Wing	1860	2360	1640	2120
Fuselage & Tail	2640	2790	2730	2880
Landing Gear	1030	1030	1000	1000
Nacelle Rotation	400	400	-	-
Air Induction	-	-	350	350
Installation Penalties	200	200	200	200
Propulsion	9360	9460	8700	8770
Nacelles	1310	1330	950	950
Gas Generators (cores)	3250	3280	2130	2160
Fans	800	830	2000	2020
Nozzles & Thrust Vectoring	450	470	1200	1200
Valves & Ducting	-	-	1420	1440
Transmissions & Shafts	2550	2550	-	-
Controls & Starting	400	400	400	400
Fuels & Water Systems	600	600	600	600
Other Systems As in baseline	7600	7600	7600	7600
TOTAL of Airframe+Propulsion+ Other Systems	23090	23840	22220	22920
Expendable Payload	3150	3150	3150	3150
Unfueled Takeoff Weight (UTOW)	26240	26990	25370	26070
Emergency Landing Fuel & Water	800	800	800	800
Emergency Landing Weight (ELW)	23890	24640	23020	23720
TOGW with Max. Internal Fuel	41240	41990	40370	41070
Vertical Takeoff Thrust	36240	36735	36750	37120
Relative Core Size Factor	1.126	1.141	1.226	1.238
Relative Fan Size Factor	0.842	0.853	0.917	0.926
VTO Time on Station min. (baseline mission)	90	90	90	90
STO Time on Station min. (baseline mission)	219	236	189	202
Max. Operating Radius n.mi.	1130	1227	1060	1150
Emergency OEO Thrust/ELW ,wet	1.097	1.078	1.102	1.080
Emergency OEO Thrust/ELW ,dry	1.071	1.052	0.975	0.956

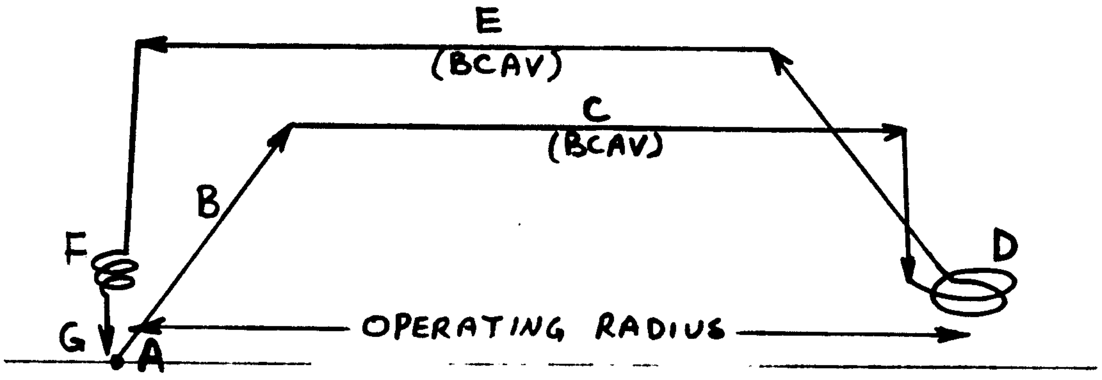


(a) SHAFT-DRIVEN V/STOL AIRCRAFT



(b.) GAS-DRIVEN V/STOL AIRCRAFT

Figure 1. - Aircraft Configuration



	SEGMENT	NOTES
(A)	TAKEOFF	VTO with thrust/weight >1.08, 2.5 minutes. or STO with thrust/weight >0.80, 2.5 minutes
(B)	CLIMB	At 80% max. power to outbound cruise H and M.
(C)	CRUISE OUT	Best H and M for minimum fuel out.
(D)	LOITER	H=10000 ft., 0.3< M < 0.6 , best M for max. TOS.
(E)	RETURN CRUISE	Best H and M for minimum return fuel.
(F)	HOLD	H=5000 ft., M=0.3 for 5 minutes.
(G)	VERTICAL LANDING	All missions, 2.5 minutes at full power.

ALTERNATE MISSION : MAXIMUM OPERATING RADIUS

Segment (A), takeoff, is STO in all cases.
Segment (D), low altitude loiter, not in mission.
Segments (C) and (E), cruise, use BCAV for maximum radius of operation with full internal fuel load at takeoff.

Figure 2. - Mission Profile Schematic

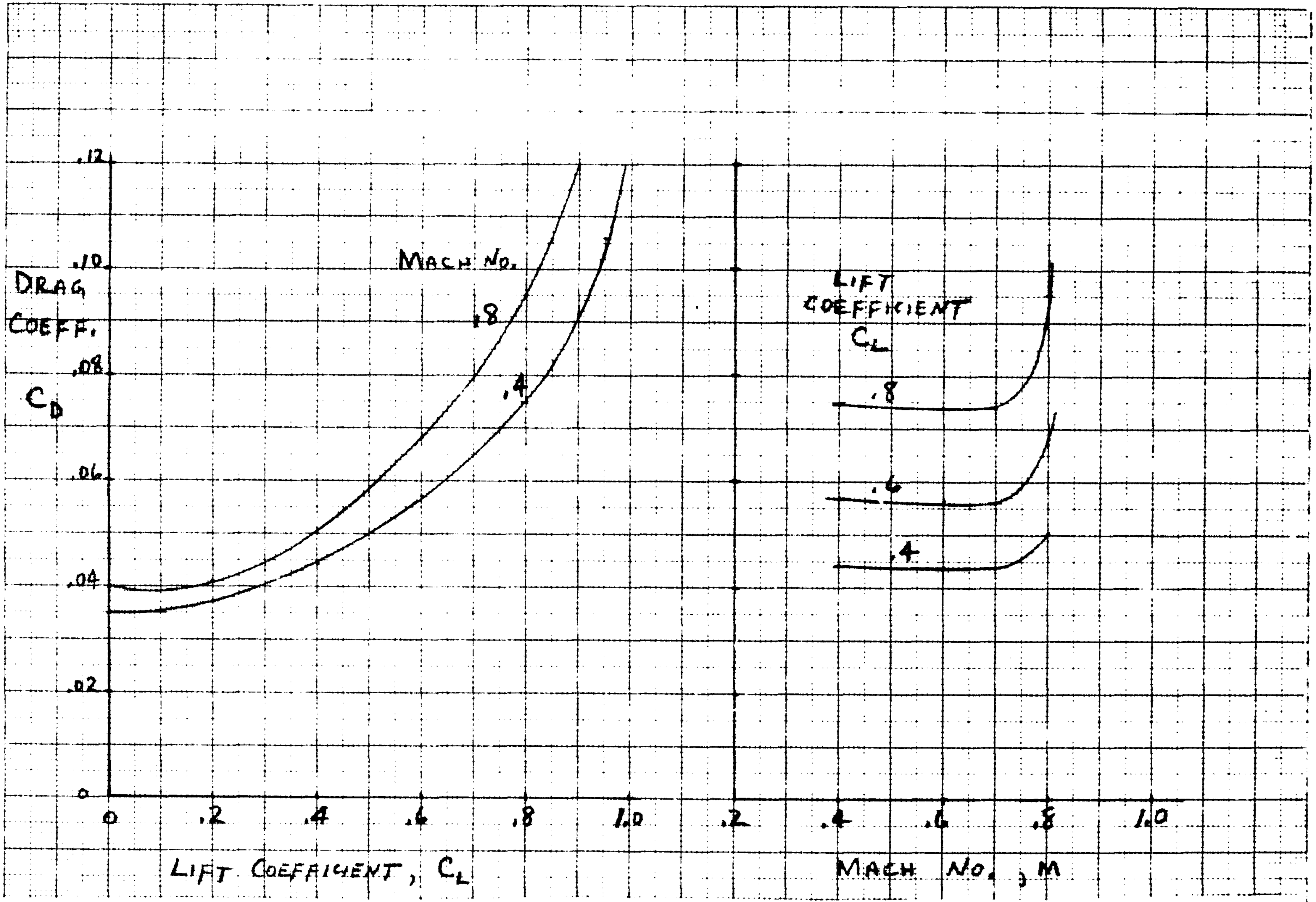


Figure 3. - Lift and Drag of baseline aircraft configuration including external stores. Assumed same for shaft-driven or gas-driven aircraft. Body fineness=6, Wing area=300 sq.ft., Aspect ratio=6, Taper ratio=.33, Mean thickness to chord=.18

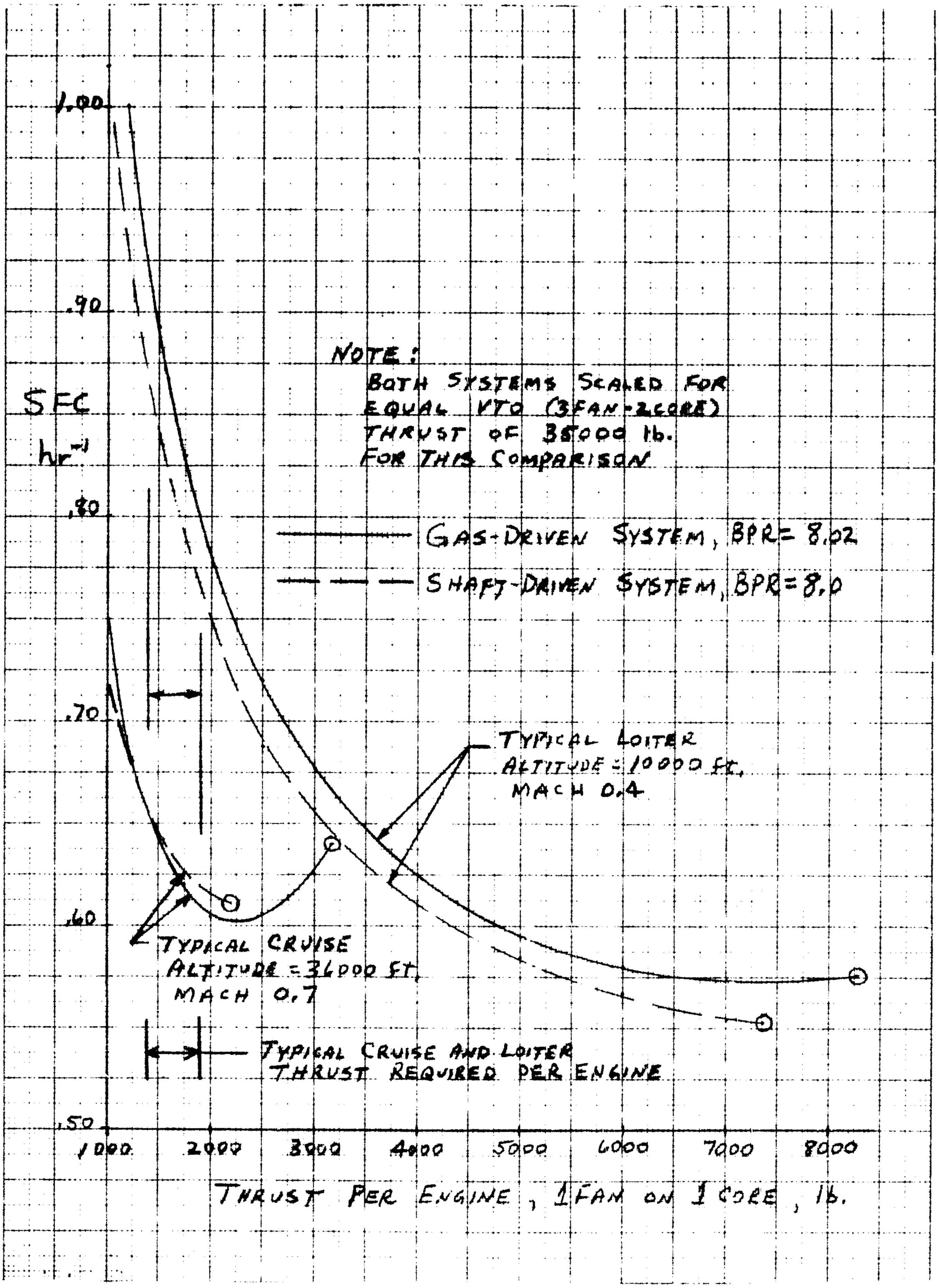


Figure 4. - Typical thrust and specific fuel consumption for gas and shaft systems. Cruise mode with BPR=8.

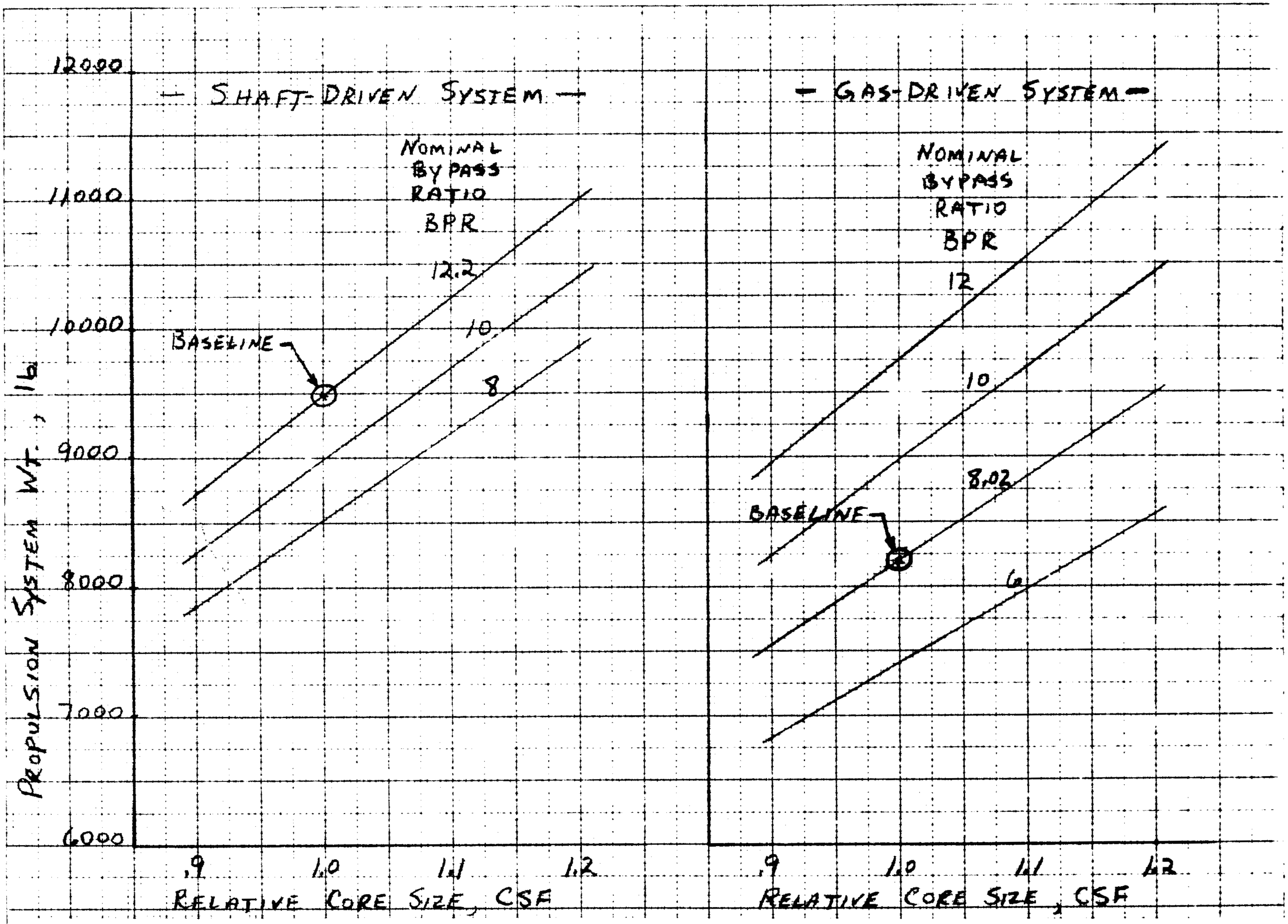


Figure 5. - Total installed propulsion system weight. Shaft and gas systems with 3 fans and 2 cores.

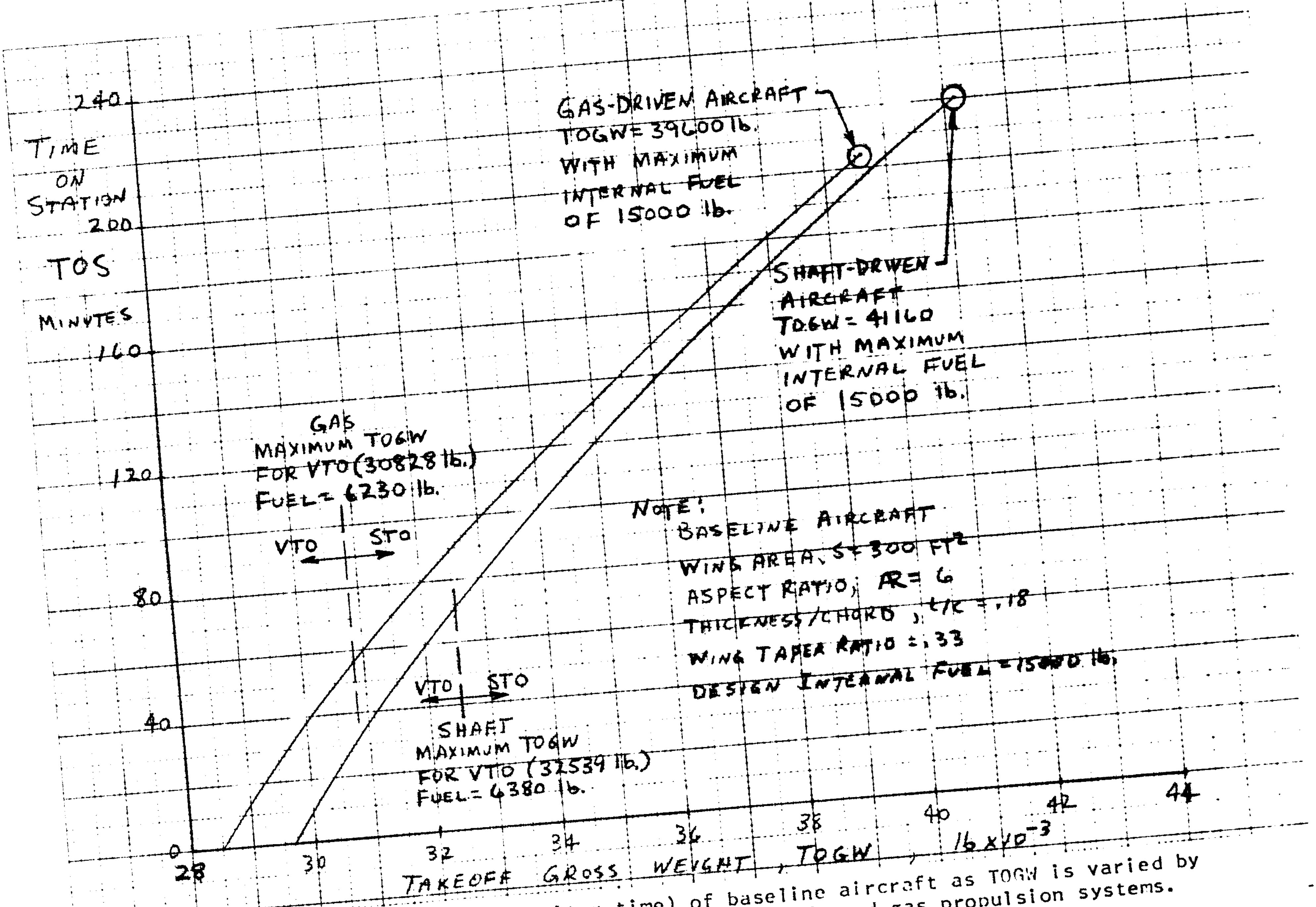


Figure 6. - Endurance (allowable loiter time) of baseline aircraft as TOGW is varied by varying fuel load. Baseline mission with baseline shaft and gas propulsion systems.

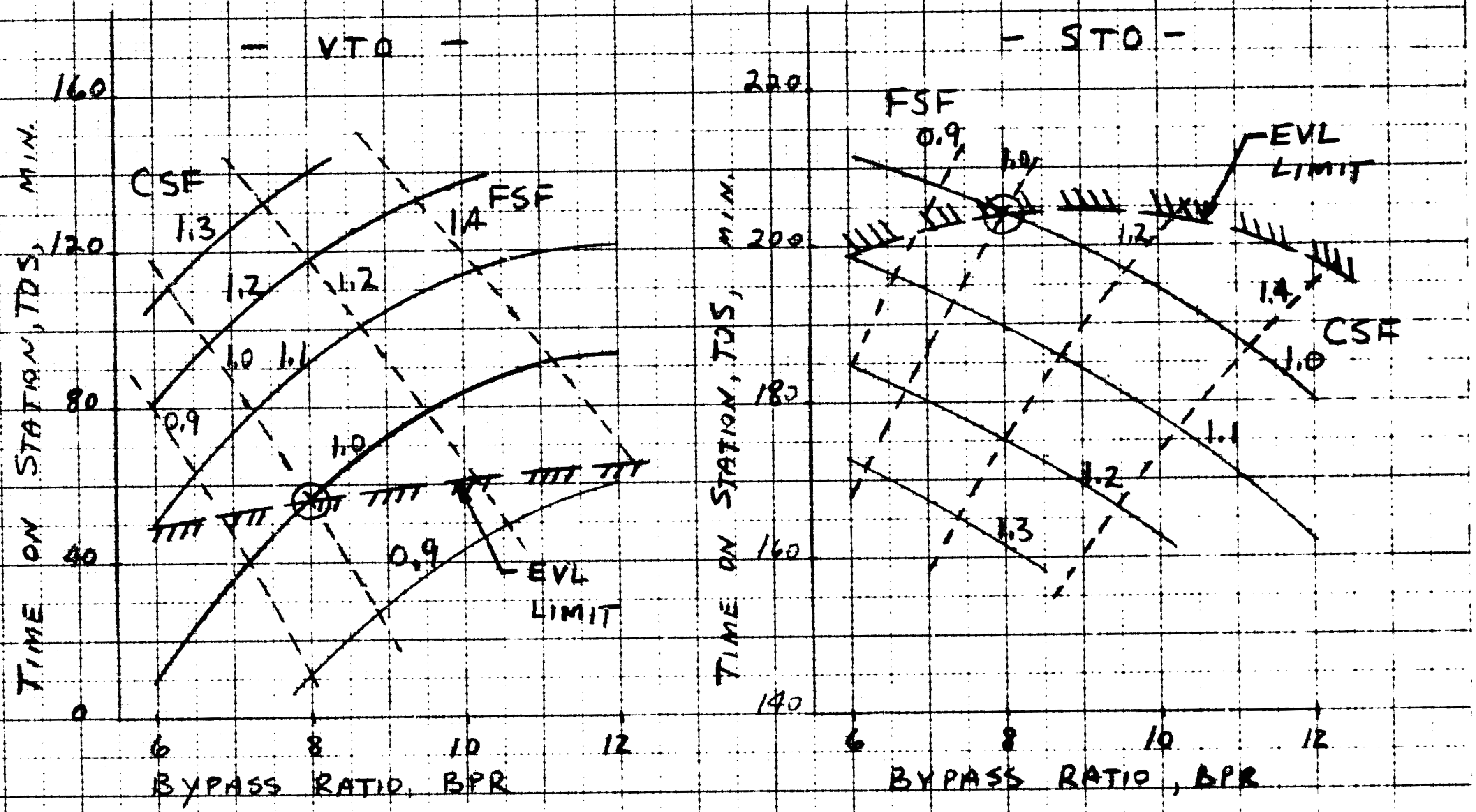


Figure 7. - Gas-driven V/STOL Aircraft. Effect of relative core size (CSF) and nominal bypass ratio on Time on Station (TOS) for baseline aircraft and baseline mission.

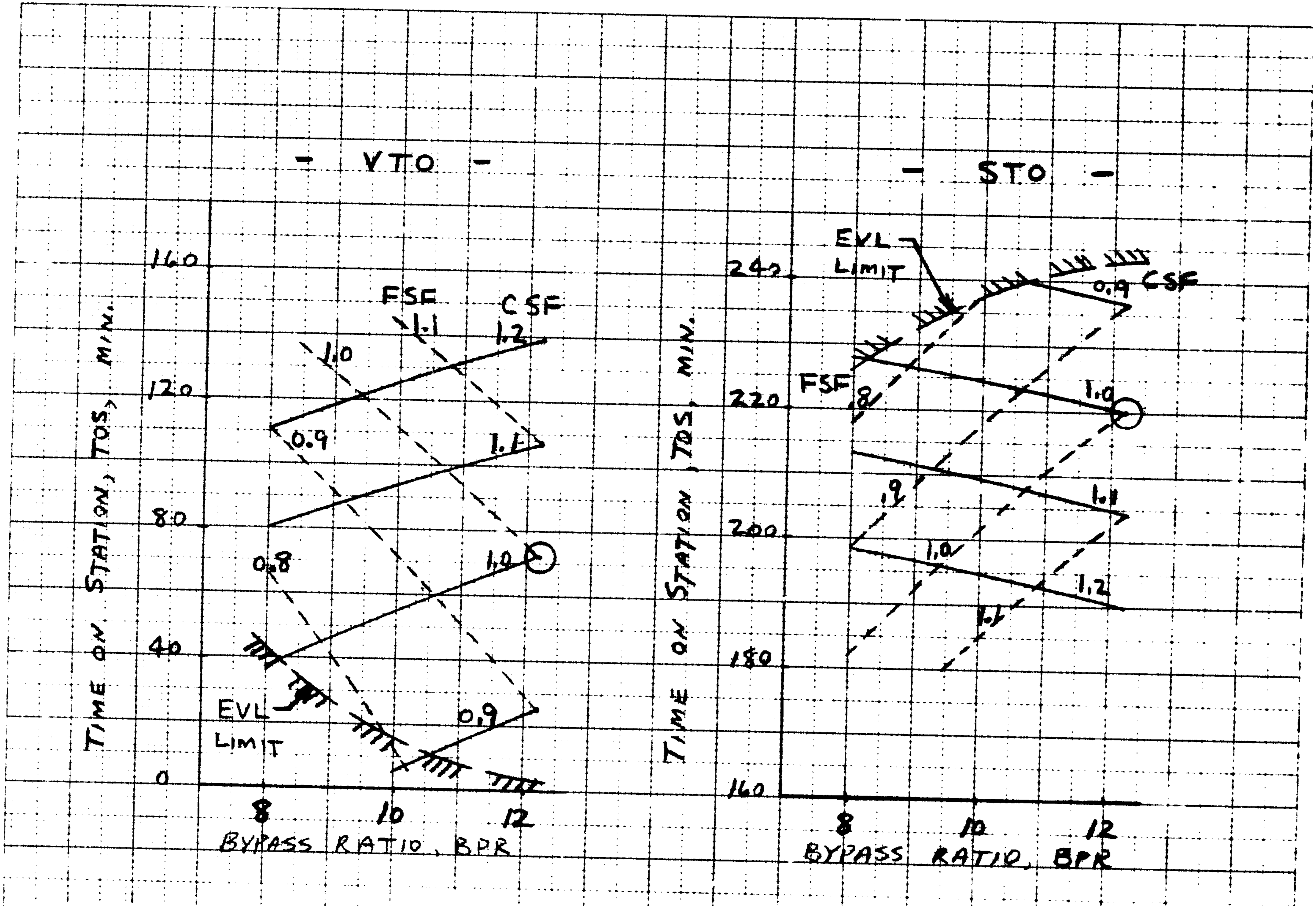


Figure 8. - Shaft-Driven V/STOL Aircraft. Effect of relative core size (CSF) and nominal bypass ratio on Time on Station (TOS) for baseline aircraft and baseline mission.

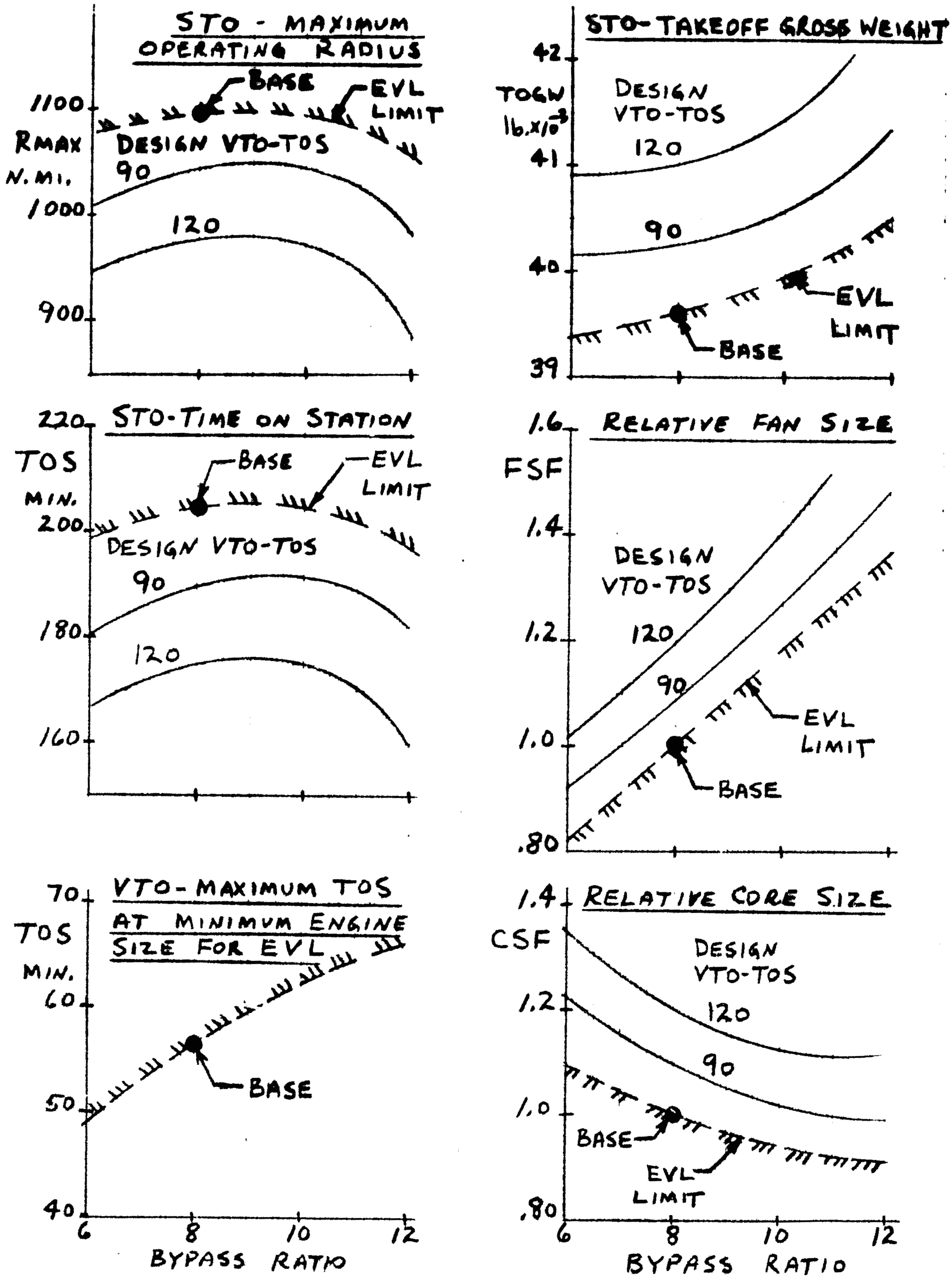


Figure 9. - Gas-driven System. Baseline Aircraft. Effect of nominal BPR and Design VTO-TOS of baseline mission on aircraft performance and propulsion system size.

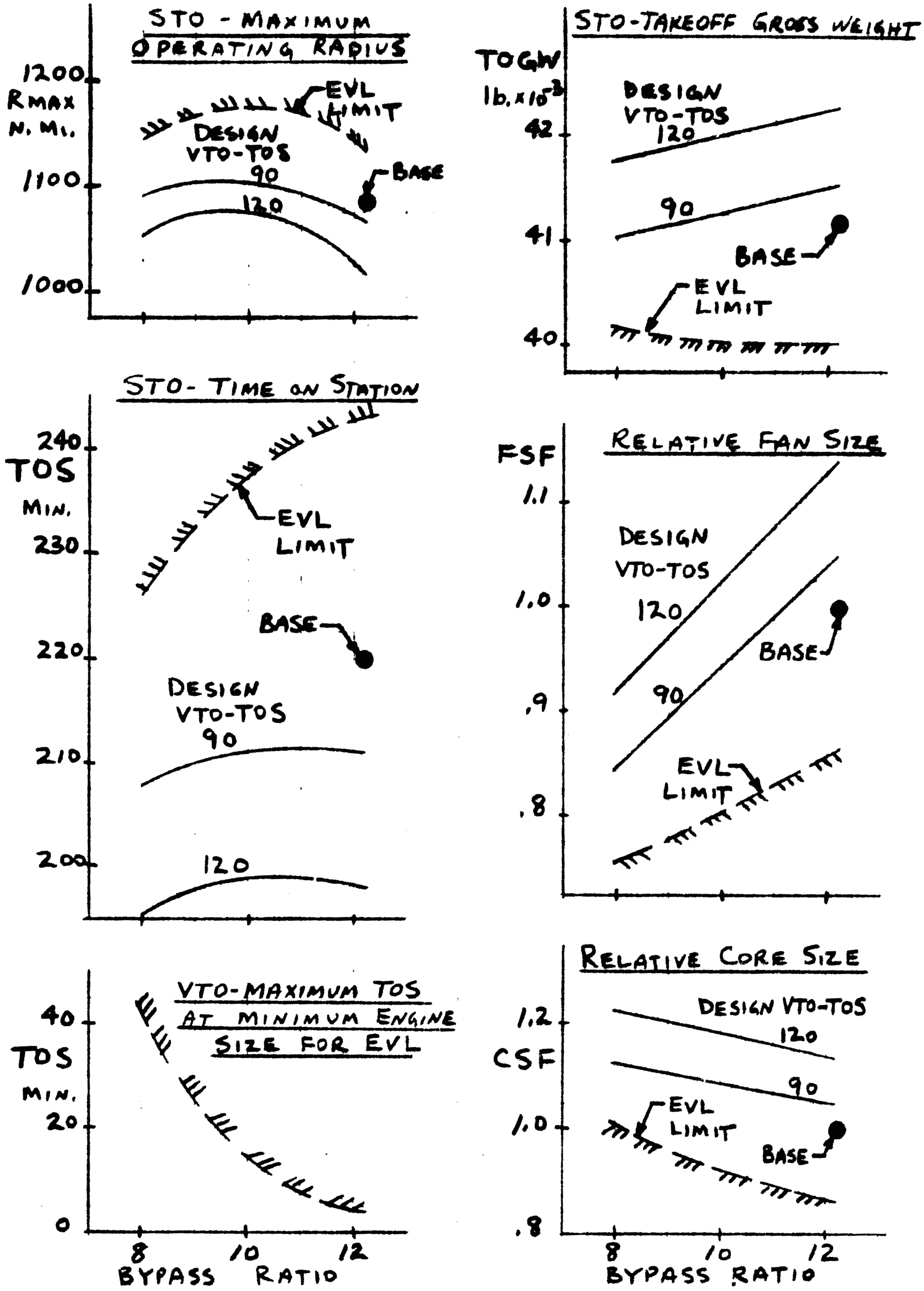


Figure 10. - Shaft-driven System. Baseline Aircraft. Effect of nominal BPR and Design VTO-TOS of baseline mission on aircraft performance and propulsion system size.

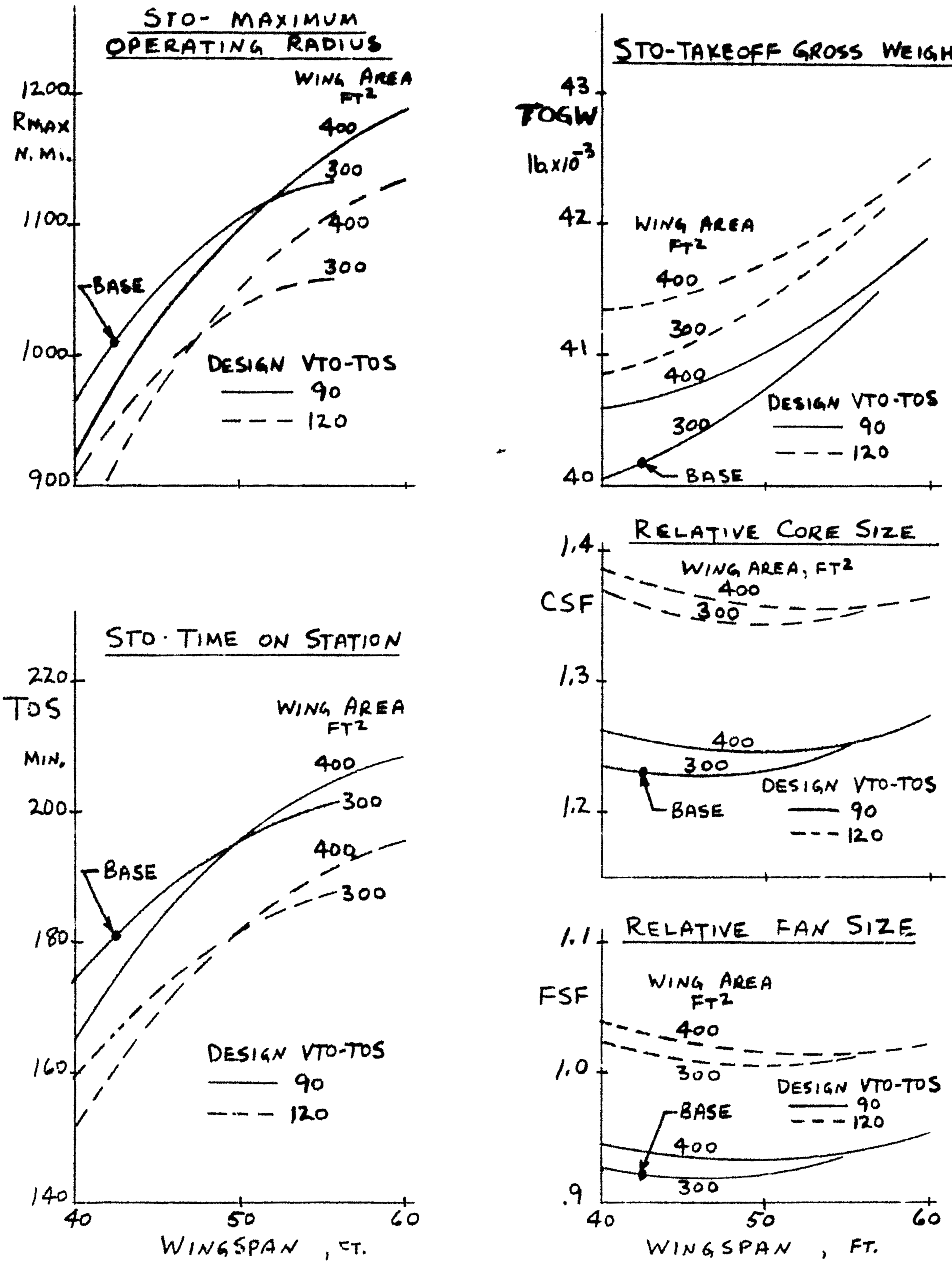


Figure 11. - Gas-driven System, BPR=6.0 . Effect of aircraft wingspan and wing area for different Design VTO-TOS on baseline mission.

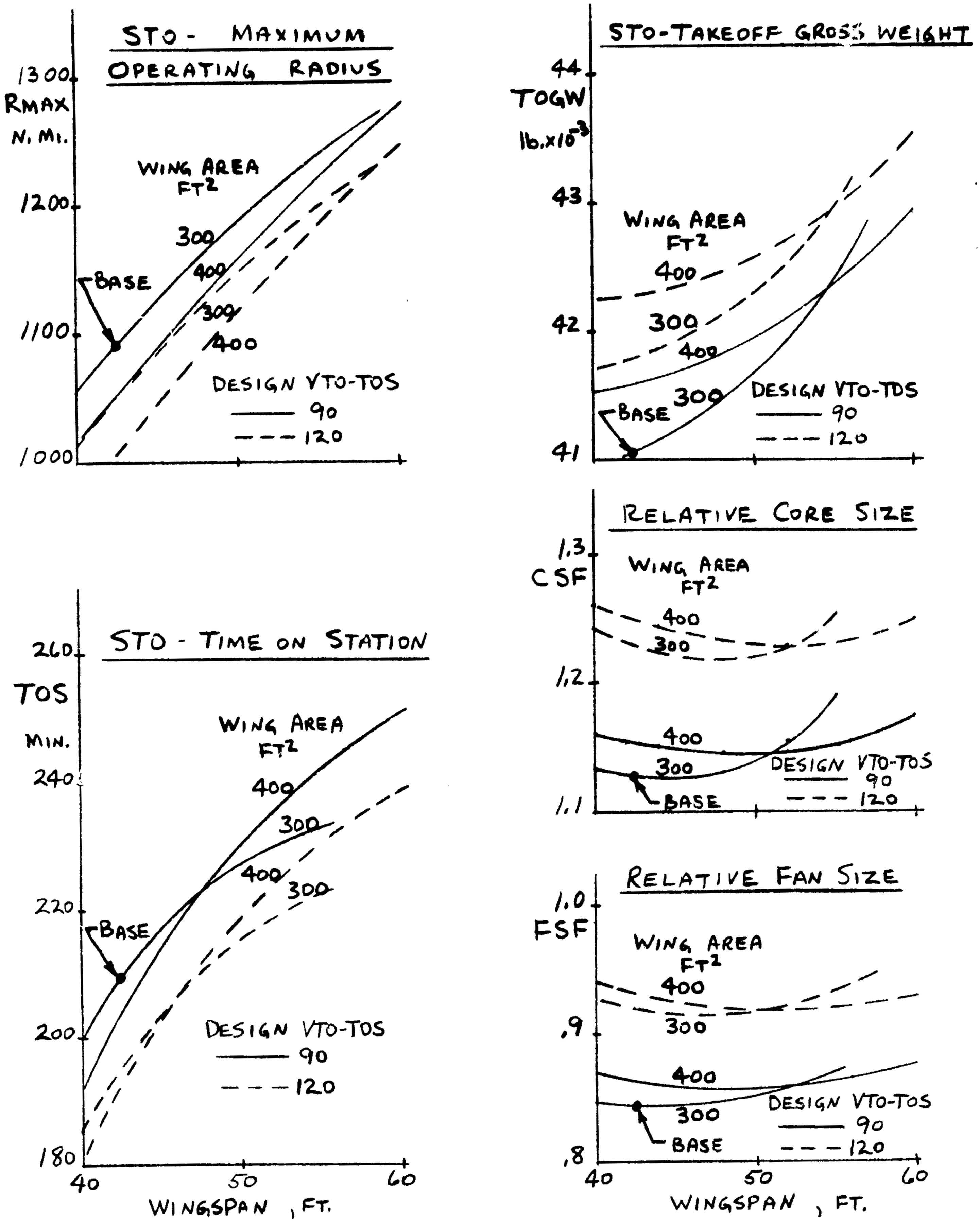


Figure 12. - Shaft-driven System, BPR=8.0 . Effect of aircraft wingspan and wing area for different Design VTO-TOS on baseline mission.