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# STEADY STATE ANALYSIS OF ENERGY TRANSFER CONTROL (ETC) AND COMPRESSOR BLEED CONCEPTS OF REMOTE LIFT FAN CONTROL

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16. Abstract

Two new concepts of control for VTOL aircraft remote lift fans are analyzed and discussed. Both concepts employ flow transfer among lift fans located in separate parts of the aircraft in order to obtain attitude control moments in hover and low-speed flight. The results presented are from a digital computer analysis of the YJ97/LF460 remote drive turbofan, although qualitative conclusions should apply to any remote fan system. The basic operating principles of the two systems are described, and their steady-state moment generating capabilities are discussed. Lift-recovery strategies for component failures are also analyzed.

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# STEADY STATE ANALYSIS OF ENERGY TRANSFER CONTROL (ETC) AND COMPRESSOR BLEED CONCEPTS OF REMOTE LIFT FAN CONTROL

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## SUMMARY

This report discusses two concepts of control for VTOL aircraft remote lift-fan systems: the Energy Transfer Control (ETC) concept and a compressor-bleed concept. The compressor-bleed concept is new and has not been covered in previous literature. Both systems employ cross ducting to permit flow transfer among lift units located in different parts of the aircraft. This method of control allows one unit to increase in thrust at the expense of the opposite unit, which is the ideal situation for the attitude control of a hovering VTOL aircraft. The results presented are from an analytical study of the YJ97/LF460 remote drive turbofan. The analysis was performed using a digital computer and nonlinear equations simulating two inter-connected turbofans. Though specific results are for the YJ97/LF460 system, the qualitative conclusions should apply to any remote fan system. The YJ97/LF460 was chosen for study because it is proposed for use in a VTOL research aircraft.

The basic operating principles of the ETC and compressor-bleed systems are described, and their steady-state moment-generating performance is discussed. The unusual strategies used to recover lift after component failures are outlined for each system, and a comparison of lift-recovery effectiveness is made between the two systems. Both systems are potential candidates for future use but must overcome problems of complexity.

## INTRODUCTION

VTOL aircraft have been the subject of continuing research over the past decade. Recent studies by NASA have shown that commercial VTOL transports powered by turbofan engines show promise in meeting the requirements for a quiet, clean transportation system that is not dependent on large airport facilities. To minimize the number of engines, proposed VTOL transports use the same engines for cruise propulsion, lift, and attitude control in hover (refs. 1 to 3). The requirements of attitude and height control in hover place new demands on the engine control system. Also, the requirement of safe operation after lift unit failures has led to novel and complicated control strategies. This analytical study was motivated by the need to determine the feasibility of new concepts being suggested for the VTOL application. The YJ97/LF460 remote fan system was chosen for study because it is proposed for use in a VTOL research aircraft (refs. 1 to 3).

In a remote drive turbofan, a hot gas generator, such as the YJ97, drives a fan, such as the LF460, by means of a short duct. This permits flexibility of installation as illustrated in figure 1(a), which shows the YJ97/LF460 combination in two possible arrangements. The LF460 fan is unconventional in the respect that the turbine blades are mounted about the circumference of the fan; this results in very short fan length. Figure 1(b) shows how the YJ97/LF460 engines are arranged in two proposed VTOL research transports (refs. 1 and 3). The two aft fuselage-mounted fans face horizontally to provide cruise thrust, and the remaining four fans face vertically to provide lift. During cruise, the four vertically facing fans are shut down. During hover, the thrust of the cruise fans is vectored downward by large "lobster tail" thrust deflectors to provide additional lift.

This report discusses only hover and low-speed operation of the YJ97/LF460 system. In order to provide attitude control moments, the ideal situation is to increase the thrust of one fan while reducing the thrust of the opposite fan by an equal amount. This could be accomplished in the normal way by changing gas generator power setting. However, this requires gas generator oversizing to accommodate the rare situation when maximum control thrust is required.

A more efficient way of obtaining control moments takes advantage of the fact that one fan has to lose thrust while the opposite fan is gaining thrust. Ideally, gas-generator flow can be transferred from the low side to the high side, and control moments can be obtained without any gas-generator oversizing. Several methods have been proposed to accomplish this, among them the Variable Area Scroll (VAS) concept (ref. 4), and the Turbine Energy Modulation (TEM) concept (ref. 5). Both of these systems are covered in the literature and will not be discussed here. The subjects of this report are two recent and promising control concepts, the Energy Transfer Control (ETC) system (ref. 6) and a compressor-bleed system. The compressor-bleed system is a new development not covered in previous literature.

A qualitative description of the operation of each system is given, followed by a comparison of their steady-state performance in normal operation. Failure control strategies are presented for each system, and examples are given to show the amount of lift that can be recovered following gas-generator or fan failures. Performance calculations for normal operation do not assume a specific aircraft configuration, but a six-engine VTOL transport aircraft is assumed for the failure examples. The transient performance of the ETC and bleed systems, which is also critical for the VTOL application, is discussed in references 6 and 7. All results presented in this report were produced by a transient simulation of the YJ97/LF460 system programmed for a digital computer. The equations used in the analysis are given in reference 7.

## YJ97/LF460 SYSTEM DESCRIPTION

The YJ97 engine (ref. 8) is shown in figure 2. It has a single rotor, a constant area exhaust nozzle, and variable compressor stators. As a pure turbojet, it produces 23 400 newtons (5270 lbf) of thrust at its military rating. Table I summarizes the predicted performance of the YJ97 for its military rating at sea-level, standard-day conditions. For application as a gas generator in a remote fan system, the standard exhaust nozzle of the YJ97 is removed, and the exhaust gas is used to drive the fan turbine. The fan-turbine inlet area is sized to bring the YJ97 to its rated power level.

Preliminary design has been completed for the LF460 lift fan (ref. 9) shown in figure 3. The fan is 1.5 meters (60 in.) in diameter and is driven by a single-stage tip turbine. The design thrust of the LF460 is about 66 700 newtons (15 000 lbf), however, a single YJ97 can only power the LF460 to 56 850 newtons (12 780 lbf) thrust. The LF460 was designed for use in a flow-transfer system; therefore, the power of more than one YJ97 is needed to drive the LF460 to its full design thrust.

The gas-generator exhaust flow is distributed around the entire circumference of the fan by means of a scroll that is divided into two halves, each feeding $180^{\circ}$ of the total arc. During emergencies, half of the scroll may be sealed off, cutting the impingement arc to $180^{\circ}$ and reducing the effective turbine-inlet area to 50 percent of normal. (Emergency procedures will be discussed more fully in a later section.)

Table I summarizes the performance of a single YJ97 driving a single LF460 at sea level on a standard day, with the YJ97 at its military power setting. An 11-percent total-pressure loss was assumed to occur between the YJ97 discharge station and the LF460 turbine inlet. For this report the data in table I represent the "design point" of the YJ97/LF460 system, and all data presented are normalized with respect to the numbers given in table I. Since flow transfer for moment control is essentially a temporary operating condition, the design point of table I is the condition of maximum continuous thrust for normal takeoff at maximum aircraft gross weight. The YJ97 also has an emergency rating of 105 percent speed; use of this rating requires an engine teardown and inspection. Figure 4 shows the variation of LF460 thrust with YJ97 speed. For study purposes 92 percent speed was chosen as the nominal YJ97 power setting for approach and landing at minimum aircraft gross weight.

# PRINCIPLES OF OPERATION

## Energy Transfer Control (ETC) System

The basic ETC system as configured for normal operation is shown schematically in figure 5. The schematic shows two turbojet gas generators each driving a tip-turbine-driven lift fan. Each gas generator drives the nearest fan turbine by means of a short duct. Each fan has a $360^{\circ}$ scroll, which is split into two separate $180^{\circ}$ segments. A cross duct connecting the exhaust ducts of the two gas generators is also shown. Two butterfly valves are located just upstream of each fan scroll.

Assuming each gas-generator - fan unit to perform identically, both fans produce equal thrust when all four valves are wide open. This condition is shown in figure 5(a). Ideally, there is no crossflow and each fan produces the same thrust that it would if the cross duct were not there.

When differential thrust is required for moment control, the pair of valves upstream of one of the fans is partially closed as shown in figure 5(b). This reduces the effective discharge area for the two gas generators thereby increasing the back pressure in the ducting system. If the fuel flow to the two gas generators were held constant, this increase in back pressure would cause both gas generators to lose speed and result in a lift loss for both fans. However, if the gas generators have constant-speed governors, fuel flow is increased to prevent a speed loss; and the gas temperature in the exhaust ducting increases. In addition to a temperature increase, the fan turbine on the unthrottled side ("high side" in fig. 5(b)) receives more flow because of the restriction upstream of the opposite fan. The combined effects of increased flow, temperature, and pressure on the high-side fan turbine result in more power output and increased fan speed and thrust. Compared with the trim condition, the fan turbine on the throttled side receives less flow at a higher temperature. A pressure drop occurs at the valves, but this is partly offset by the increased pressure in the ducting. The net result of these effects is that the throttled side fan loses some thrust, but not enough to equalize the thrust increase on the unthrottled side. Therefore, some thrust spoiling is required on the throttled side to maintain total thrust constant. This spoiling is accomplished by louvers in the fan exhaust stream, which are partly closed when a thrust loss is required.

To summarize, the ETC system operates by raising the discharge temperature of the gas generators while maintaining them at a constant speed. The amount of crossflow, and hence the amount of control moment, can be varied by modulating the butterfly valves.

The ETC system can also be configured to compensate for gas-generator or fan failures. Figure 6(a) shows the action taken for a gas-generator failure. The failed gas generator is shut down and isolated by a shutoff valve. In order to maintain the correct discharge area for the one remaining gas generator, one of the butterfly valves is closed upstream of each fan. This cuts out $180^{\circ}$ of the scroll admission arc and consequently half of the fan-turbine inlet area. This procedure recovers about 50 percent of the lift available before the failure. More important, it results in nearly equal thrust from both fans; without flow transfer from the good side to the failed side, a large unbalanced moment would result. The two butterfly valves that are not closed may still be used to modulate differential thrust for attitude control just as in normal operation.

Figure 6(b) shows the corrective action proposed for a fan failure. In this situation the failed fan is isolated by shutting the two butterfly valves upstream. To recover some of the lost lift, an emergency nozzle is opened up to discharge the gas-generator exhaust directly to the atmosphere. Some crossflow is required to equalize thrust between the good fan and the nozzle on the failed side; this flow results from partly closing the butterfly valves on the good side and by sizing the emergency nozzle to accept the flow of more than one gas generator. Attitude-control moments are difficult to obtain in the fan-out condition, but some moment can be produced by spoiling and unspoiling the good fan without changing the butterfly valve positions. This results in nonconstant lift during moment-control applications, but coupling between lift and moment may be acceptable for emergencies.

Figure 7 shows an overall schematic of the ETC system in a typical six-engine VTOL transport (ref. 3). All the necessary valves are shown. Each pair of lift units requires a shutoff valve at the two ends of the cross duct. This allows individual starting of the gas generators and permits the isolation of the duct in event of hot gas leakage.

## Compressor-Bleed System

The compressor-bleed system of flow transfer is shown schematically in figure 8. As in the ETC system, each gas generator drives the nearest fan by means of a short duct. Each gas generator also has a compressor-bleed manifold, which supplies air to the cross duct connecting the two lift units. In the trim condition (fig. 8(a)) all valves remain closed except for leakage, and both fans produce equal thrust (assuming identical performance). The lift units are effectively isolated from one another in trim, and each performs as if the cross duct were not there. For study purposes the trimmed thrusts of the ETC and bleed systems were assumed identical even though the butterfly valves in the ETC system add a small pressure loss in the wide open position.

If differential thrust is needed for moment control, compressor-bleed air is taken from the gas generator on the low side and injected into the gas generator exhaust stream on the high side. This is accomplished by operating the valves as shown in figure 8(b). An alternate mechanization can also be used, which replaces each pair of valves in figure 8 with a single three-way valve. This mechanization is shown in figure 9. Such a scheme would be desirable to reduce the total number of components.

Regardless of how the system is mechanized, the addition of bleed air to the gas generator exhaust stream causes more flow to reach the fan turbine on the high side. As a result, an increase in exhaust duct pressure on the high side is required to maintain this additional flow. If the fuel flow to the high-side gas generator were kept constant, the speed would drop and a decrease in fan thrust would result. However, if gas-generator speed is kept constant by a governor, fuel flow is increased. This results in a temperature increase and a duct pressure increase consistent with the higher flow rate. The combined effects on the high-side fan turbine are similar to those of the ETC system: an increase in pressure, temperature, and flow resulting in more turbine power output and an increase in fan thrust and speed.

The behavior of the low-side fan and gas generator is typical of any turbofan system being required to provide high compressor-bleed flows. If gas-generator speed is to be held constant, the turbine-inlet temperature must increase to provide equivalent power output at a lower flow rate; this temperature increase is reflected in the gas-generator exhaust temperature. As in the ETC system, the low-side fan turbine receives less flow than in the trim condition, but at a higher temperature, so that some fan spoiling is needed to balance the thrust increase on the high side. The need for spoiling could be eliminated by reducing the gas-generator speed demand on the low side, but spoiling has the desirable characteristic of fast thrust response and is also useful in emergency operation.

In summary, the operation of the bleed system during moment demands resembles the ETC system in that the discharge temperature of the gas generators is raised while their speed is kept constant. The amount of temperature increase, and thus the amount of differential lift, can be modulated by controlling the crossflow with the bleed valves. More detail on the performance differences between the ETC and bleed systems will be given in the analytical results.

Failure control is less effective in the bleed system than in the ETC system since high-energy turbine exhaust gas is not ducted to the failed side. Lift recovery by means of a bleed-burn nozzle with ejector was selected as the best overall failure system for the compressor-bleed concept. Figure 10 shows a schematic of the bleed-burn system in a six-engine aircraft. The left- and right-side lift units are modulated for roll control; the fore and aft units are modulated for pitch control. Since the four pitch control units are modulated as pairs, they are shown connected by a single cross duct. The emergency interconnect valve is closed during normal operation to prevent interaction between the pitch and roll control functions. The emergency nozzles are also shut off during normal operation.

Failure control for the bleed system is accomplished by the same corrective action regardless of whether a gas generator fails, a fan fails, or both fail simultaneously. The failed unit is isolated (not necessarily shut down) by closing its bleed and injection valves. The bleed ducts of all the good units are manifolded together by opening the emergency interconnect valve. The combined bleed flow is then heated in a combustor and expanded through the emergency ejector on the failed side to recover some of the lost lift. The combustor obviously must have quick lighting characteristics (similar to present day altitude relight equipment for conventional combustors). Moment control during failures is accomplished by spoiling and unspoiling the fan opposite to the failed unit as in the ETC system fan-out case.

## ANALYTICAL PROCEDURE

The results presented in this report were produced by a digital computer program which simulates the dynamics of the YJ97/LF460 system. A single basic program was used with appropriate modifications depending on whether the ETC or compressor-bleed system was being analyzed. The simulation included all major components of an interconnected VTOL lift system: two gas generators, cross ducting, valves, and two fans with spoilers. Figure 11 shows schematically the components that were included in the analysis for each system. The equations used in the analysis are presented in reference 7.

Steady-state accuracy of the ETC system simulation was compared with ETC experimental results presented in reference 6, and the agreement was within 3 percent. The data in reference 6 were adjusted to account for differences between the two YJ97's used in the test and for the effect of nonstandard-day conditions. Also, reference 6 was only for two YJ97's interconnected in the ETC system configuration; it contained no experimental data on the LF460 since these fans have not yet reached the hardware stage of development.

One assumption worthy of note was made in the analysis of the bleed system in the equations governing the mixing of compressor-bleed air with the YJ97 exhaust stream. Total pressure at the YJ97 turbine discharge station was assumed equal to the total pressure after mixing. A detailed analysis of the mixing process was not attempted, however.

## STEADY-STATE PERFORMANCE

### Normal Operation

This section presents the steady state performance of the Energy Transfer Control (ETC) and compressor-bleed systems of flow transfer, which were described qualitatively in a previous section. In normal operation the purpose of these systems is to develop thrust differences between interconnected lift fans for aircraft attitude control. Although large thrust differences are maintained for only a short time in actual flight, the steady-state moment-generating capability of these systems is of interest since it shows how significant variables interact, and identifies the limits on maximum moment production. Although the results presented are for steady-state conditions, the transient operating limits are the ones applicable during moment-generating situations due to the short duration of moment requests in flight. Both systems depend on this fact when operating at the YJ97 military power setting. For example, the steady-state exhaust gas temperature (EGT) limit of the YJ97 is 1019 K (1835$^{\circ}$ R). This is the EGT shown in table I for the YJ97/LF460 design point. In order to generate any moment, this steady-state limit has to be exceeded. The transient EGT limit that applies in this case is 1144 K (2060$^{\circ}$ R) (ref. 6), and this is the factor that limits moment production capability.

All results presented are for the sea-level static, standard-day condition. One hundred percent inlet pressure recoveries have been assumed.

ETC system. - For the ETC system, moment produced is a function of butterfly valve angle, $\theta_v$, upstream of the fan turbine on the low (throttled) side. Figure 12 shows the variation of significant parameters as valve angle is varied from zero degrees (fully open) to the point where transient temperature limits are exceeded. For illustrative purposes the effects of spoiling are left out in figure 12.

Both YJ97 gas generators are run at full military power (101.5 percent speed) while the valves are modulated. Thrust, temperature, pressure, and flow are normalized with respect to the design point values given in table I. The solid line of figure 12(a) shows the increase of high-side thrust, and the dashed line shows low-side thrust. This figure shows that the low-side fan requires spoiling in order to balance the thrust increase on the high side.

Figure 12(b) shows the variation of YJ97 exhaust-gas temperature (EGT). Both gas generators operate at nearly the same back pressure except for the small differential required to pass flow through the cross duct. Since the back pressures are nearly the same, the resulting temperatures at 101.5 percent speed are nearly the same, explaining the overlap of the high- and low-side temperature curves in figure 12(b). The EGT limit is reached at a valve angle of 33.5$^{\circ}$, which corresponds to a normalized thrust increase of 0.24 on the high side, or 13 700 newtons (3070 lbf). Thus, with spoiling on the low side, a thrust difference of 27 400 newtons (6140 lbf) can be obtained while maintaining a constant total thrust of 114 000 newtons (25 600 lbf).

Figures 12(c) to (e) show the variations of LF460 turbine-inlet conditions accompanying valve movement. Inlet temperature, pressure, and flow increase on the high side. On the low side, temperature increases but pressure and flow decrease because of the throttling effect of the valves. The net effect of these changes is a small loss in thrust on the low side (see fig. 12(a)). In order to maintain constant speed at a higher back pressure, more fuel flow is needed; this effect is shown in figure 12(f). Figure 12(g) shows the change in fan speed accompanying the thrust changes. The LF460 limit speed of 104 percent is not critical for this case. Finally, figure 12(h) shows the reduction in compressor stall margin; a 0.213-steady-state margin is cut to 0.158 at full moment production.

For this study stall margin $\psi$ was defined as

$$\psi = \left[\frac{(P_3/P_2)_{stall}}{(P_3/P_2)}\right]\left[\frac{\left(\dot{w}_2\sqrt{\theta}/\delta\right)}{\left(\dot{w}_2\sqrt{\theta}/\delta\right)_{stall}}\right]-1$$

where $P_3/P_2$ is compressor pressure ratio and $\dot{w}_2\sqrt{\theta}/\delta$ is compressor corrected flow rate. The subscript "stall" indicates value at stall as taken from the YJ97 compressor map.

Compressor-bleed system. - The performance of the bleed system is similar to the ETC system in many significant respects. Figure 13 shows the variation of important parameters as a function of compressor-bleed flow expressed in percent of total compressor flow. Both YJ97 gas generators are held at 101.5 percent speed. Figure 13(a) shows the variation of LF460 thrust as bleed injection is increased. As in the ETC system, the low-side fan must be spoiled to balance the thrust on the high side. Figure 13(b) shows YJ97 turbine exhaust gas temperature (EGT). The transient EGT limit is reached at a bleed rate of 12.8 percent, or 4.02 kilograms per second (8.87 lbm/sec). This results in a normalized thrust increase of 0.24 on the high side, which is the same as that produced by the ETC system. The LF460 turbine-inlet conditions are slightly different for the bleed system than for the ETC system (see figs. 13(c) to (e)). The major difference is that high-side LF460 turbine-inlet temperature is less than for the ETC system because of the cooling effect of injecting bleed air into the YJ97 exhaust stream. The thrust increase of 0.24 for the bleed system occurs for a crossflow of 4.02 kilograms per second (8.87 lbm/sec) at 651 K ($1172^{\circ}$ R). The same thrust increase occurs for the ETC system at 3.13 kilograms per second (6.91 lbm/sec) of crossflow and 1144 K ($2060^{\circ}$ R). Thus, for a given thrust increase, the bleed system transfers more air but at a lower temperature. Figure 13(g) shows that the LF460 rotor speed changes are of the same magnitude for the bleed system as for the ETC system. Figure 13(h) shows the difference in compressor operating points on the high and low sides. The YJ97 supplying the bleed moves away from stall, but the one on the receiving side drops to a margin of 0.158 at maximum moment production.

Landing condition. - One of the useful features of the ETC and bleed systems is their ability to generate large control moments irrespective of gas-generator power setting. Figure 14 illustrates this fact for the ETC system. For this figure YJ97 speed is 92 percent; this results in a thrust level of about 0.56 compared with full military power used at takeoff. Once again, thrust is normalized with respect to the design point value of table I. Figure 14(a) shows that a high-side normalized thrust increase of 0.24 can be generated with a valve angle of $38.0^{\circ}$. Figure 14(b) shows that the EGT associated with this thrust increase is less than for the takeoff condition. Figure 14(c) shows that a stall margin of 0.142 remains at full control in the landing condition compared with 0.158 in the takeoff condition. Thus, the ETC system can produce the same control moment at 92 percent YJ97 speed that it can produce at 101.5 percent. Temperature levels are lower, but a little less compressor stall margin is left over at full control. Control sensitivities are similar: $38.0^{\circ}$ of valve angle at 92 percent speed gives the same moment as $33.5^{\circ}$ at 101.5 percent speed.

Figure 15 summarizes the performance of the bleed system at 92 percent YJ97 speed. A thrust increase of 0.24 is achieved at a compressor bleed flow of 17.0 percent, or 4.28 kilograms per second (9.44 lbm/sec). Again, YJ97 EGT is well within limits. Stall margin at full control is 0.142. As in the takeoff condition the ETC and bleed systems have nearly identical performance.

## Failure Operation

This section discusses the performance of the ETC and bleed systems during various failure situations. For a hovering VTOL aircraft the first necessity in event of a lift unit failure is to eliminate any unbalanced moments. Furthermore, the lift system should be designed to recover as much thrust as possible after failures so that the aircraft will be able to hover and land safely. The gross weight of VTOL transport aircraft is usually limited by the total lift available after failures (refs. 1 to 3). Hence, any improvement in failure performance is valuable since it potentially increases the payload of the aircraft.

A VTOL lift system must still provide attitude control moments after failures. For the results presented here each system was required to produce 50 percent of normal attitude control power after a failure. This is consistent with VTOL aircraft handling qualities guidelines (ref. 10). For study purposes 100-percent control power is assumed to require the full normalized thrust difference of 0.48 so 50-percent control power requires a difference of 0.24. For a given aircraft the full capability of the moment generating system may not be required during normal operation, and the same would also hold true for failure situations.

A qualitative treatment of failure control strategies was given in an earlier section. In the following discussion the performance of the ETC system will initially be presented without reference to a particular aircraft configuration. This approach is not possible with the compressor-bleed system because total lift recovery depends on the number of engines in the aircraft. Hence, a six-engine aircraft is analyzed as an example for the bleed system. Finally, the total lift recovery of the two systems is compared for the six-engine example configuration. Throughout this discussion, no assumptions are made about aircraft gross weight; the decision of sizing the aircraft to match lift system capabilities is left to the airframe designer.

Unfailed units. - The YJ97 gas generator has an emergency rating of 105 percent speed. An unfailed pair of lift units can utilize this rating to compensate for the loss of lift from another pair having a failed component. Figure 16 summarizes the performance of the ETC system at the emergency rating. The maximum thrust increase available for moment control is limited to 0.117 by the transient YJ97 EGT limit. Thus, a good pair of interconnected YJ97/LF460 units can be run at the emergency rating and still produce nearly half of the 0.24 thrust increase obtainable under normal conditions. This effectively meets the requirement of 50-percent normal attitude control power during emergencies and results in a trimmed lift of 1.072 for each fan compared with 1.00 at the military rating.

Figure 17 shows the performance of the bleed system at the emergency rating. Once again, performance is similar to the ETC system. The failure control strategy for the bleed system is such that the full range of control shown in figure 17 is not utilized, as will be discussed in a subsequent section.

ETC system gas-generator failure. - Figure 18 shows a schematic of the ETC system as configured for a gas-generator failure. One valve upstream of each fan turbine is closed; this diverts all flow through only 50 percent of the scroll thus cutting the effective turbine-inlet area in half. The fan on the failed side receives about half the flow produced by the good gas generator and produces a normalized thrust of 0.519. The fan on the unfailed side produces a normalized thrust of 0.561, so it must be spoiled slightly in order to achieve trim.

Figure 19 explains why the good gas generator is run at only 99.7 percent speed rather than the emergency rating of 105 percent speed. The reason is that sufficient temperature margin must be left over to provide 50 percent of the normal moment control. With only one valve being modulated and about half the normal flow rate, a valve deflection of $31.5^{\circ}$ on the unfailed side results in the required thrust increase of 0.12 on the failed side. This is 50 percent of the thrust increase of 0.24 which can be used for moment control in normal operation. The LF460 turbine map (ref. 9) used in the analysis for figures 18 and 19 was the same as that used for normal operation. LF460 turbine-inlet area was cut to 50 percent of normal in the analysis, but no other correction was attempted in predicting the performance of the LF460 for this operating condition.

ETC system fan failure. - Several fan failure control strategies have been suggested in connection with the ETC system (refs. 1 to 3). Figure 20 illustrates the concept recommended in this report. The failed LF460 is isolated by closing the two valves upstream. An emergency nozzle is opened up by means of a blowout disk or some other simple device. The two valves upstream of the good fan are partly closed in order to divert flow to the failed side. Both gas generators are run at the emergency rating of 105 percent speed; in figure 20 the emergency nozzle was sized to result in a normalized YJ97 EGT of 1.065 (1085 K, 1955$^{\circ}$ R) on the unfailed side. This is the same EGT resulting from normal operation at 105 percent speed and was selected, somewhat arbitrarily, as the maximum temperature for continuous operation in emergencies.

In this concept both gas generators are run continuously at 105 percent speed, and all height control is accomplished by the unfailed pairs of lift units. Moment control about the axis involving the failed unit is accomplished by spoiling and unspoiling the good fan. In figure 20 the good fan produces a normalized thrust of 0.796, and the emergency nozzle produces 0.556. Thus, if the good fan is not spoiled, a normalized thrust difference of 0.24 exists between the fan and the nozzle. This is 50 percent of the normal control power resulting from an increase of 0.12 on one side and a decrease of the same magnitude on the other side. By spoiling the fan to a thrust of 0.316, a moment of the opposite polarity can be obtained.

The method just outlined has two obvious drawbacks. The first is that a large amount of fan spoiling is required: from a thrust of 0.796 (45 300 N or 10 180 lbf) down to 0.316 (18 000 N or 4040 lbf). A complicated spoiler design may be required to accomplish this amount of thrust modulation without stalling the fan. The second problem is whether a nonconstant total lift is acceptable during moment applications. Since large moment demands are usually of very short duration, this type of height-attitude coupling is probably tolerable in emergencies.

Other fan failure systems were analyzed in this study including ones that obtain control moments by valve modulation. They were found not to be superior in lift recovery and required an extra modulating valve upstream of the emergency nozzle. All fan failure systems studied had great difficulty in meeting the criterion of 50 percent normal control power.

ETC system valve and duct failures - This section briefly covers possible failure modes that were not investigated in detail. Since the butterfly valves in the ETC system operate in pairs, a single inoperative valve is not a great problem provided that it stays in the wide open position. Failure of a cross duct in the ETC system can potentially be handled by closing valves at each end of the duct and isolating it. A firewall around the duct is absolutely required since any leakage would destroy the surrounding structure. Two kinds of failures cannot be corrected by the ETC system. The first is failure of the short duct between the gas generator and fan; the second is a fan failure caused by a gas-generator failure. This might result from debris damaging the fan turbine. These two kinds of failures must be prevented by proper design. If they are considered as possible kinds of failure, they nullify the otherwise good failure performance of the ETC system.

Bleed-system lift unit failure. - The bleed system uses the same lift-recovery strategy regardless of whether a gas generator, a fan, or both fail. This strategy is illustrated in figure 21 for a specific aircraft configuration. Unlike the ETC system, the failure performance of the bleed system is dependent on the number of engines the aircraft has; for example purposes a six-engine aircraft is shown. This number is consistent with the results of airframe studies (refs 1 to 3). In figure 21 the failure of a wing mounted lift unit is assumed. For the configuration shown this is a more difficult situation than the failure of a forward or aft unit since no unfailed pair remains to bear the burden of attitude control in the roll axis.

Figure 21(a) shows the distribution of compressor-bleed air for the trim situation. In normal operation the centrally located inter-connect valve is closed; during emergency operation it is opened to permit combined bleed flow from all the good engines to reach the failed location. The failed unit itself is isolated from the cross ducting system by closing its bleed and injection valves. The failed unit need not be shut down completely if it can produce partial lift. It also may be restarted if possible.

In order to recover lost lift, the compressor-bleed air reaching the failed location is heated in a burner to 2222 K ($4000^{\circ}$ R) and expanded through a converging-diverging nozzle. The converging-diverging nozzle is necessary to take full advantage of the high supply pressure of the compressor-bleed air. The nozzle total pressure is set by the lowest pressure feeding the ducting system; in figure 21 this is the compressor discharge pressure of the YJ97 opposite to the failed unit, which is run at 94.1 percent speed. In this analysis a 15-percent duct total-pressure loss was assumed, making the total pressure at the emergency nozzle 84.1 newtons per square meter (122 psia). The temperature of 2222 K ($4000^{\circ}$ R) is consistent with current advanced technology afterburner gas temperatures. In making the thrust calculation a fuel-air ratio of 0.04 was assumed. Also assumed was an ejector thrust augmentation ratio of 1.25. This ratio is consistent with available technology (ref. 11). The thrust recovery calculated with these assumptions and a nozzle airflow rate of 11.2 kilograms per second (24.6 lbm/sec) was 21 000 newtons (4730 lbf), or a normalized thrust of 0.370.

The engine opposite the failed unit is run at constant speed and bleed rate. All lift modulation for height control is accomplished by the forward and aft engines. To achieve trim about the roll axis, the YJ97 opposite the failed unit must be cut back to 94.1 percent speed and the fan must be spoiled. The bleed rate of 5.90 kilograms per second (13.0 lbm/sec) results in a normalized YJ97 EGT of 1.065 (1086 K, $1955^{\circ}$ R), which was selected as the maximum continuous temperature for emergencies.

The forward and aft engines are run at 105 percent speed when maximum lift is required for height control. In the trim condition 1.32 kilograms per second (2.9 lbm/sec) is bled from each YJ97 compressor. At 105 percent speed this results in a normalized EGT of 1.103 (1125 K, $2024^{\circ}$ R).

Moment control in the failure situation is illustrated in figure 21(b). Roll control is accomplished by spoiling and unspoiling the fan opposite the failed unit as in the ETC system fan-out case. Modulation is required through a thrust range of 0.610 to 0.130. This raises again the problem of spoiler design for such large amounts of modulation, and the problem of nonconstant lift during moment-control application.

Pitch control is accomplished in a manner similar to normal operation except that spoiling is not used, and the high-side units do not receive all the flow that is bled from the low-side gas generators. Figure 21(b) shows 50 percent of the normal pitch control being applied. Each high-side lift unit receives 1.54 kilograms per second (3.4 lbm/sec) of bleed and performs as shown in figure 17. The EGT of the low-side YJ97's is the limiting factor on total bleed flow; each YJ97 produces 4.17 kilograms per second (9.2 lbm/sec) of bleed at 102 percent speed and an EGT of 1.123 (1144 K, $2060^{\circ}$ R). The speed cutback from 105 percent is necessary to provide the large amount of bleed without overtemperature. This speed reduction would probably be accomplished by automatic temperature limiting in the YJ97 fuel control. The normal spoiling of the low-side fans must be deactivated since the YJ97 speed cutback more than compensates for the lift increase of the forward engines. Compared with trim, a small lift loss occurs during maximum pitch control application.

Table II compares the lift-recovery effectiveness of the ETC and bleed systems for a six-engine aircraft of the type shown in figure 21. Failure of a wing engine is assumed in the calculations. Table II is strictly for example purposes since different aircraft will require varying amounts of thrust modulation to obtain 50 percent of normal attitude control power. Table II illustrates the superior lift recovery of the ETC system for fan and gas generator failures. Furthermore, the ETC system resorts to the fan spoiling method of control, which results in nonconstant total lift, only in the relatively rare fan-out case. The bleed system also uses this method in the gas-generator-out case, which is expected to occur more frequently in flight than fan failures. Not shown, however, is the simultaneous gas-generator and fan failure for which the ETC system is ineffective. The significance of table II is that aircraft gross weight must be selected to permit safe hovering with the levels of lift recovery shown.

Bleed system valve and duct failures. - As in the ETC system, valve failures can be handled but corrective action is required. A valve jammed in the closed position necessitates closing all the other valves and operating the lift units without crossflow. A cross-duct failure is handled by closing all valves and operating the lift units independently. A failure of the hot duct between gas generator and fan is treated the same as any lift unit failure, that is, according to the procedure shown in figure 21.

# DISCUSSION

This section discusses development and operational aspects of the ETC and bleed systems. In normal operation the two systems were shown to have similar performance. In failure operation the ETC system was shown to recover more lift in fan-out or gas-generator-out situations. Each system has unique development and operational problems.

## Components

For the ETC system one major problem area is the development of flightworthy valves and ducts that can withstand the 1144 K ($2060^{\circ}$ R) peak temperatures. Such components do not presently exist in reasonable weights and sizes. The problems of service life, safety, maintainability, and cost are primary in commercial airline operations, and hot ducts are not attractive in this respect. The ducts in the bleed system are by no means cool at peak temperatures of 700 K ($1260^{\circ}$ R), but they represent an advantage over the ETC system. They are free of the coking problems associated with exhaust ducts, and they are smaller in diameter due to the higher pressure, which is roughly four times as great as for the ETC system. This means greater strength is required, partly offsetting the advantage of smaller size and less thermal insulation. Three-way valves to meet bleed system requirements will probably have to be developed, but valves already exist for handling compressor-bleed air in flight applications.

If fail-operational capability were not a criterion, the bleed system would almost certainly be preferred for its cooler ducts. Failure operation, however, raises one of the bleed system's development problems, namely, the design of a fast lighting bleed-burn ejector for emergency use. The system shown in figure 21 for failure operation assumes a high level of technology with a gas temperature of 2222 K ($4000^{\circ}$ R) and an ejector thrust augmentation factor of 1.25. The assumptions reflect realistic technology levels, but no actual component of this type exists. A bleed-burn ejector would require extensive demonstrations to prove satisfactory reliability for commercial operations. The bleed system also requires a manifold to draw off compressor-bleed air in large quantities (up to about 22 percent of total YJ97 airflow for the failure case shown in fig. 20). The ability to actually extract such a large amount of bleed air has not yet been demonstrated.

Both systems require the development of fan spoiling assemblies that are light and compact and do not excessively degrade steady-state performance. This problem is already being researched (refs. 1 to 3).

## Systems

Overall system testing of the ETC and compressor-bleed concepts is required to prove their adequacy for flight applications. Two YJ97 turbojets, without fans, have been run successfully with interconnected exhaust ducts (ref. 6). This demonstration has shown the feasibility of many aspects of the ETC system: notably, the ability to obtain the predicted amounts of flow transfer and the ability of the YJ97 to withstand transient overtemperatures and reduction of stall margin. No comparable demonstration has been made for the bleed system.

Both systems suffer from undesirable complexity though the bleed system has fewer components. Reliability, maintainability, and cost are unquestionably the major problem areas for these systems.

The analysis in this report has assumed that opposite lift units will be matched in thrust; hence, aircraft trim can be obtained without crossflow. This will not be the case in a real situation. A small amount of crossflow may be required to match the thrust of unequal engines, and this will raise temperature. Hence, unmatched engines will always tend to cut into moment capability in excess of trim. This should be kept in mind in matching moment capability to aircraft requirements.

## Failure Operation

In practice, realizing the fail-operational capabilities of the ETC and bleed systems is likely to be an enormous problem. In the case of the ETC system, condition monitoring capable of discriminating between fan and gas-generator failures must be used to ensure proper corrective action for either case. Ideally, the system should always detect failures promptly and accurately but should never report false alarms. This level of reliability indicates the need for a very sophisticated monitoring system.

The ETC system uses an unusual mode of fan operation during gas-generator failures. The LF460 fan is designed for flow admission to the turbine around the full $360^{\circ}$ of scroll arc, but the fan must also be able to operate at a $180^{\circ}$ admission arc in the gas-generator-out condition if the ETC system is to realize its full fail-operational potential. The ability of the fan to operate reliably at this abnormal condition must be thoroughly demonstrated in order to satisfy commercial safety requirements.

The interconnected exhaust ducting of the ETC system produces the effect of automatic compensation for gas-generator failures. Any loss of exhaust pressure on one side will automatically result in crossflow to the failed side even in advance of any valve manipulations by the control system. This effect tends to minimize transient thrust losses from the fan on the failed side. The bleed system does not have this feature; trim after gas-generator failures must be accomplished solely by action from the pilot or autopilot. This is also the case with the ETC system after fan failures. Unbalanced moments of this magnitude must be corrected quickly to keep the aircraft right side up. Spoiling the fan opposite the failed unit appears to be the only way of handling abrupt lift losses from one side; as long as large attitude upsets are avoided, total lift recovery can be delayed for a few seconds without incurring large altitude losses.

The exhaust interconnect feature of the ETC system also produces one of its disadvantages. To prevent back flow of hot gas through a failed gas generator, a check valve must be closed. This means that the "failed" unit cannot be restarted even though the failure may have been temporary, for example, a compressor stall. Every gas generator failure subjects two fans to the $180^{\circ}$ scroll admission condition, which is potentially damaging to the fans.

The bleed system failure strategy leads to different monitoring requirements and control problems. As discussed earlier, the same action is taken for gas-generator failures, fan failures, or simultaneous failures of both. Thus, it is not necessary to discriminate successfully between fan and gas-generator failures as in the ETC system. The failed unit is isolated from the rest of the system, but it may produce partial lift or be restarted. The fans are never subjected to partial admission operation; thus false alarms are less likely to cause damage. Unlike the ETC system, the bleed system can return to normal operation following a false alarm or temporary failure. This flexibility also simplifies checkout since the entire failure system can be demonstrated on the ground without subjecting any components to severe operating conditions.

The main disadvantages of the bleed system result from the fact that during failures the basic method of producing lift is completely different from that used in normal operation. The high-performance bleed-burn ejector must be ignited, and the valve that interconnects all the ducts must be opened. An essentially constant duct pressure must be maintained in order to keep the emergency nozzle near its design point, yet flow transfer must still occur among the unfailed units to provide attitude control. The design of this type of control system was not examined in detail for this study.

To summarize, both failure systems pose serious problems in demonstrating their ability to operate successfully in the commercial environment. The ETC system recovers more lift after gas-generator or fan failures, but it cannot withstand simultaneous failures of both. It obtains its good performance by using hot gas ducts and a failure monitoring system that must discriminate between fan and gas-generator failures. In exchange for less lift recovery, the bleed system offers cooler, smaller ducts and somewhat fewer total components. It is more flexible in operation and checkout and does not require discriminating between fan and gas-generator failures. Its main disadvantage is the need for a specialized bleed-burn ejector solely for emergency use.

## CONCLUSIONS

Two concepts for flow transfer in VTOL aircraft remote lift-fan systems have been identified and discussed: the Energy Transfer Control (ETC) system and a compressor-bleed-air transfer system. The compressor-bleed system is new and has not appeared in previous literature. In normal operation the two systems have identical steady-state moment generating capabilities. Both systems are limited in moment capability by transient temperature limits; a moment request of either polarity results in higher gas-generator back pressures, higher temperatures, and reduced stall margin.

Partial system tests have verified many aspects of the ETC system's feasibility. No comparable demonstration has been made for the bleed system.

Even disregarding failure control modes, both systems are undesirably complex, and each has untried features that could render the concept unfeasible. In the ETC system flightworthy valves and ducts are the main problem. For the bleed system valves and ducts could still be a problem although they are substantially cooler. Also, the capability of high-performance gas generators to provide large, rapidly varying bleed rates has not been demonstrated. The ETC system can use a standard YJ97 gas generator, but the bleed system would require design of a bleed manifold. For both concepts the design of efficient fan spoiler systems is an important problem. Both systems use complicated failure control strategies that are as yet unproven.

The ETC and bleed systems are potentially feasible for the VTOL aircraft application, but many practical problems remain to be solved. The entire justification of these systems hinges on the need for large control moments and fail-operational capability. The absence of such requirements weighs heavily against the use of these flow-transfer systems with their attendant complexity. Large transport aircraft have the above requirements, but low cost, maintainability, and safety must be conclusively demonstrated for either system to gain general acceptance.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 13, 1973,
501-24.

# APPENDIX - SYMBOLS

| | |
|---|---|
| $F$ | thrust |
| $N_F$ | fan rotor speed |
| $N_G$ | gas-generator rotor speed |
| $P$ | total pressure |
| $T$ | total temperature |
| $\dot{w}$ | mass flow rate |
| $\dot{w}_f$ | fuel flow rate |
| $\delta$ | pressure ratio, $P_2/P_{std}$ |
| $\theta$ | temperature ratio, $T_2/T_{std}$ |
| $\theta_v$ | butterfly valve angle |
| $\psi$ | stall margin |

Subscripts:

| | |
|---|---|
| stall | value at stall |
| std | standard day |
| 0 | design-point value |

For engine station designations see fig. 11.

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TABLE I. - YJ97/LF460 DESIGN-POINT PERFORMANCE

[Sea-level standard-day conditions; YJ97 military rating.]

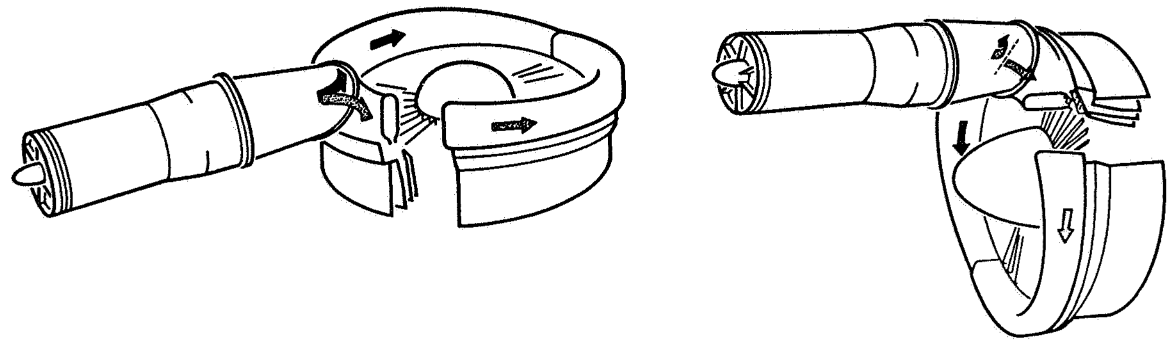
| YJ97 gas generator | |
|---|---|
| Compressor inlet pressure, $P_{2_0}$, $kN/m^2$; psia | 101.4; 14.70 |
| Compressor inlet temperature, $T_{2_0}$, K; $^oR$ | 288.2; 518.7 |
| Exhaust gas temperature (EGT), $T_{5_0}$, K; $^oR$ | 1019; 1835 |
| Exhaust gas pressure, $P_{5_0}$, $kN/m^2$; psia | 365.2; 52.96 |
| Exhaust gas flow rate, $\dot{w}_{5_0}$, kg/sec; lbm/sec | 32.00; 70.54 |
| Fuel flow rate, $\dot{w}_{f_0}$, kg/sec; lbm/sec | 0.6074; 1.339 |
| Rotor speed (101.5 percent of design), $N_{G_0}$, rad/sec; rpm | 1452; 13 855 |
| **LF460 fan** | |
| Fan inlet pressure, $P_{22_0}$, $kN/m^2$; psia | 101.4; 14.70 |
| Fan inlet temperature, $T_{22_0}$, K; $^oR$ | 288.2; 518.70 |
| Turbine inlet temperature, $T_{54_0}$, K; $^oR$ | 1019; 1835 |
| Turbine inlet pressure, $P_{54_0}$, $kN/m^2$; psia | 325.0; 47.13 |
| Turbine inlet flow rate, $\dot{w}_{54_0}$, kg/sec; lbm/sec | 32.00; 70.54 |
| Total thrust, $F_0$, N; lbf | 56 850; 12 780 |
| Rotor speed (92.26 percent of design), $N_{F_0}$, rad/sec; rpm | 415.4; 3967 |

TABLE II. - LIFT RECOVERY AFTER FAILURES

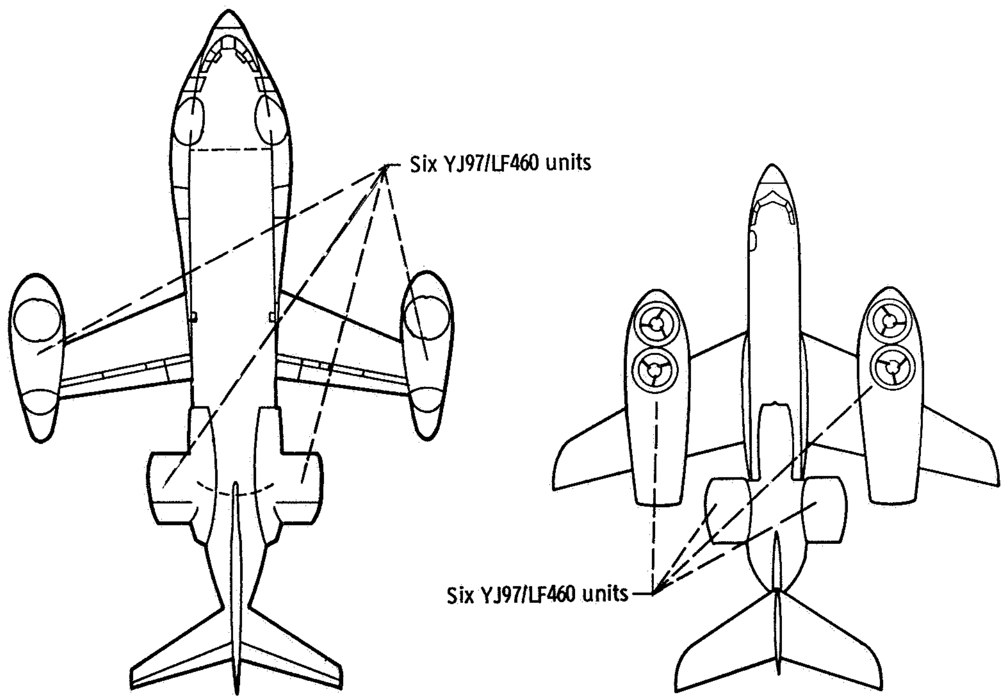
[Assumptions: (1) Six-engine aircraft, two forward, two aft, one on each wing; (2) wing unit failed; (3) 50 percent of normal control power required about all axes; (4) sea-level, standard-day conditions.]

| | Normalized lift recovery, $F_{tot}/6F_0$ | | |
|---|---|---|---|
| | Trim | Maximum pitch control | Maximum roll control |
| ETC system | | | |
| YJ97 failure | 0.890 | 0.890 | 0.890 |
| LF460 failure | .901 | .901 | [a]0.861/0.941 |
| Bleed system | | | |
| YJ97 or LF460 failure | 0.835 | 0.825 | [a]0.795/0.875 |

[a]Attitude control by spoiling and unspoiling fan. Total lift depends upon whether a positive or negative moment is required.



(a) Uninstalled.




(b) Two aircraft concepts.

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Figure 1. - YJ97/L460 configurations.

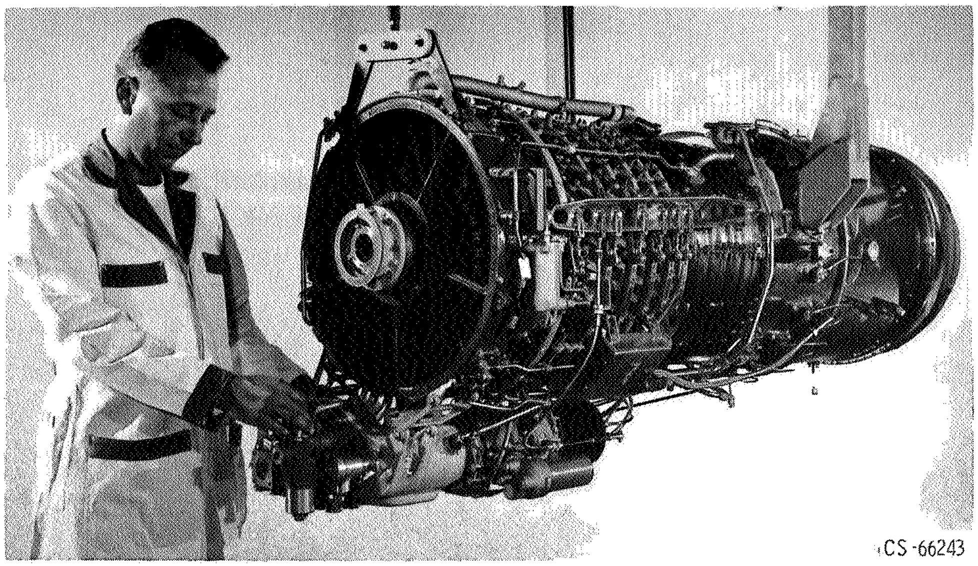



Figure 2. YJ97 turbojet.

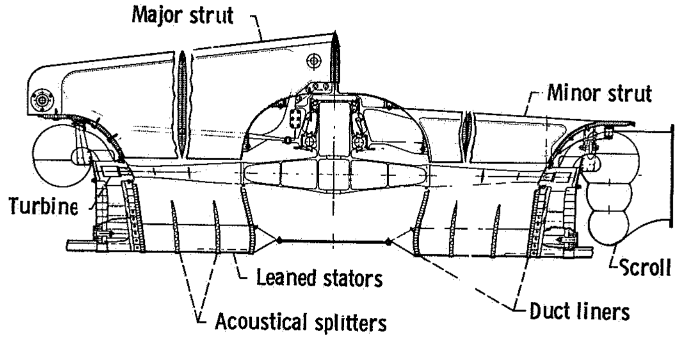



Figure 3. - LF460 lift fan layout.

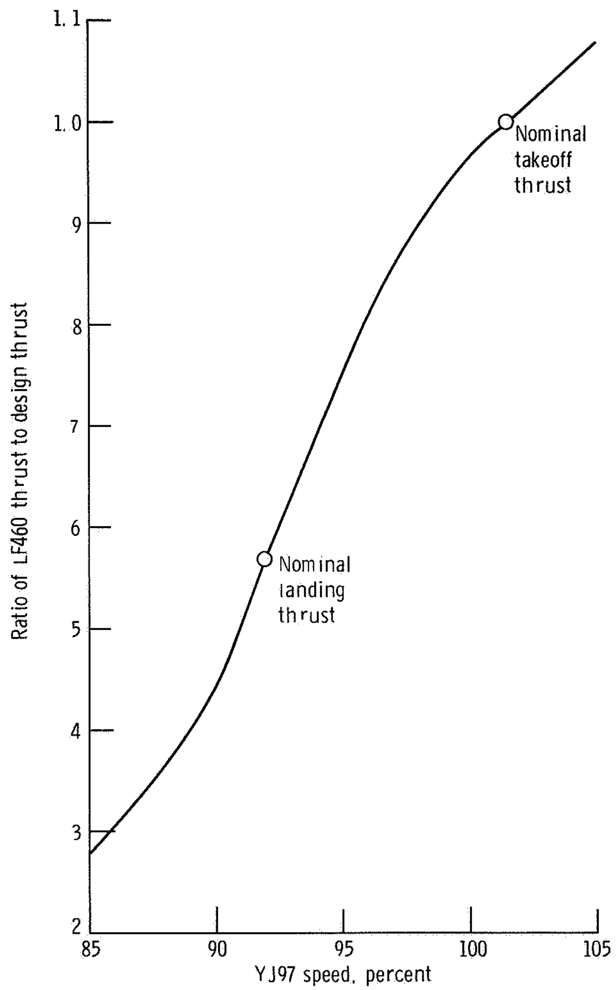
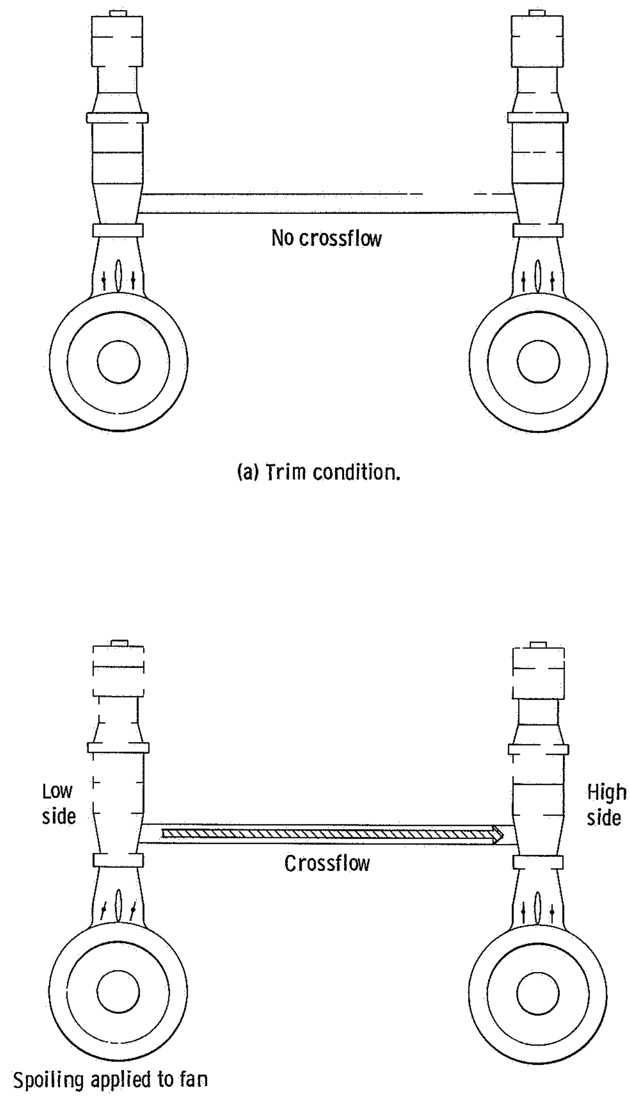



Figure 4. Fan thrust as function of gas generator speed. No flow transfer




(a) Trim condition.

(b) Moment condition.

Figure 5. Energy-transfer-control (ETC) system.

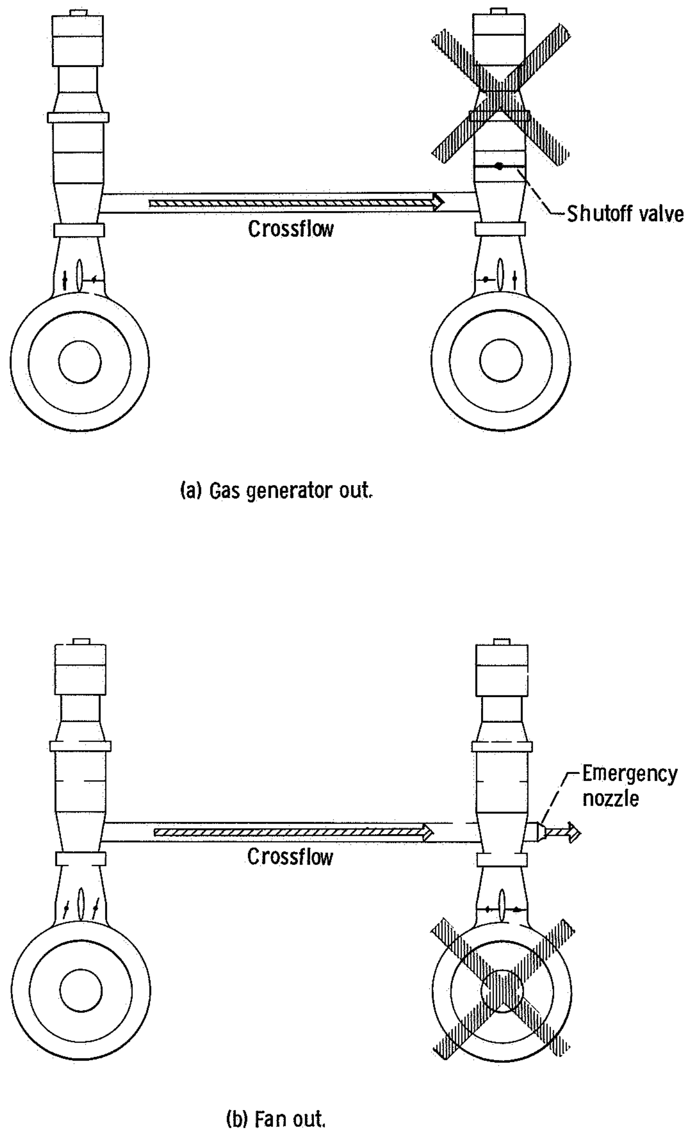



Figure 6. ETC system failure control.

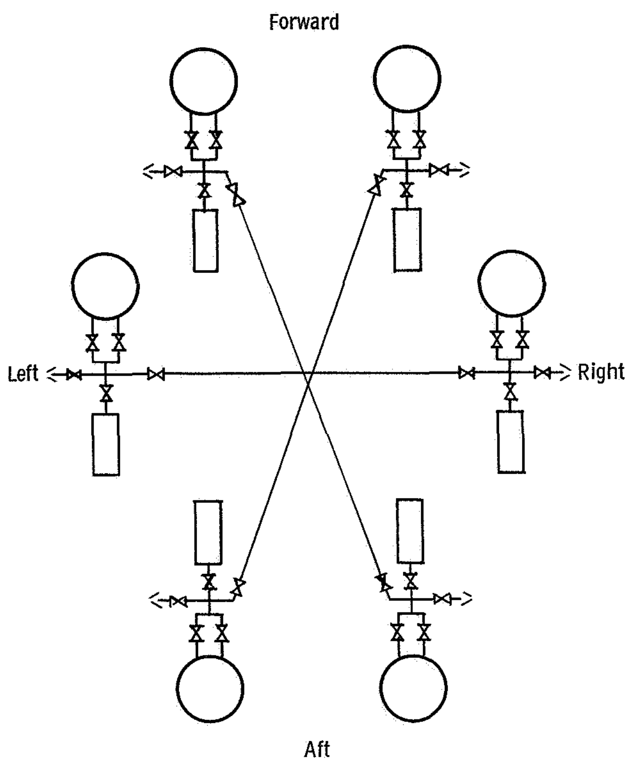
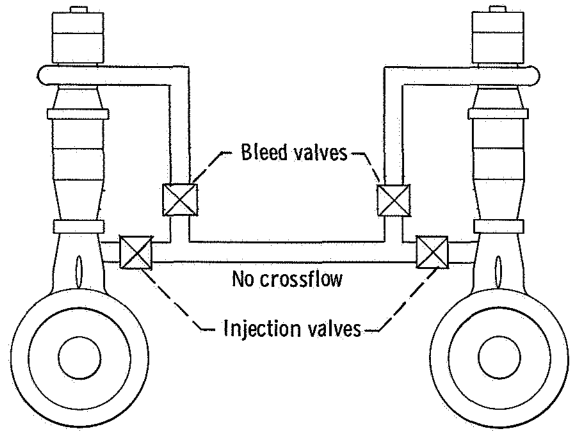
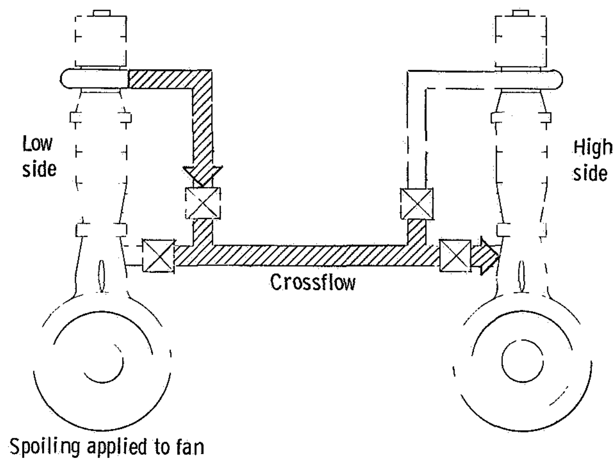


Figure 7 ETC system in six-engine aircraft.

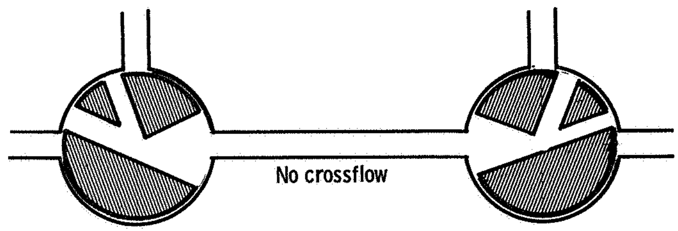


(a) Trim condition.

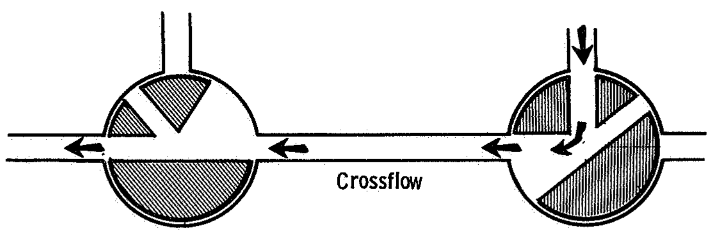


(b) Moment condition.

Figure 8. Compressor-bleed system.




(a) Trim condition.




(b) Moment condition

Figure 9. - Bleed system valve schematic.

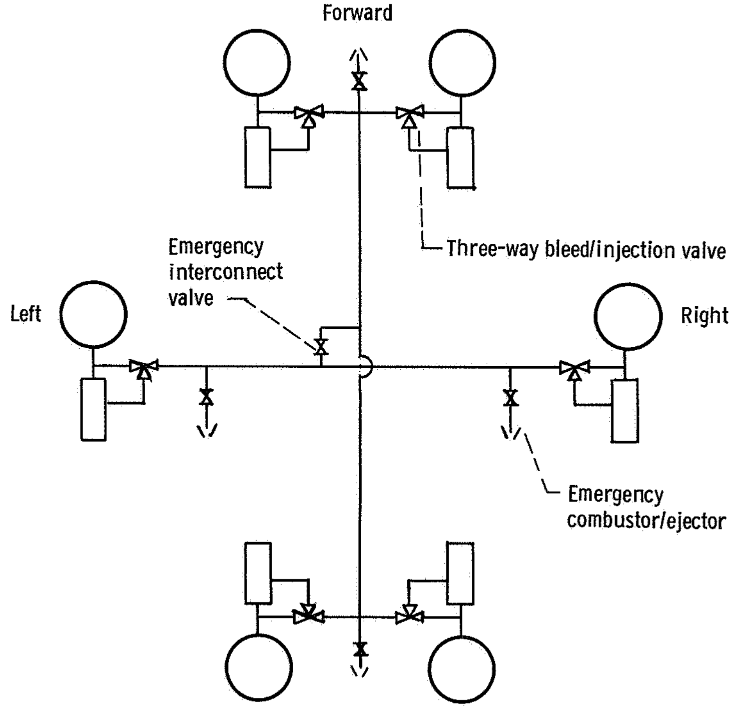
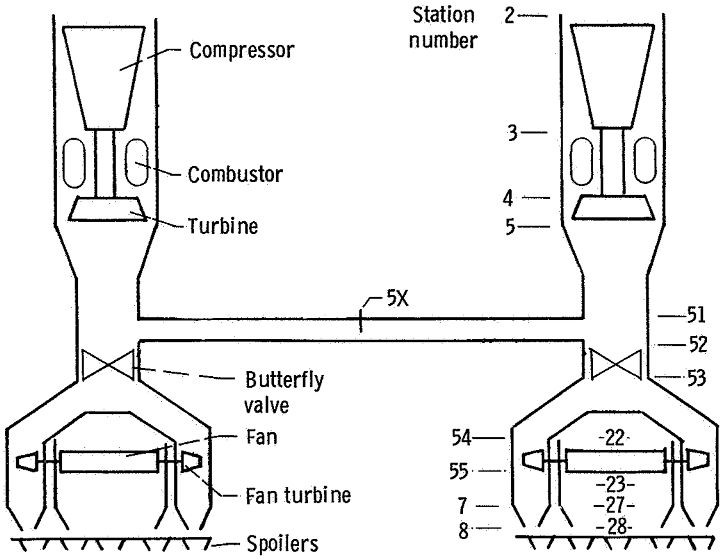
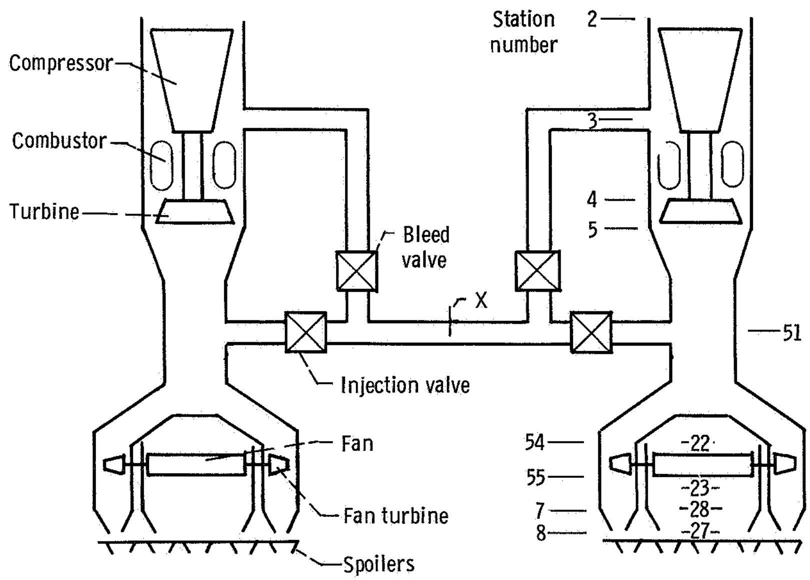



Figure 10. Compressor bleed system in six-engine aircraft.




(a) ETC system




(b) Compressor-bleed system.

Figure 11. Component schematic.

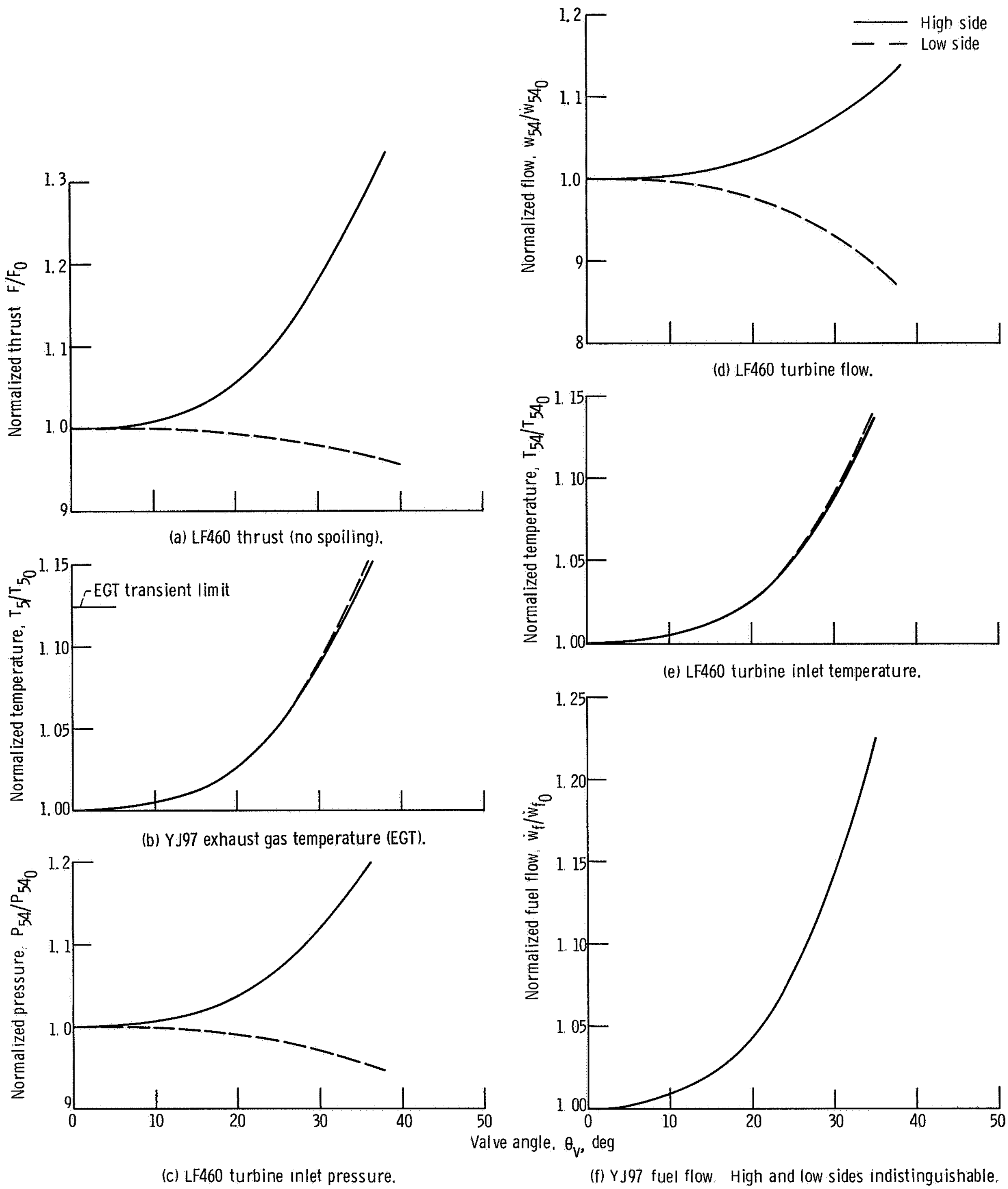
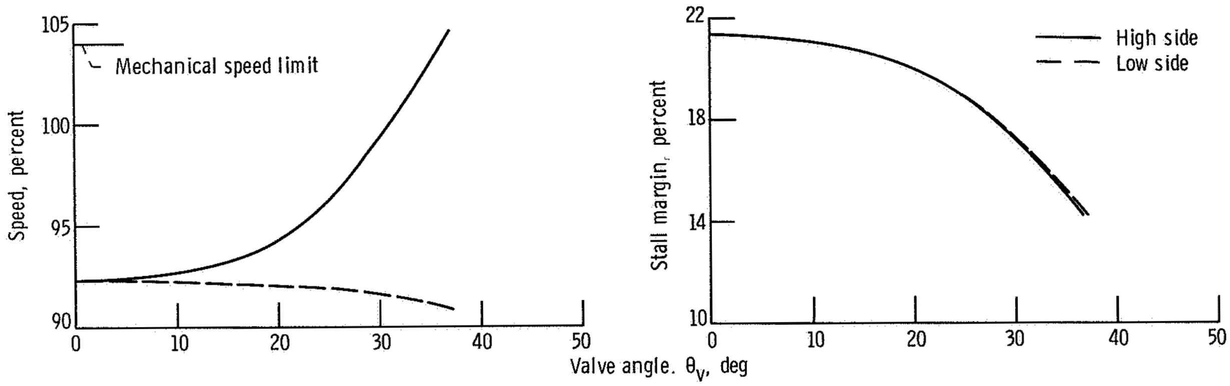



Figure 12. ETC system steady-state performance at 101.5 percent YJ97 speed (takeoff).




(g) LF460 rotor speed.

(h) YJ97 compressor stall margin.

Figure 12. Concluded.

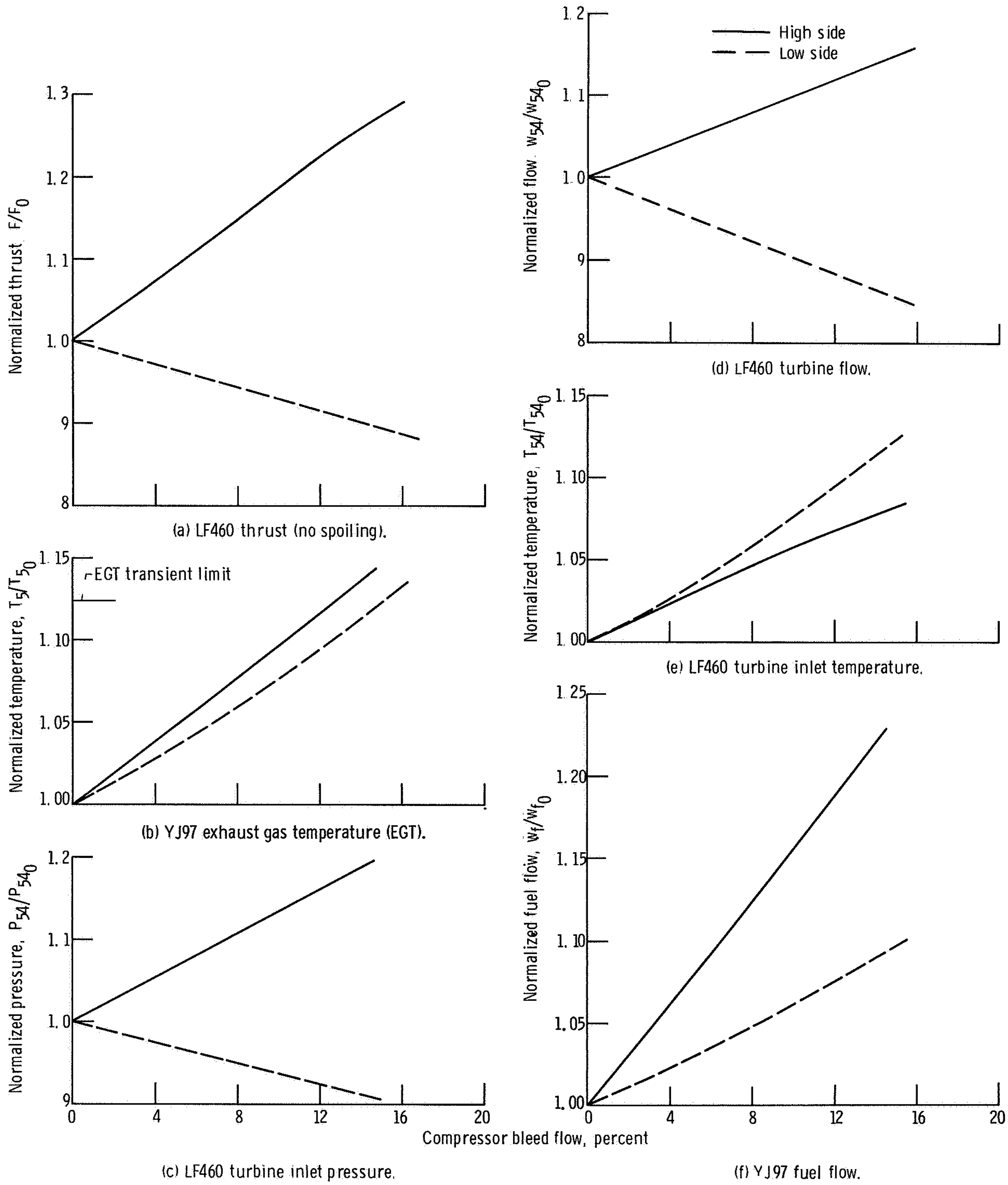
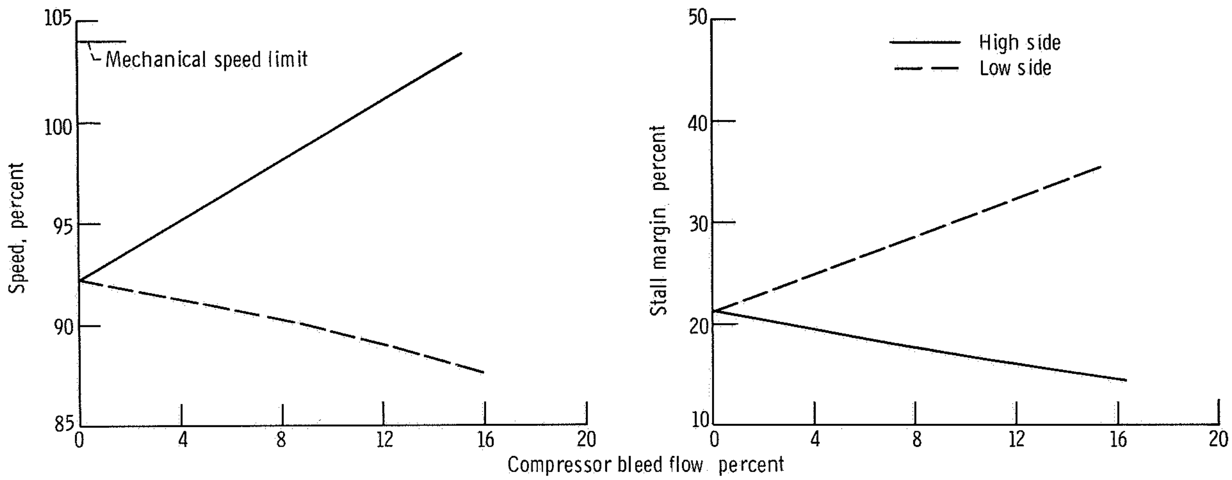


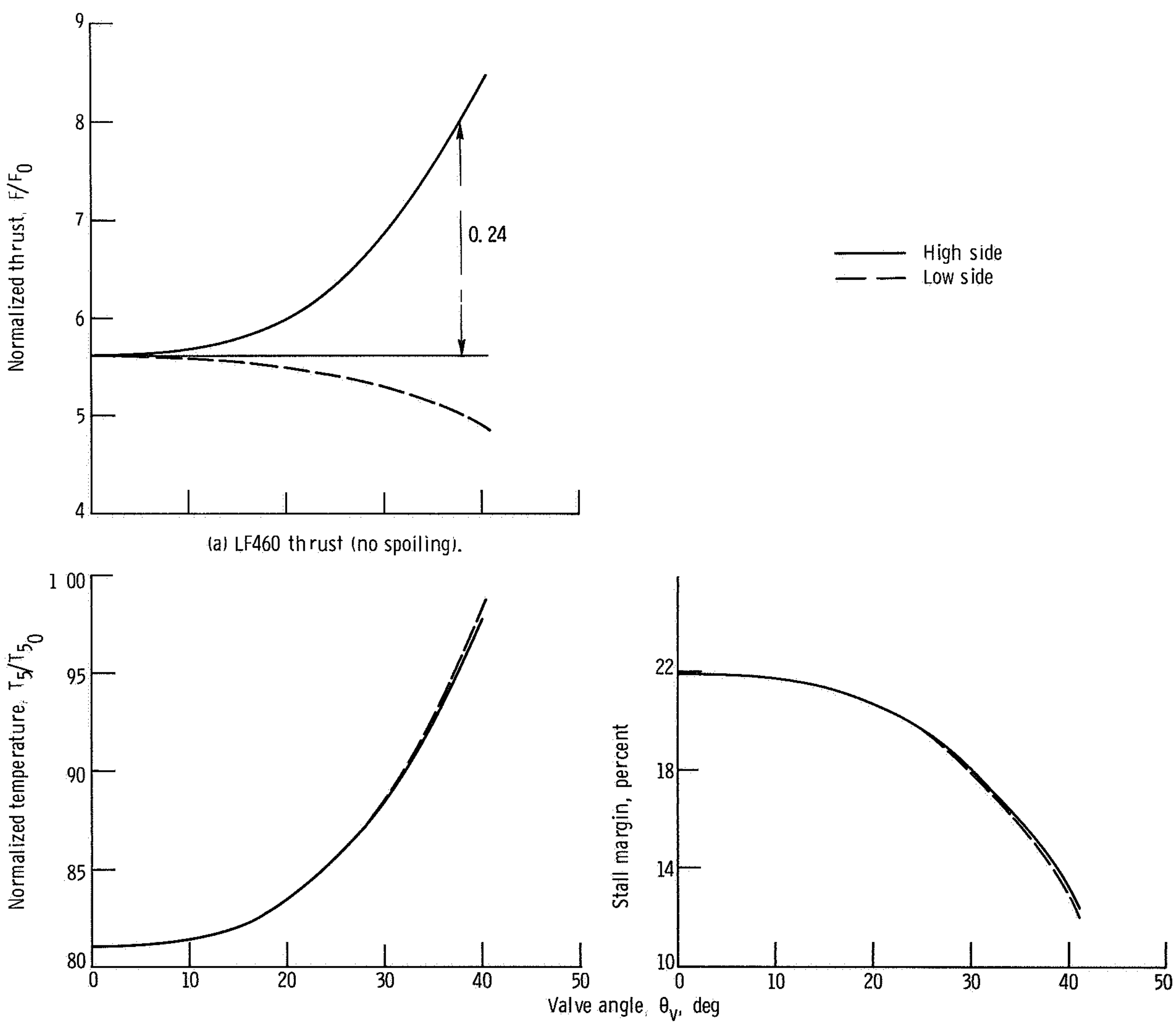

Figure 13. Bleed system steady-state performance at 101.5 percent YJ97 speed (takeoff).




(g) LF460 rotor speed.

(h) YJ97 compressor stall margin.

Figure 13. Concluded.




(a) LF460 thrust (no spoiling).

(b) YJ97 exhaust gas temperature (EGT).

(c) YJ97 compressor stall margin.

Figure 14. ETC system steady-state performance at 92 percent YJ97 speed (landing).

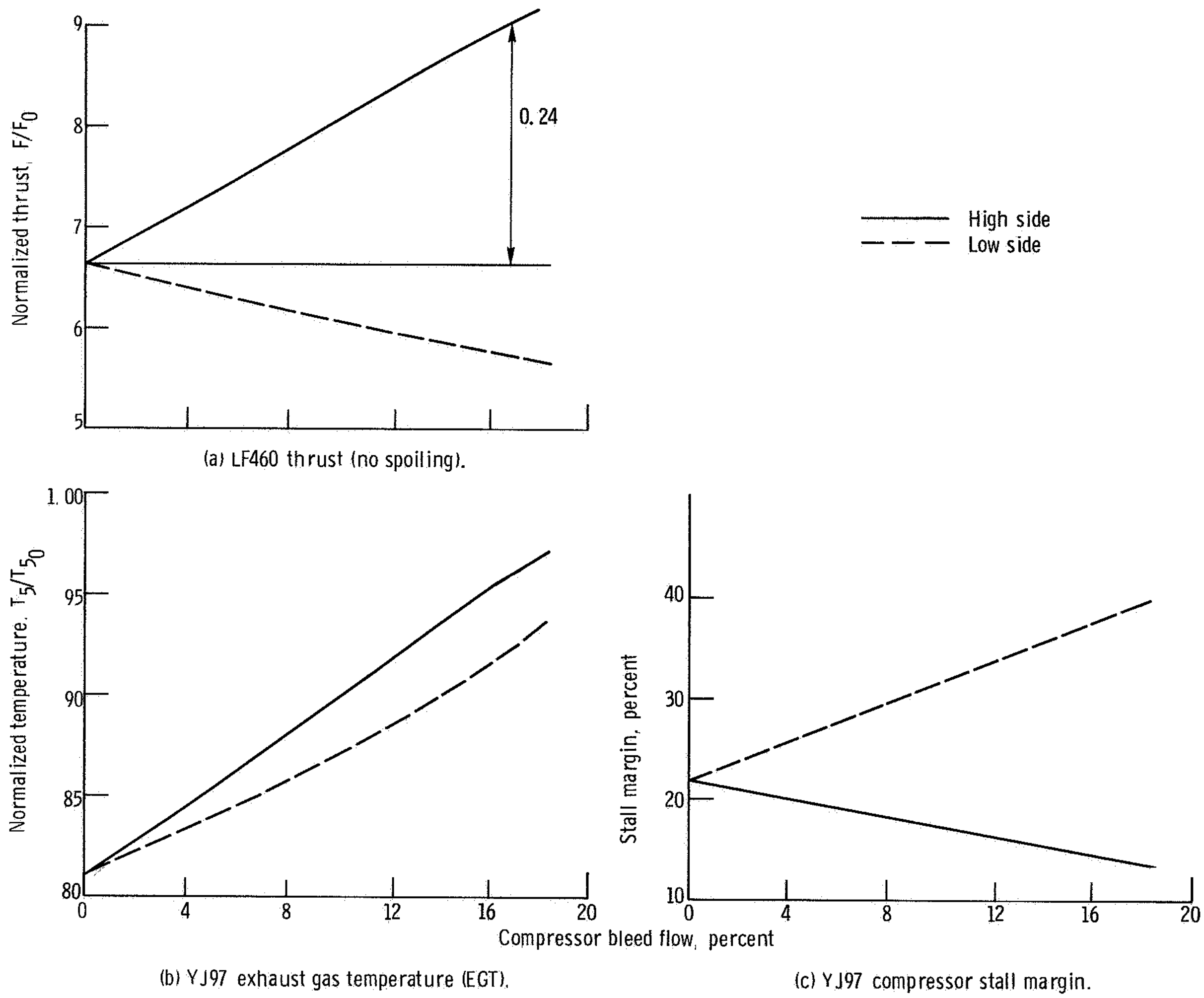
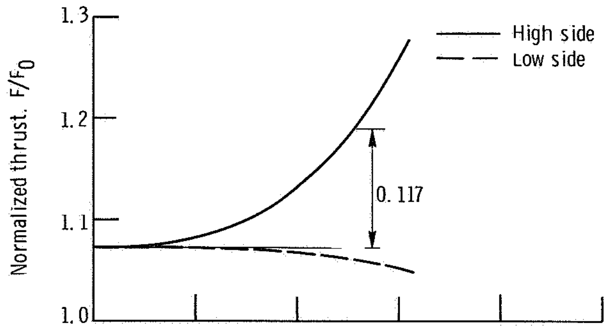
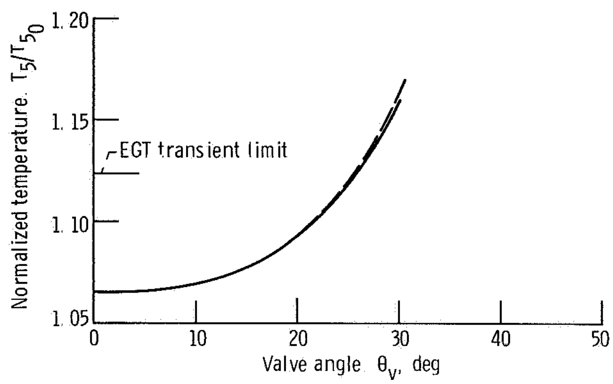



Figure 15. Bleed system steady-state performance at 92 percent YJ97 speed (landing).

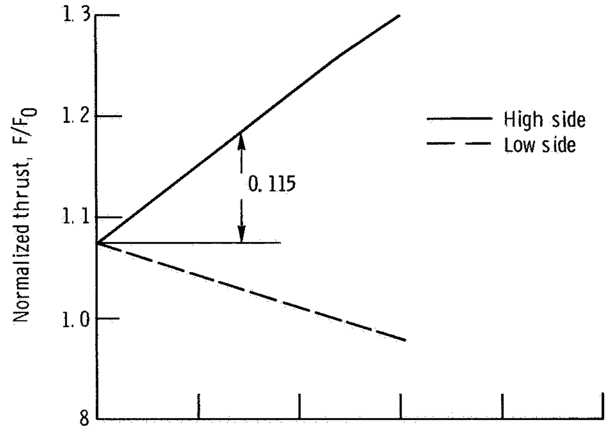



(a) LF460 thrust (no spoiling).

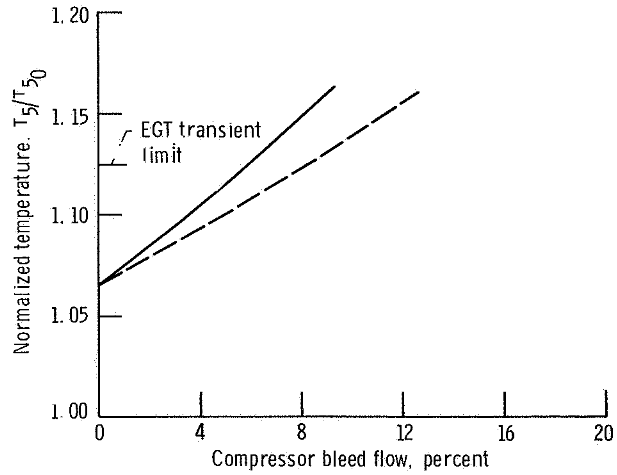



(b) YJ97 exhaust gas temperature (EGT).

Figure 16. ETC system steady-state performance at 105 percent YJ97 speed (emergency).




(a) LF460 thrust (no spoiling).




(b) YJ97 exhaust gas temperature (EGT).

Figure 17. Bleed system steady-state performance at 105 percent YJ97 speed (emergency).

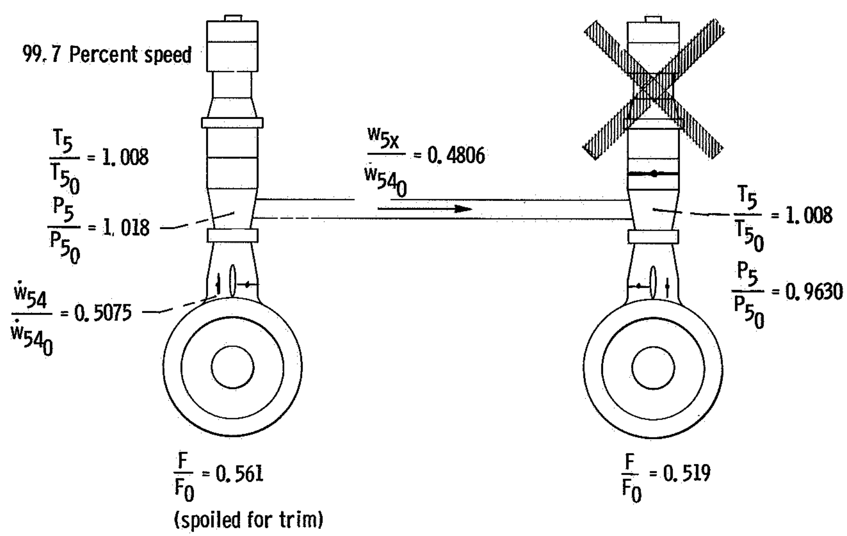
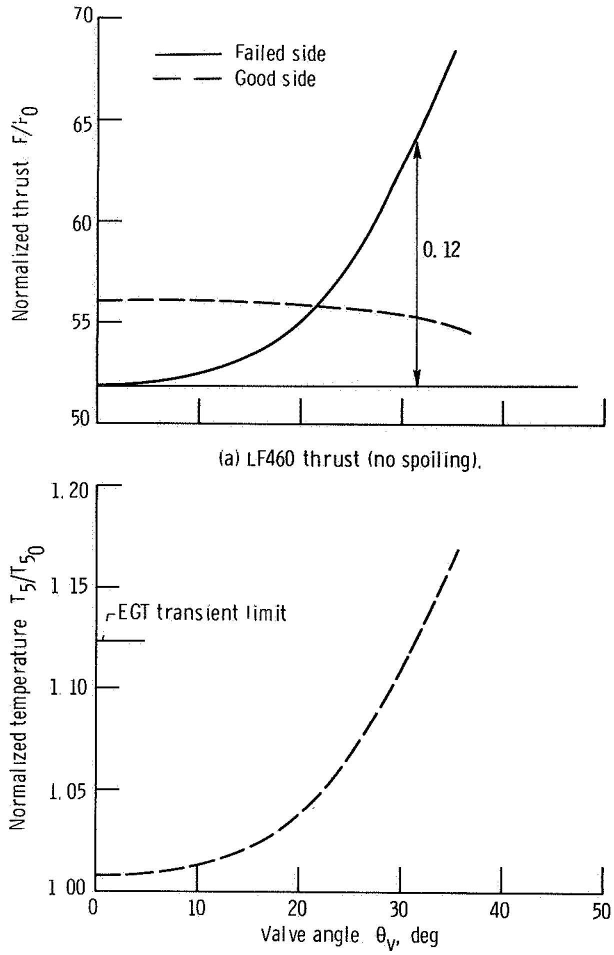



Figure 18. - ETC system steady-state performance YJ97 failure condition.




(a) LF460 thrust (no spoiling).



(b) YJ97 exhaust gas temperature (EGT).

Figure 19. ETC system steady-state performance YJ97 failure condition. Good YJ97 run at 99.7 percent speed.

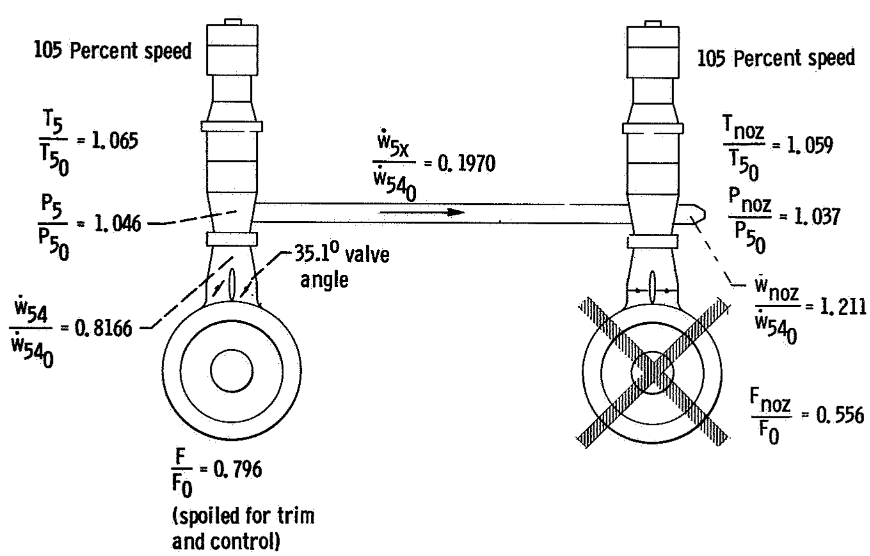
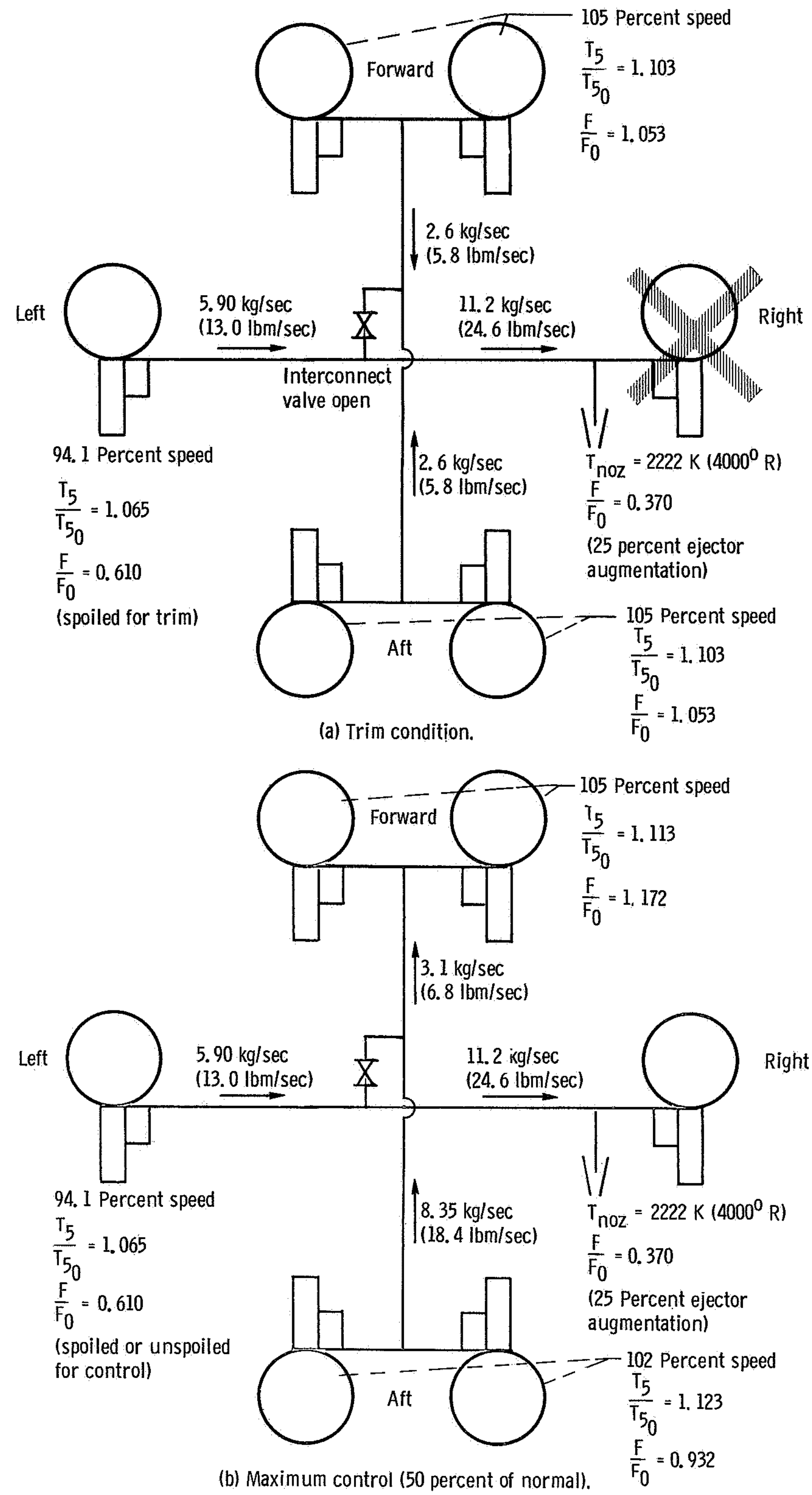



Figure 20. - ETC system steady-state performance in LF460 failure condition.




(a) Trim condition.



(b) Maximum control (50 percent of normal).

Figure 21. Bleed system steady-state performance failure condition. Emergency ejector used.



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