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PRELIMINARY STUDY OF AN AIR GENERATOR-REMOTE LIFT FAN PROPULSION SYSTEM FOR VTOL TRANSPORTS

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Cleveland, Ohio
August 1971

This information is being published in preliminary form in order to expedite its early release.

E-6543

ABSTRACT

A simplified mission analysis was performed to evaluate the effects of tip-turbine pressure ratio and lift-fan pressure ratio on payload and noise of a VSTOL airplane. The propulsion system consisted of four 15 000 pound thrust lift fans, eight 7500 pound thrust lift fans, and four air generators which were also used as the cruise engines. A range of 500 statute miles with two takeoffs and landings was selected along with a cruise Mach number of 0.75 at an initial cruise altitude of 25 000 feet. The allowable gross weight was calculated to be 88 700 pounds. Cruise L/D was varied parametrically from 8 to 12 to determine its impact on the propulsion system and payload. Cruise performance calculations showed that the four air generators used as cruise engines provided reasonable cruise performance. A tip-turbine pressure ratio of 4 and a lift fan pressure ratio of 1.15 gave a near maximum payload of 12 600 pounds (62 passengers). From these preliminary results, it is concluded that the remote air generator lift fan propulsion system is a promising VSTOL transport propulsion system.

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SUMMARY

A simplified mission analysis using a VSTOL airplane was performed to evaluate the effects of tip-turbine pressure ratio and lift fan pressure ratio on the payload and noise of a remote-drive VTOL lift system which consisted of four 15 000 pound thrust lift fans, eight 7500 pound thrust lift fans, and four air generators which were also used as the cruise engines. A range of 500 statute miles with two takeoffs and landings was selected along with a cruise Mach number of 0.75 at an initial cruise altitude of 25 000 feet. The allowable TOGW (dictated by one air generator out emergency operation) was calculated to be 88 700 pounds. Cruise L/D was varied parametrically from 8 to 12 to determine its impact on the propulsion system and payload capability.

Off-design (cruise) performance calculations showed that the four air generators used as cruise engines provided reasonable cruise performance. Cruise fuel was calculated using the Breguet equation for a climbing cruise. Finally, payload was calculated by subtracting operating weight empty and fuel weight from airplane gross weight. For the range of tip-turbine pressure ratio examined, this simplified analysis shows that a tip-turbine pressure ratio of 4 will allow a near maximum payload. A lift fan pressure ratio of 1.15 and a tip turbine pressure ratio of 4 gave a near maximum payload of 12 600 pounds (62 passengers). At higher fan pressure ratios noise increased and payload decreased due to an increase in hover fuel and an increase in air generator weight.

INTRODUCTION

Vertical takeoff and landing aircraft are currently under study as a means for improving short-hand intercity air transportation. VTOL can relieve airport congestion and reduce air time delays, and can service communities currently without air transportation. A number of VTOL transports have been studied in this country and abroad. Various aircraft configurations and various means of providing vertical lift (e.g., rotors, tilting propellers, and high-bypass-ratio lift fans) were studied (refs. 1, 2, and 3). None was outstandingly superior so that there is still interest in many of the concepts.

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In reference 4, the requirements and problem areas of low-pressure ratio lift fan propulsion systems are reviewed. The lift fan system has a number of features that qualify it for civilian STOL transports. These are: (1) good potential for meeting reduced noise limitations, (2) provision for safe management of failure of power plant or thruster, (3) good passenger and airline appeal for resulting aircraft, (4) capability of high cruise speed approaching that of conventional jet transports, (5) direct use of available gas turbine technology, and (6) elimination of mechanical transmissions. Two general types of lift-fan system are currently being worked on, the integral system and the remote system. The integral system is similar to a high-bypass ratio turbofan in which the fan is powered by a coaxially mounted gas turbine engine. In the remote type, the fan and its drive turbine are separately located from the powerplant, and the working fluid is delivered through ducts to the turbine mounted at the tips of the fan blades. The remote system wherein hot gas from a turbojet engine is delivered to the tip turbine has been under investigation for a number of years (ref. 5) by the General Electric Company and was used in the XV-5A VTOL aircraft (ref. 6).

A second remote system uses a gas turbine driven fan (air generator) to supply compressed air to a burner upstream of the remote tip turbine. During cruise the lift fans are inoperative and air from the air generator is exhausted in the conventional manner so that the air generator operates as a conventional turbofan engine. The present study is concerned solely with a particular air generator-lift fan VTOL system currently being considered at the Lewis Research Center.

This system consists of four 15 000 pound thrust remote lift fans and eight 7500 pound thrust lift fans driven by gas generated just upstream of the tip turbines in auxiliary burners fed by four low bypass ratio, high fan pressure ratio air generators. Cross ducting is provided between each pair of air generators so that the thrust loss with one air generator out can be minimized. During cruise, the lift fans are inoperative and the fan exhaust is exhausted through cruise nozzles.

The objective of the study is to optimize the parameters of the air generator and remote tip-turbine lift fan. For the air generator, turbine-inlet temperature was varied from 1900° to 2500° F, overall pressure ratio from 12 to 21 and fan pressure ratio from 2.73 to 4.37. Bypass ratio was a dependent variable to produce the air required by the auxiliary burner which operated at 1440° F and supplied working fluid to the 7500 and 15 000 pound thrust remote lift fans. Specific values of the air generator parameters were selected based on weight, dimensions, and specific fuel consumption.

The parameters of the remote tip-turbine lift fan were selected by performing a preliminary mission analysis. The propulsion systems examined were installed in a particular airplane which cruised at Mach 0.75 and 25 000 feet. Range was 500 statute miles and included 5 minutes of hover to account for two takeoffs and two landings. Gross weight was calculated from consideration of emergency conditions so payload varied as tip-turbine pressure ratio varied from 2.5 to 4.0, lift fan pressure ratio varied from 1.15 to 1.35, and cruise lift to drag ratio from 8 to 12. Takeoff noise was also calculated to illustrate the payload noise characteristics of the propulsion systems.

METHOD OF ANALYSIS

Propulsion System Requirements

Mission. - The mission selected to evaluate the propulsion system is as follows:

Stage length, st mi	500
Cruise Mach number	0.75
Cruise altitude, ft	25 000
Nominal takeoff noise goal @ 500 ft, PNdB	95
Hover time for two takeoffs and two landings, min	5

VTOL transport. - The type of VTOL transport assumed in this study is shown in figure 1. There are four large lift fans mounted in the high wing, each capable of producing 15 000 pounds of lifting thrust at sea level on a 90° F day. At the wing tips and the forward and aft fuselage stations, there are eight half-size lift fans producing an additional 60 000 pounds of lift thrust. The four air generators are mounted in pairs on the wing. Each air generator supplies two of the full-size lift fans or four of the half-size lift fans. Air generators are interconnected so that there is no one-to-one correspondence between fans and air generators. During liftoff and landing, the air flow is deflected downward to provide additional lift thrust (the level varying slightly depending on the design of the air pump). The nominal value of total lifting thrust on a 90° F day was 128 000 pounds.

The gross weight of the VTOL transport was calculated for normal operation, operation with one air generator out, and operation with two full-size lift fans out. The least of these values was taken to be the transport gross weight for the nominal mission. For normal operation, a vertical thrust to gross weight ratio of 1.1 was assigned and a control thrust to weight ratio of 1.25 giving a gross thrust to weight ratio of 1.375. For the air generator out and full-size lift fan out cases, vertical thrust to weight ratio was 1.05 and control thrust to weight ratio 1.125. The air-generator out case was critical and resulted in a gross weight of 88 700 pounds.

Simplifying assumptions were made concerning the operating weight empty less propulsion system weight (50% of gross weight) and the transport aerodynamics (cruise L/D was varied parametrically from 8 to 12). Reserve fuel was assigned to be 3.5% of gross weight and fuel to accelerate and climb to cruise conditions from transition was assigned to be 3% of gross weight. The airplane fractional weight that varied with propulsion system designs were (a) propulsion system weight, (b) fuel for two takeoffs and landings (5 min of hover), and (c) fuel to cruise the 293 statute miles of the nominal 500 statute miles total range (207 st mi were allotted for climb and letdown).

Propulsion System

The two major elements of the air generator lift fan propulsion system are shown in figure 2 (the remote drive lift fan and the air generator).

Air enters the air generator through an acoustically treated inlet. All of the air is compressed by the low-pressure compressor, or fan. The air delivered by the low compressor is split: part of it is collected in a scroll to form the delivered air supply, the ultimate product of the air generator. The remaining air goes through the high-pressure compressor, burner, and high pressure turbine. These three components make up the so-called high spool of the air generator which is, in reality, a gas generator for the low pressure turbine. This turbine drives the low pressure compressor, and these two components along with the connecting shaft constitute the low pressure spool. The shafts for the two spools are concentric. The exhaust from the low pressure turbine is ducted through an exhaust system which turns the flow through ninety degrees to produce a vertical thrust or lift for takeoff and landing.

A computer program provides a design point configuration for the air generator. The thermodynamic performance, including the discharge thrust, is completely described, along with the dimensions and weight. Detailed thermodynamic performance, size, and weight are also calculated for the principal components.

The length and weight of the inlet acoustic treatment and the exhaust system calculated by this computer program are appropriate for the configuration shown in figure 2. However, the actual inlet and exhaust systems used may differ from those shown. It was assumed in this study that the sonic inlet would suppress forward propagating turbomachinery noise to a level low enough that it would contribute a negligible amount to the total propulsion system noise.

The computer program of reference 7 provides a preliminary design and analysis tool for an entire tip-turbine-driven lift fan assembly. This program is particularly adaptable to parametric studies of the effect of changes in the principal design variables of both the fan and turbine on the performance of the entire assembly. Considerable attention is given to the scroll which delivers the working fluid to the tip turbine. In the propulsion systems considered herein, the cold ducts that deliver the low pressure compressor discharge air from the air generator to the lift fan are interconnected and just upstream of the scroll inlet to each lift fan is an auxiliary burner with a maximum outlet temperature of 1440° F.

Air generator. - The computer program for the design and performance of an air generator has considerable inherent flexibility in that no less than 44 independent parameters may be specified for any one air generator design. For all air generators, ambient pressure was 2116 pounds per square foot and ambient temperature 90° F. Total pressure recovery of the inlet was 0.95.

For each air generator considered, the size was determined to be that required to supply two full-size lift fans each of which delivered 15 000 pounds of thrust at liftoff. The low-pressure compressor was designed with a constant hub radius and 3 to 5 stages with a corrected tip speed at the compressor inlet of 1200 feet per second and a design point polytropic efficiency of 0.895. Average axial inlet Mach number was 0.6 and inlet hub-tip radius ratio was 0.5 for the first rotor. Diffusion through the compressor was regulated by selecting axial velocity-ratio across the compressor to be 0.75. Average aspect ratio of the first two stages (which affects both length and weight of the low compressor) was 3. The design value of low compressor pressure ratio was varied between 2.73 and 4.37 to provide a tip-turbine pressure ratio of 2.5 to 4.0 assuming a pressure loss through the ducts and scrolls of 8.4%.

The scroll diameter, corresponding to the maximum flow area in the scroll, was sized by the scroll Mach number of 0.3 and a selected configuration wherein the two delivery ducts are contiguous.

Most of the parameters required to describe the high compressor were used in the same manner as for the low compressor. The similar parameters are:

Flow path	constant hub
Number of stages	6 or 7
Corrected tip speed, ft/sec	1100
Efficiency	0.895
Axial velocity ratio	0.75
Overall pressure ratio	12 to 20

Four input parameters were required to establish the performance and geometry of the combustor. The reference burner inlet velocity was fixed at 60 feet per second so that the resultant flow area, or radial height, of the burner was a dependent variable. Burner length was determined from this height and the prescribed ratio of burner length to height, 3. A lower heating value of 18 400 Btu per pound of JP fuel and a burner efficiency of 0.98 were used to compute fuel-air ratio.

One of the most significant parameters in the performance of the air generator is the stator inlet temperature to the high turbine. In this study it was varied from 1900° to 2500° F. Rotor cooling air (as a percent of high compressor discharge airflow) was scheduled to be 5.7 to 14.7% to reflect current technology in turbine-blade material and cooling airflow to maintain blade integrity. A high turbine loss coefficient of 0.4 was used to calculate efficiency of the one-stage turbine.

The large work extraction from the low turbine reduces the density of the working fluid so that a large flow area is required at the turbine exit. Flow area together with an assigned exit hub tip radius ratio of 0.6 permitted turbine exit diameter to be calculated. The loss factor for the low turbine was assigned to be 0.4 and resulted in a turbine efficiency of 0.88 to 0.89.

The exhaust system on the core of the air generator includes both a duct and an adjustable nozzle which deflects the core flow to produce lift during takeoff and thrust during cruise. In order to provide control on the jet noise, the exhaust velocity from the nozzle was specified to be 650 feet per second. Exhaust system losses were accounted for through the use of a duct pressure loss coefficient of 0.125 which was multiplied by the square of the axial Mach number out of the turbine and by assigning a nozzle discharge velocity coefficient of 0.98.

During cruise the air pump is employed as the cruise thrusting engine to overcome airplane drag. To get the required variation of specific fuel consumption with thrust setting on a standard day + 31° F (17.2° C), the procedures described in reference 8 were employed. Maximum thrust was assigned to be that corresponding to a turbine inlet temperature 200° F less than takeoff turbine temperature. The exhaust nozzle discharge velocity coefficient was 0.98

Tip-turbine-driven lift fan. - Each of the full-size lift fans was sized to produce 15 000 pounds of thrust at takeoff on a 90° F day at sea level. The program described in reference 7 was used to compute dimensions, weight, and performance of single-stage lift fans having design pressure ratios of 1.15 to 1.35. The single-stage tip-turbine pressure ratio was varied from 2.5 to 4.0.

The temperature into the scroll was set at 1440° F so that the scroll could be constructed of conventional alloys. Inlet duct pressure ratio was 0.95 while fan inlet Mach number was 0.55 and fan hub-tip radius ratio was 0.4. For each tip-turbine driven lift fan, turbine exit axial Mach number was 0.3.

Some pertinent parameters are listed below:

Turbine pressure ratio	2.5	3.0	3.5	4.0
Air generator exit temperature, $^{\circ}$F	770	802	836	866
Fan tip speed, ft/sec	823	926	926	1030
Fan efficiency (for fan pressure ratio of 1.25)	0.831	0.840	0.840	0.843
Tip-turbine lift fan weight (for 15 000 lb thrust), lb	1065	1022	985	975

Noise calculations. - The total perceived noise is made up of jet noise from the four air generators, jet noise from the twelve lift fans, and suppressed turbomachinery noise from the twelve lift fans. Turbine jet noise from the lift fans was assumed to make a negligible contribution to total noise (whether or not this can be achieved in an actual engine remains to be demonstrated). Turbomachinery noise projected out the fan inlets and air generator inlets (which contain choking devices for noise suppression) was also assumed to make a negligible contribution to total noise. The noise rating condition was assigned to be at maximum takeoff thrust.

Jet noise, measured in PNdB, was calculated by standard methods described by the Society of Automotive Engineers in references 9 and 10. At jet velocities below 1000 feet per second, there is some uncertainty as to how overall sound pressure level (OASPL) varies. In this report, the semi-log plot of the curve of OASPL against relative jet velocity shown in figure 1 of reference 9 was extrapolated as a straight line below 1000 feet per second. While this technique is not used exclusively throughout the industry, it does agree with recent data published in reference 11.

Fan turbomachinery noise, also measured in PNdB, is a function of many things; e.g., number of rotor blades and stator blades, tip speed, spacing between rotor and stator, fan pressure ratio, thrust, and amount of nacelle acoustic treatment. In this study, it was assumed that the engines would be built with optimum stator-rotor spacing and without inlet guide vanes in order to minimize noise generation. Curves developed by the Propulsion Systems Acoustic Branch at NASA Lewis, and presented in reference 11, relate fan machinery noise to fan pressure ratio for one-stage fans. These noise curves were scaled from a net thrust of 120 000 pounds and a distance of 500 feet. According to reference 11. acoustic treatment can reduce turbomachinery noise as much as 15 PNdB, the amount of suppression used in the noise calculations of this study. Total noise was obtained by adding anti-logarithmically the suppressed turbomachinery and jet perceived noise, as described in reference 9.

RESULTS AND DISCUSSION

Lift Propulsion Performance

In this section the effects of varying air-generator parameters are presented in terms of dimensions, weights, and specific fuel consumption during hover.

Effects on air generator. - The effects of air generator overall pressure ratio and turbine temperature on air generator performance, size and weight are shown in figure 3. As overall pressure ratio increases from 12 to 21, the chief effect is an 8% reduction in specific fuel consumption (lb fuel hr per unit airflow to the tip turbine, fig. 3(a)).

Specific air generator weight per unit airflow delivered to the tip turbine decreases 3 percent and fan and core thrust of the air generator to weight increases about 7 percent. These results are for a turbine temperature of 2200° F. At this temperature level, air generator length decreases 3 percent and frontal area increases 2 percent (fig. 3(b)). The length and frontal area variations are slightly less when turbine temperature is raised to 2500° F which shrinks the air generator frontal area and length and hence volume.

The effects of turbine temperature are shown more clearly in figure 3(c) and (d). As temperature increases from 1900° to 2500° F, performance, weight, and size improve. Specific fuel consumption decreases 4 percent, specific thrust increases 9 percent, and specific weight decreases 10 percent (fig. 3(c)). Frontal area shrinks 15 percent and length 18 percent (fig. 3(d)) which would give a volume shrinkage of 30 percent.

Effects on propulsion system. - For a propulsion system having a lift fan pressure ratio of 1.20, the effects of the air generator overall pressure ratio and turbine temperature on specific thrust and specific fuel consumption at SLS conditions of the complete propulsion system are shown in figure 4. As overall pressure ratio increases from 12 to 21, specific lift thrust increases 2 percent and specific fuel consumption decreases 4 percent (fig. 4(a)). For an overall pressure ratio of 15, as turbine temperature increases from 1900° to 2500° F, specific lift thrust increases 2 percent and specific fuel consumption remains constant (fig. 4(b)).

On the basis of the above variations, a nominal air generator was selected with an overall pressure ratio of 15 and a turbine temperature of 2200° F. A higher overall pressure ratio and turbine temperature offers small performance weight and size improvements probably at some increase in development cost, original cost, and maintenance cost.

System Performance

In this section the effects of using the air generators as cruise engines and the effects of lift fan pressure ratio and tip-turbine pressure ratio on airplane payload and noise are presented. It should be recalled that assignment of various engine parameters plus the assigned acceleration levels size the system and fix aircraft takeoff gross weight. Thus, for each cruise value of lift to drag ratio, the required engine thrust is set and hence cruise specific fuel consumption. Knowing this cruise fuel can be calculated and hence payload since all other weight segments are known or assumed. In this manner, engine parameters can be related to aircraft payload.

Effects on cruise fuel. - The effects of tip turbine pressure ratio, lift fan pressure ratio, and cruise L/D on the weight of cruise fuel are shown in figure 5. For a lift fan pressure ratio of 1.15 (fig. 5(a)) cruise fuel decreases with decreasing tip-turbine pressure ratio and increasing cruise L/D. Increasing the cruise L/D from 10 to 12 results in a 900 pound fuel saving which could increase the number of passengers by 4. Similar trends are displayed in figure 5(b) for a remote fan pressure ratio of 1.25. The level is about 130 pounds higher indicating that fan pressure ratio has only a slight effect on cruise fuel.

Effects on system performance. - The weight breakdown of the dependent weight fractions is shown in figure 6 for a cruise L/D of 10 and a lift fan pressure ratio of 1.25. As tip-turbine pressure ratio increases, weights of the lift fans and hover fuel decrease, cruise fuel weight increases, and air generator stays constant above a tip-turbine pressure ratio of 3.5 (fig. 7(a)). The total of these weights decreases from 28 750 to 27 000 pounds (fig. 6(b)). The weight saving can go into payload (fig. 6(a)). As tip-turbine pressure ratio increases from 2.5 to 4.0, the payload increases from 9800 to 11 500 pounds. At 205 pounds for passenger and baggage, the tip turbine pressure ratio of 4.0 yields 56 passengers.

The effect of lift fan pressure ratio on the weight breakdown is shown in figure 7 where tip-turbine pressure ratio is 3.5 and cruise L/D is 10. As lift fan pressure ratio increases cruise fuel stays constant, hover fuel and air generator weight increase, and lift fan weight decreases. The summation of these weights increase (fig. 7(b)) so payload decreases as lift fan pressure ratio increases (fig. 7(a)). For a lift fan pressure ratio of 1.15, payload is 12 600 pounds or 62 passengers.

The tradeoff between payload and noise is shown in figure 8. A fan pressure ratio less than 1.15 is required to achieve the noise goal of 95 PNdB. However a lift fan pressure ratio of 1.15 comes close: noise is 96.2 PNdB while payload for the tip turbine pressure ratio of 4.0 is 12 600 pounds. For lift fan pressure ratios less than 1.15 cruise thrust available from the four air generators falls below the drag of an airplane having a lift to drag ratio of 10.

CONCLUDING REMARKS

A simplified mission analysis was performed to evaluate the effects of lift fan pressure ratio and tip-turbine PR on the payload and noise of a remote-drive VTOL lift system. This system consisted of four 15 000 pound thrust lift fans, eight 7500 pound thrust lift fans, and four air generators which were also used as the cruise engines.

A range of 500 statute miles was selected with a cruise Mach number of 0.75 at an altitude of 25 000 feet. The allowable takeoff gross weight, as dictated by the maximum available lift under emergency conditions and control requirements, was found to be about 88 700 pounds.

Cruise lift-drag ratios of 8 to 12 were assumed in the study. Cruise performance calculations show that the air generator cycle can be used at cruise; with the (L/D)'s assumed in this study, however, all 4 air generators would be required to provide enough cruise thrust. Cruise SFC was then used in the Breguet equation to calculate the weight of cruise fuel. Finally, payload was obtained by subtracting airframe, engine, and fuel weights from the TOGW.

For the range of tip-turbine PR's and lift-fan pressure ratios examined, a near-maximum payload (12 600 lb) was obtained with the highest tip-turbine pressure ratio considered (4) and the lowest lift fan pressure ratio considered (1.15). At higher fan pressure ratios, noise increased and payload decreased due to an increase in hover fuel and an increase in air generator weight. Noise at 500 feet was calculated to be 96.2 PNdB. As advances in noise generation and suppression are made, the noise goal of 95 PNdB should be attainable.

These results are quite encouraging and suggest that the air generator lift fan remote propulsion system is an attractive candidate for V/STOL transports.

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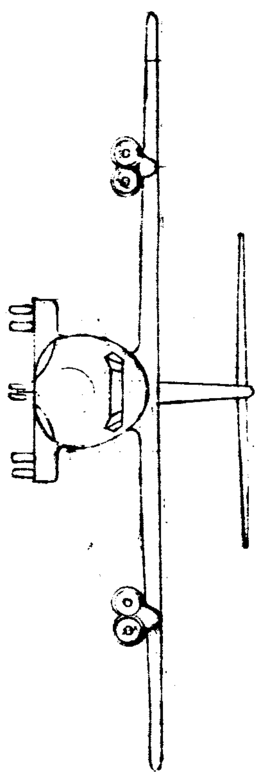


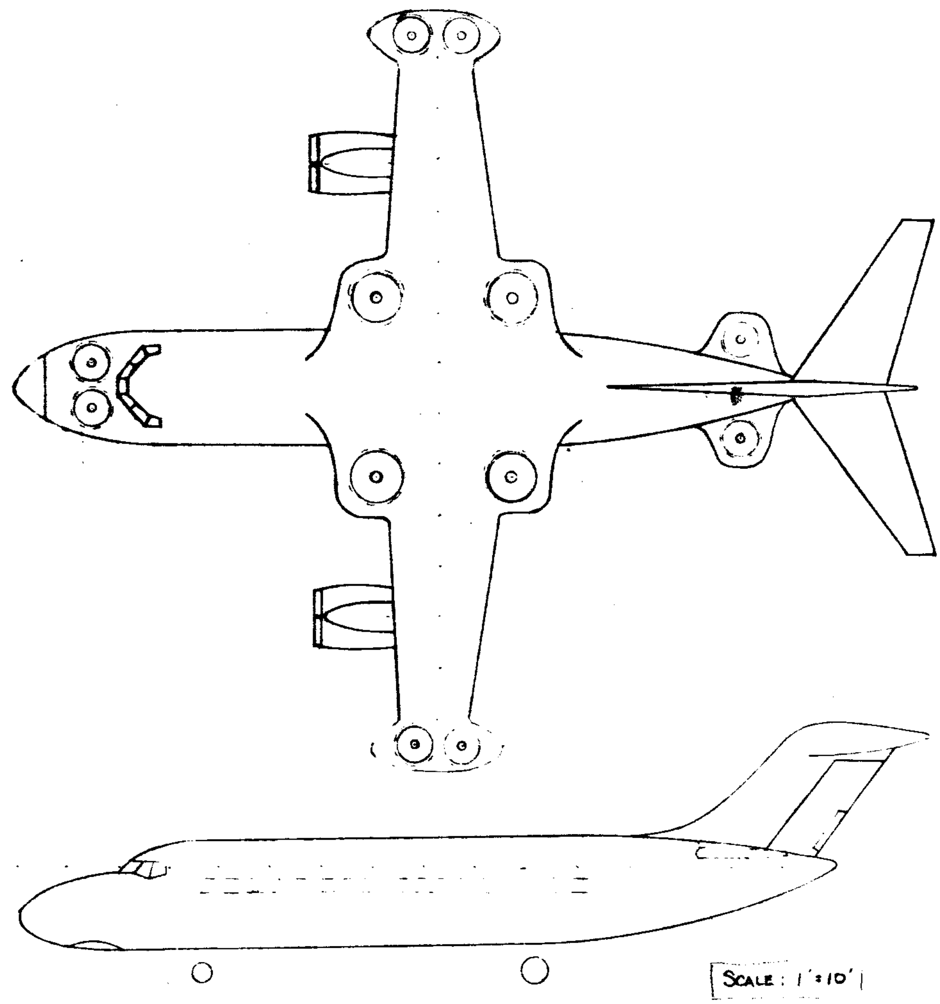
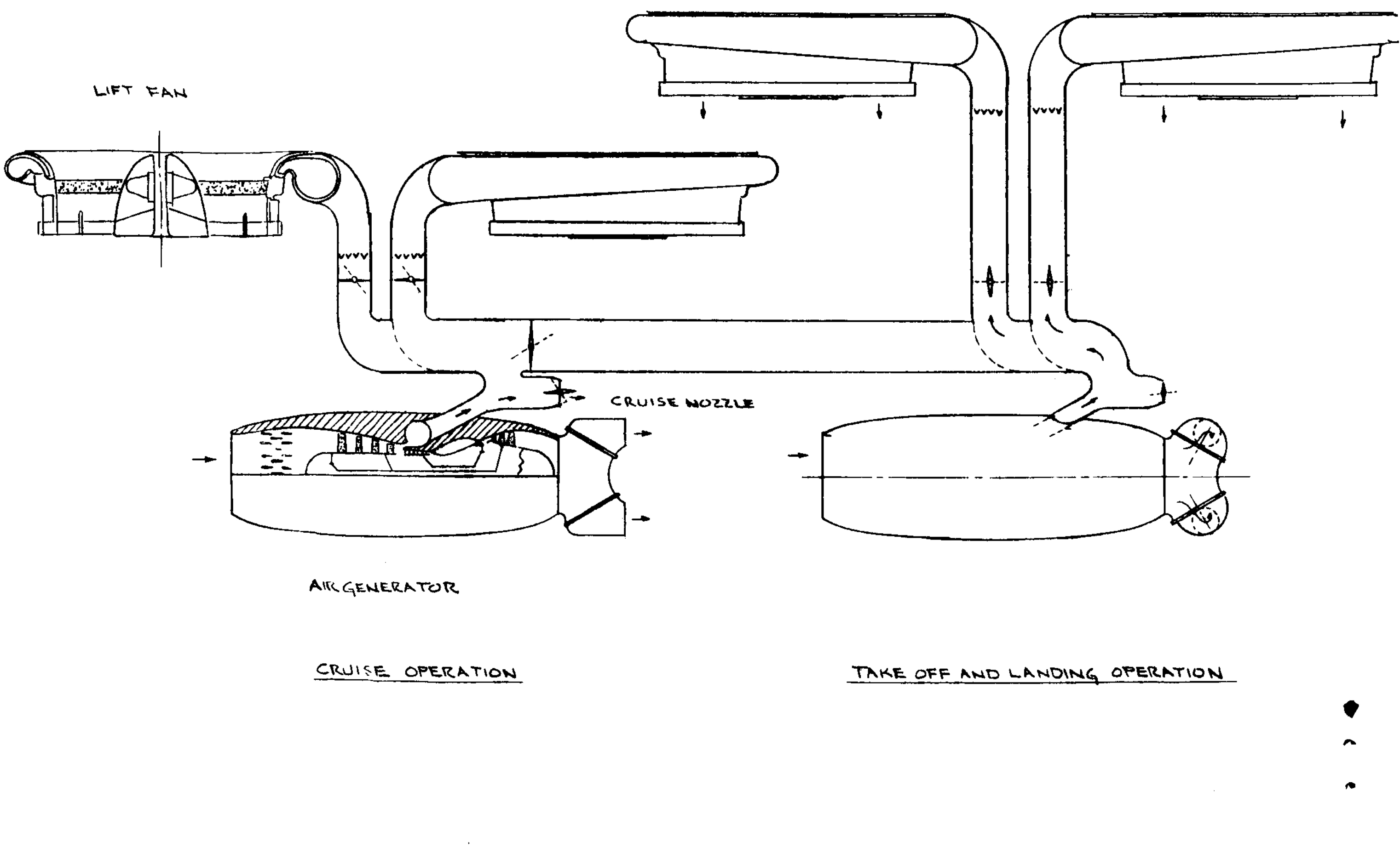


FIGURE 1. - VTOL TRANSPORT

FIG. 2

AIRGENERATOR REMOTE DRIVE LIFT FAN PROPULSION SYSTEM



CRUISE OPERATION

TAKE OFF AND LANDING OPERATION

AIR GENERATOR CHARACTERISTICS

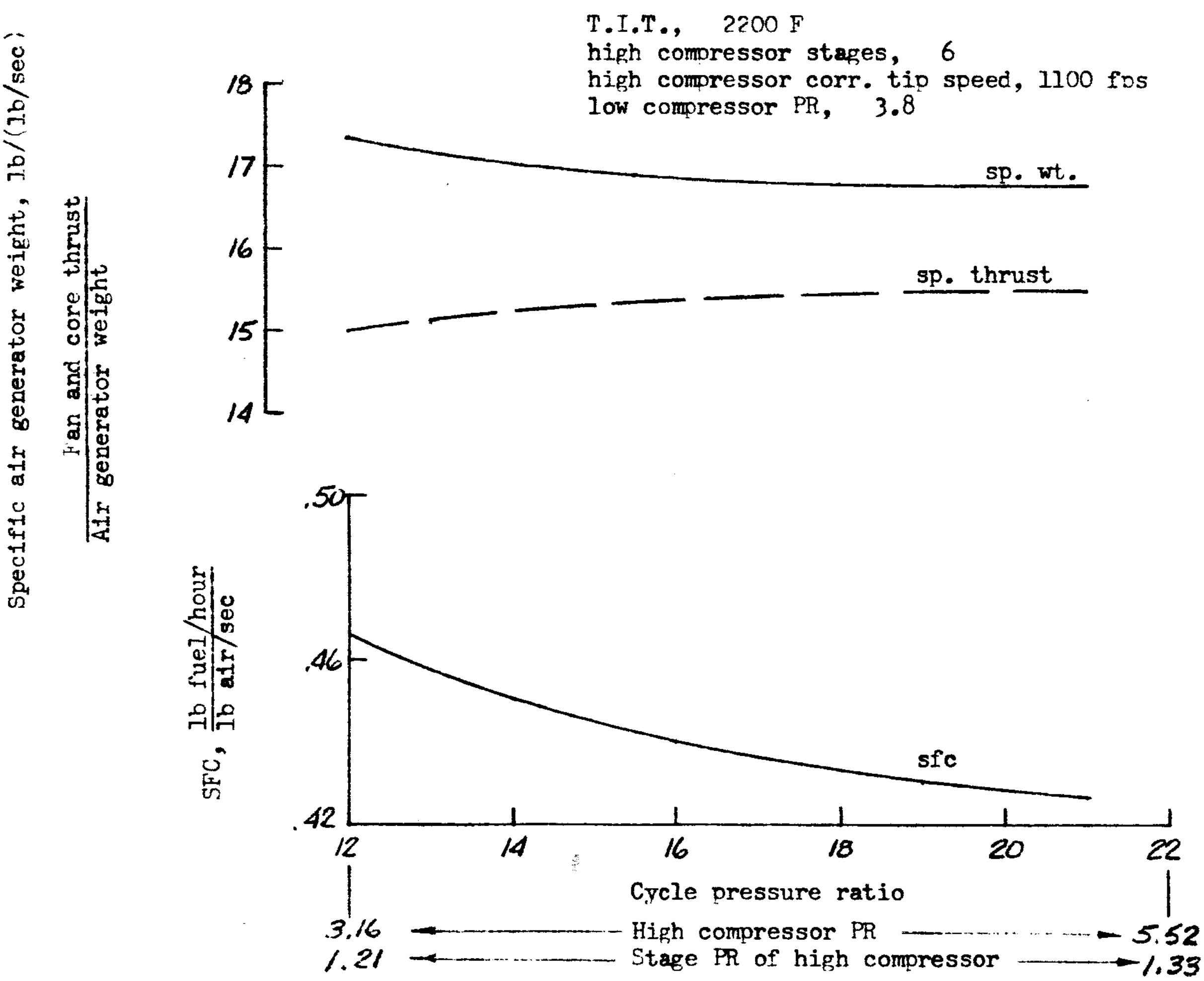


FIGURE 3 (a) – EFFECTS OF OVERALL PRESSURE RATIO ON PERFORMANCE AND WEIGHT.

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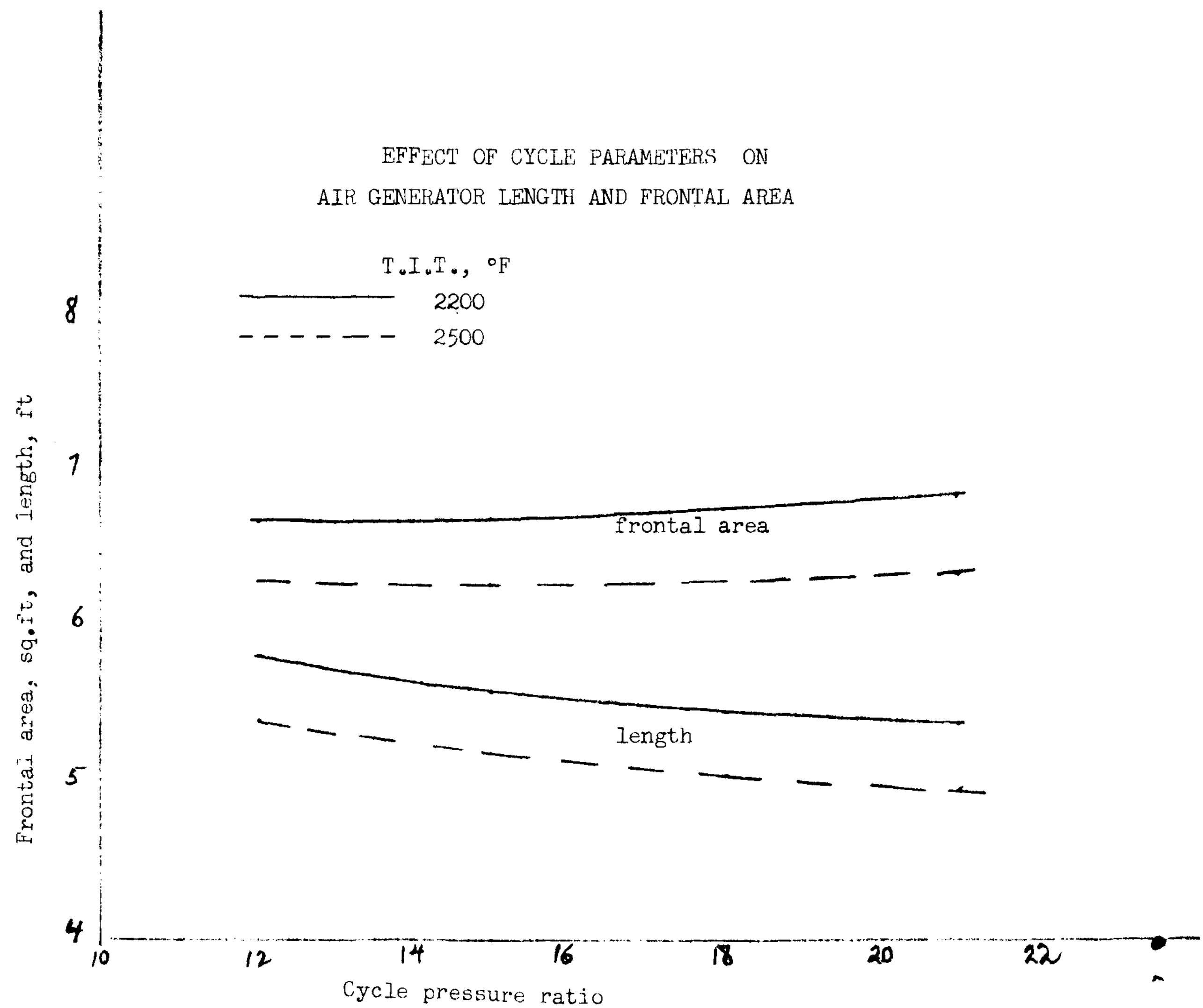

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Figure 3(b). - Effects of overall pressure ratio on engine size.

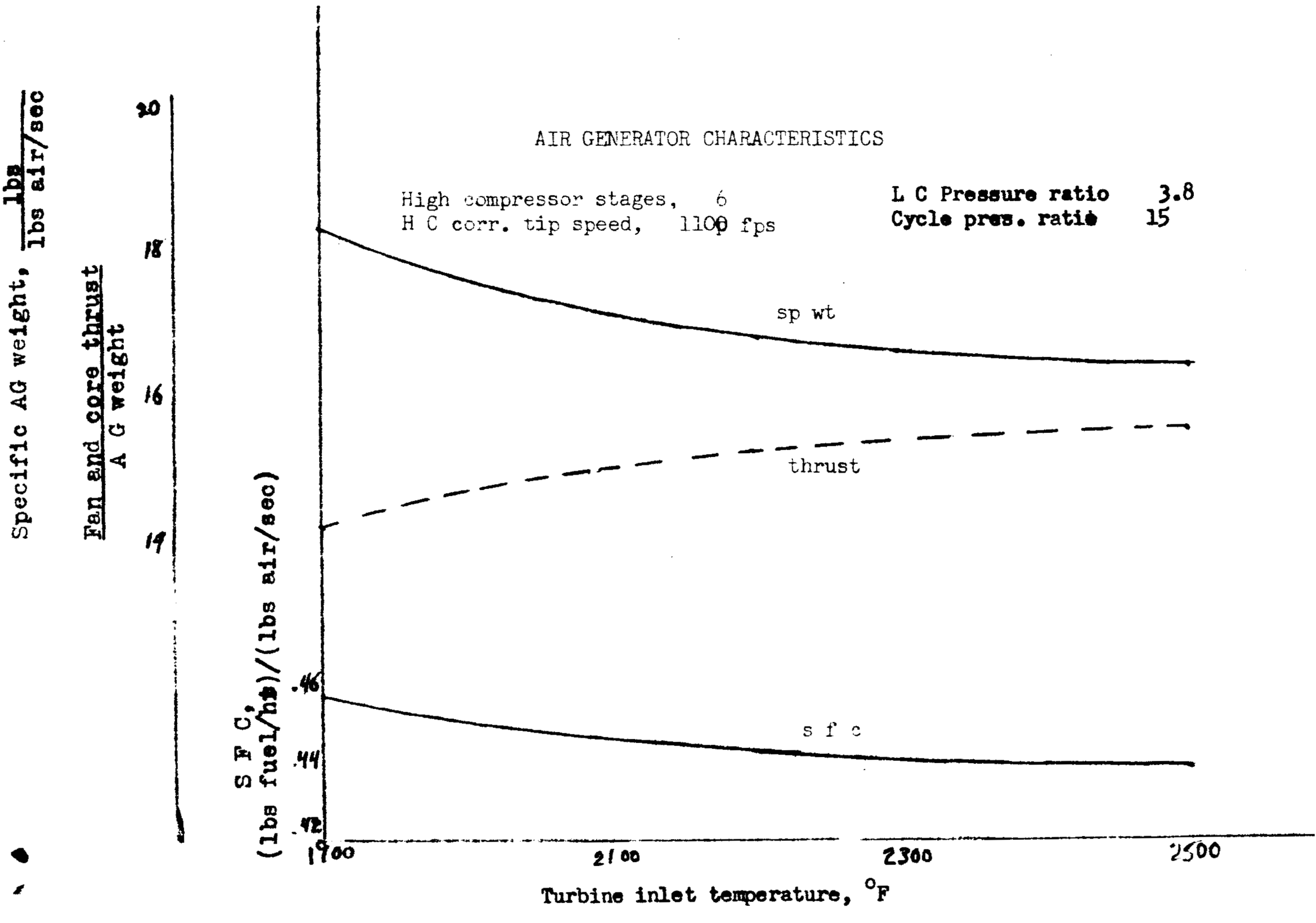

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Figure 3(c). - Effects of turbine temperature on performance and weight 6/27/71

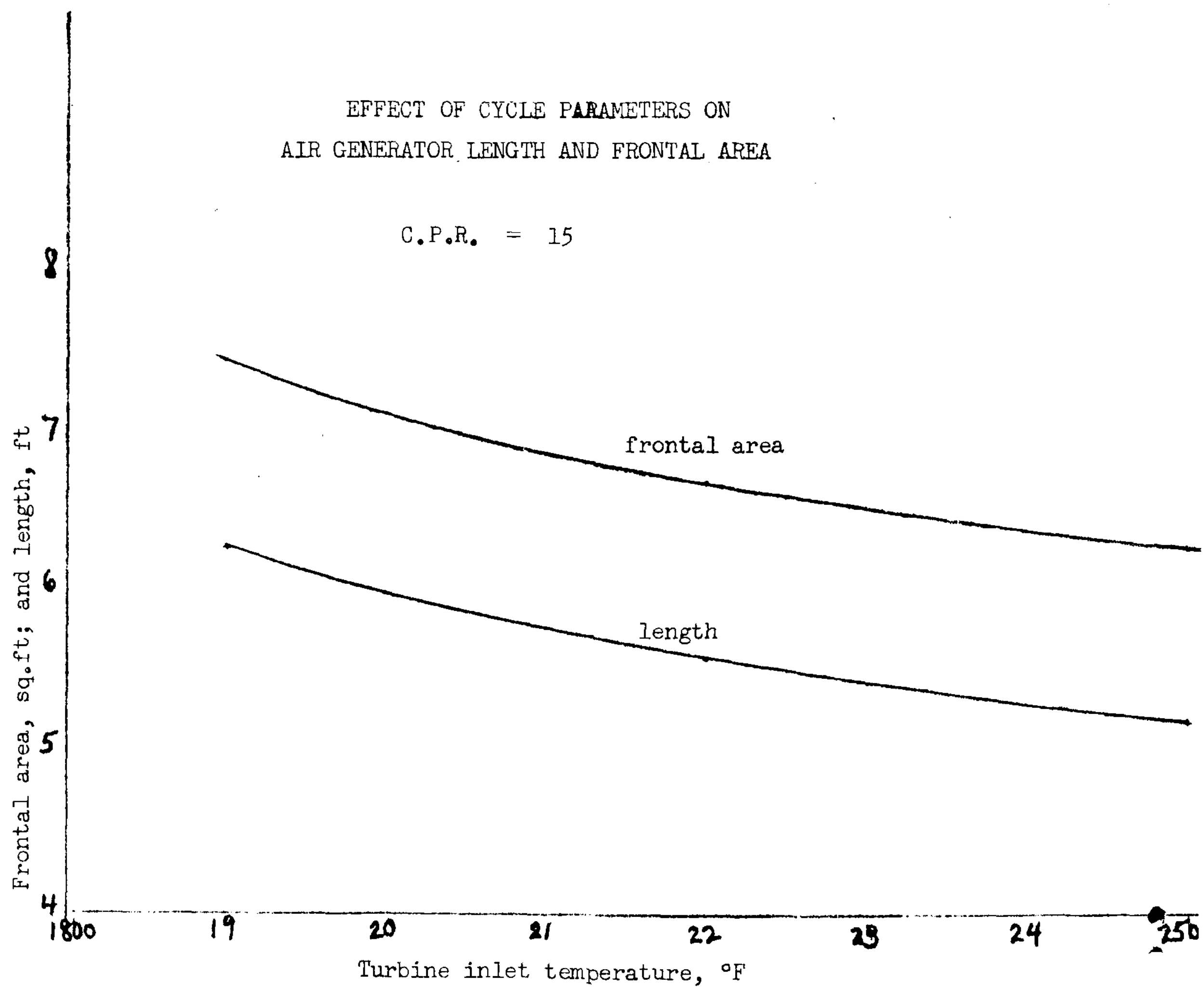
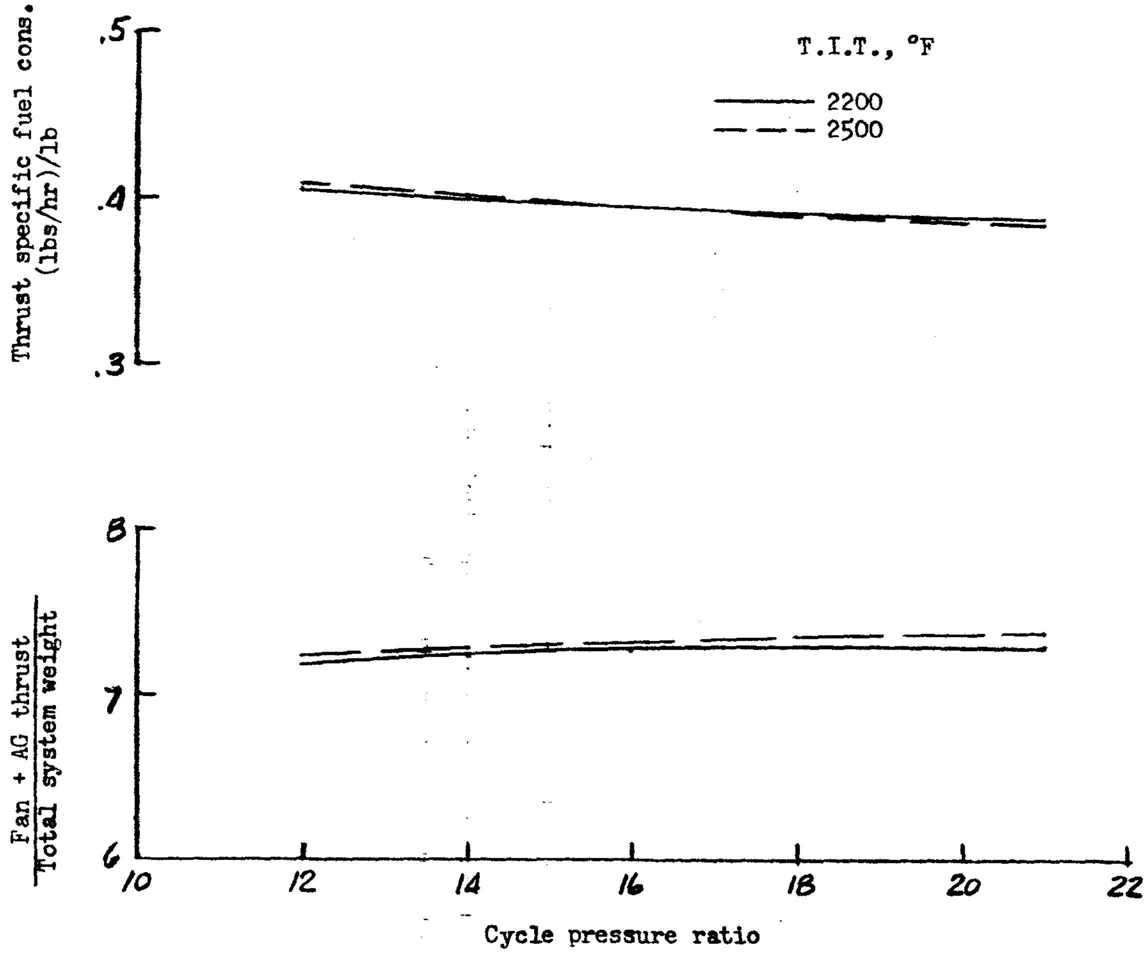


Figure 3(d). - Effects of turbine temperature on engine size.



(a) EFFECTS OF OVERALL PRESSURE RATIO ON PERFORMANCE AND WEIGHT

FIGURE 4. EFFECTS OF AIR GENERATOR PARAMETERS ON PROPULSION SYSTEM PERFORMANCE, WEIGHT, AND SIZE. LIFT FAN PRESSURE RATIO IS 1.20.

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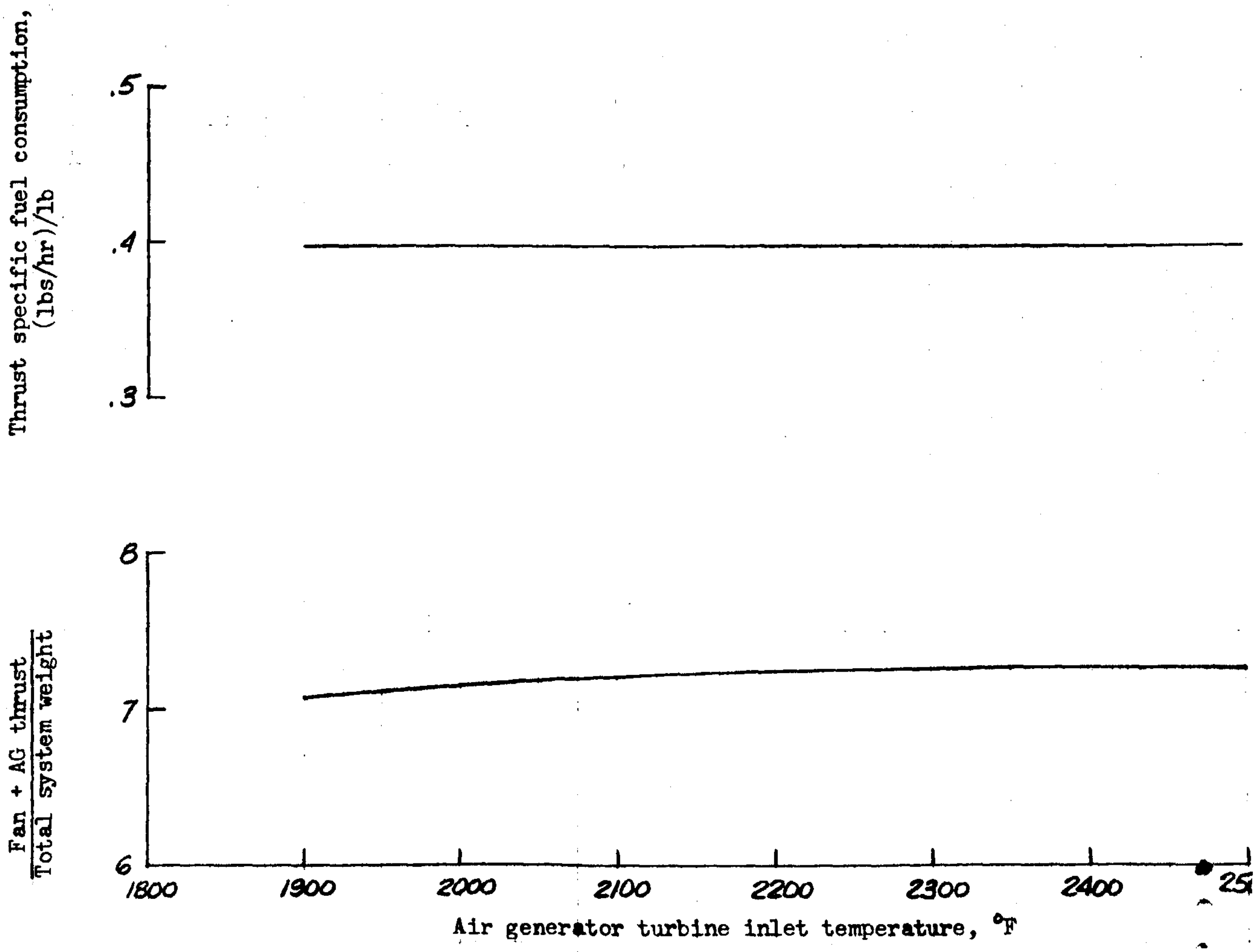

(b) Effects of turbine temperature on performance and weight. Overall pressure ratio is 15.

Figure 4 (continued)

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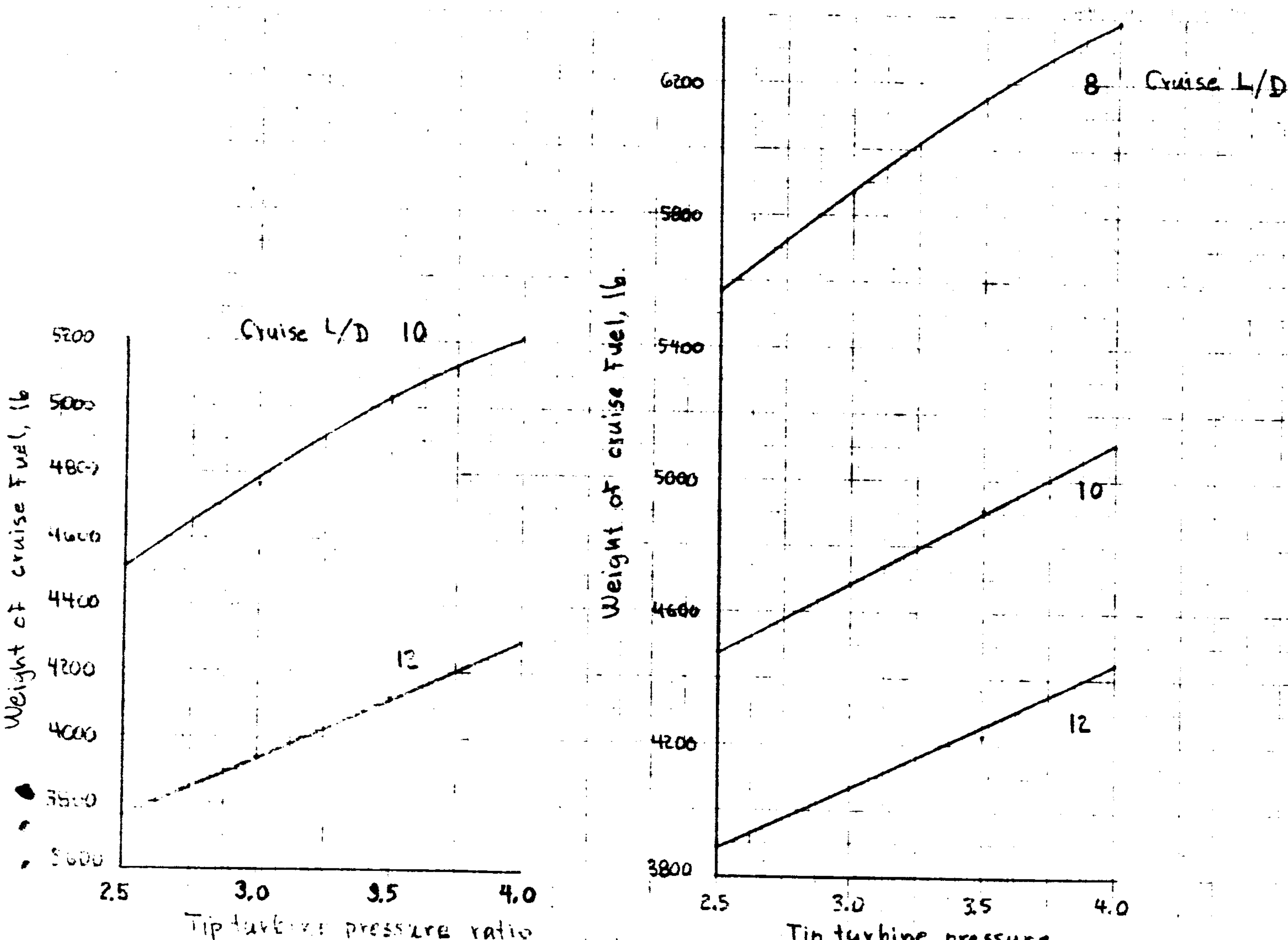
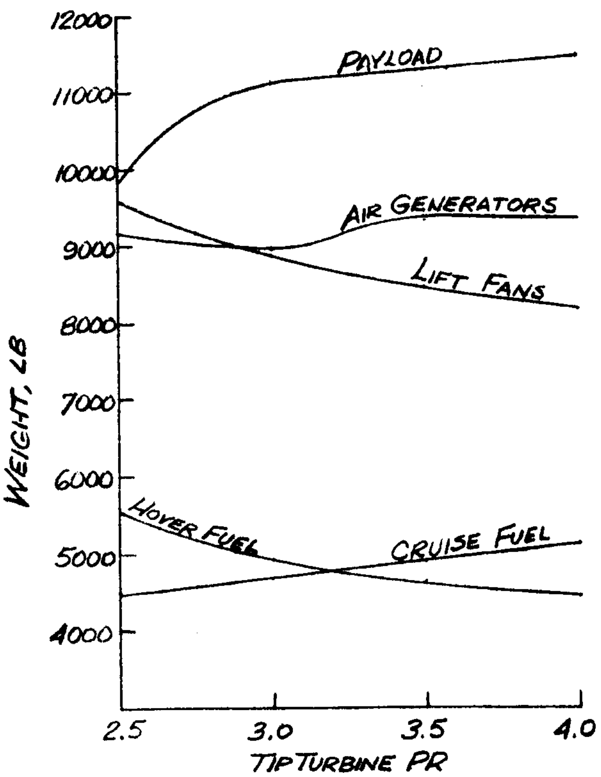


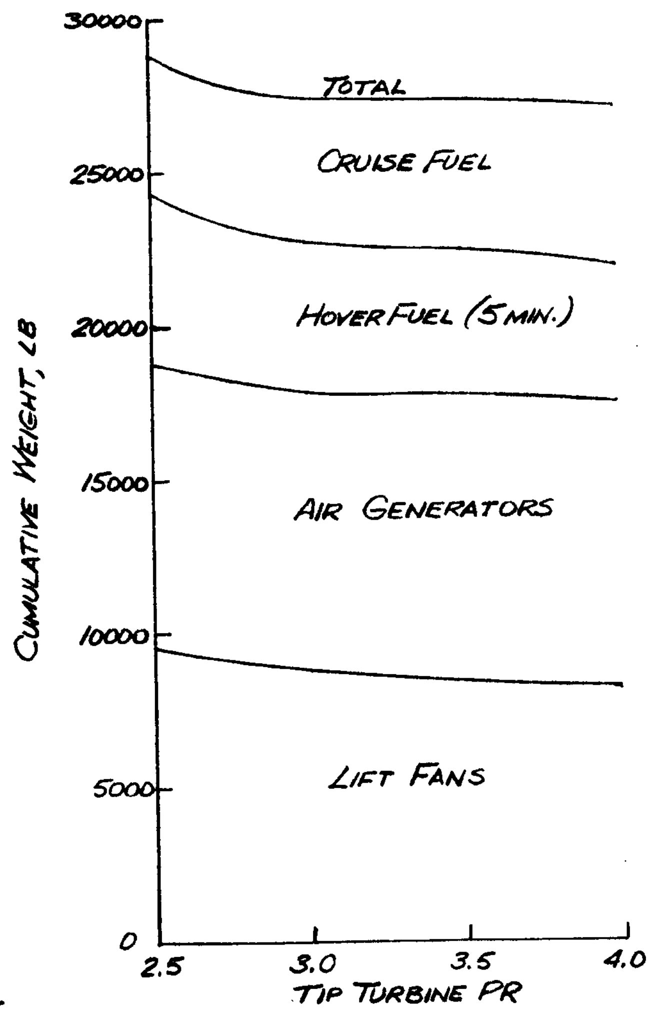
(a) Fan pressure ratio, 1.15

(b) Fan pressure ratio, 1.25

Figure 5 Effects of tip turbine pressure and cruise L/D on weight of cruise fuel.



(a) INDIVIDUAL WEIGHT TRENDS



(b) CUMULATIVE WEIGHT TRENDS

FIGURE 6 — WEIGHT TRENDS. LIFT FAN PR=1.25, L/D = 10.

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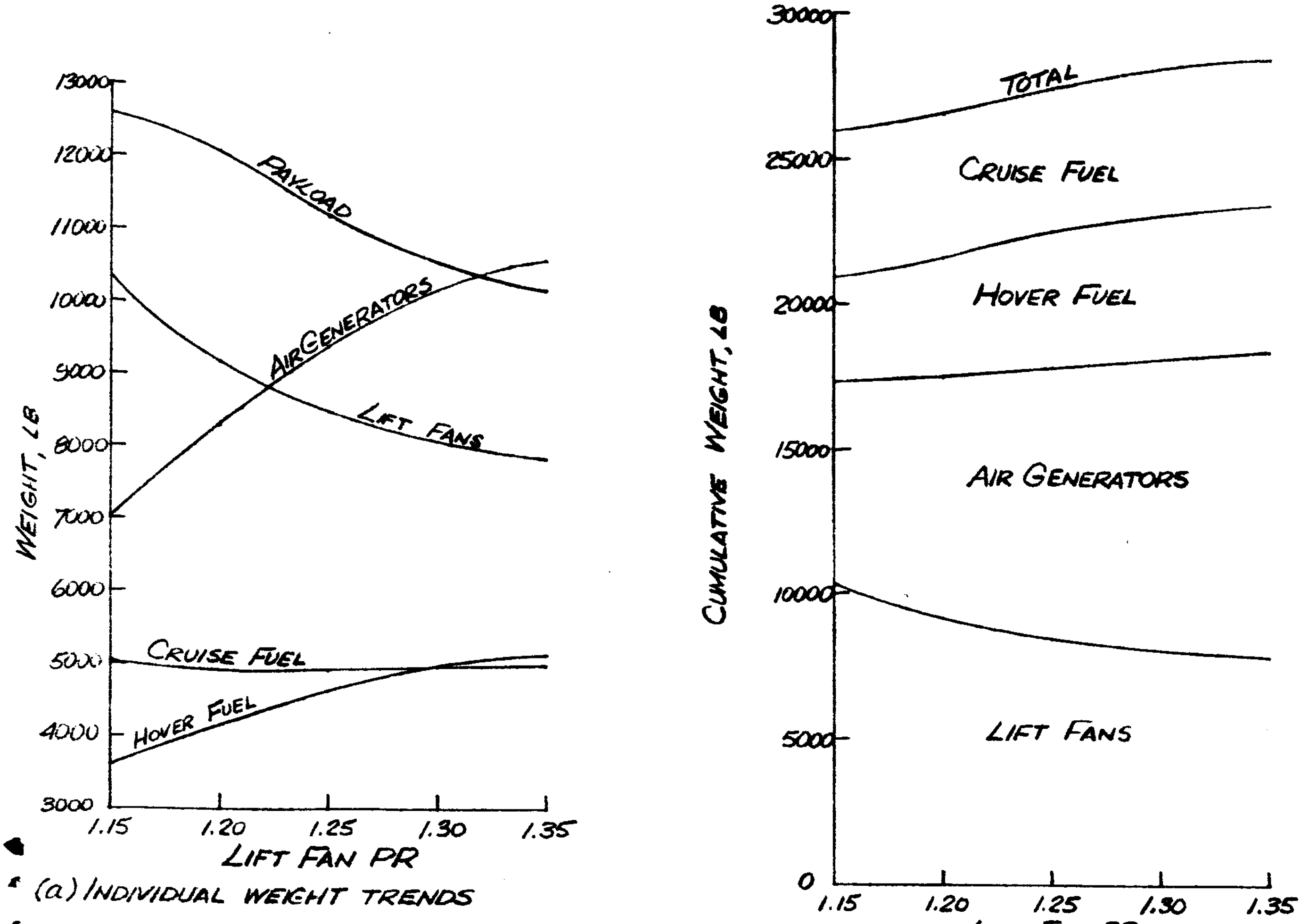

(a) INDIVIDUAL WEIGHT TRENDS

(b) CUMULATIVE WEIGHT TRENDS

FIGURE 7.— WEIGHT TRENDS. TIP TURBINE PR = 3.5, $(L/D)_{CR.} = 10$.

K.C. (MAB) 8-2-71

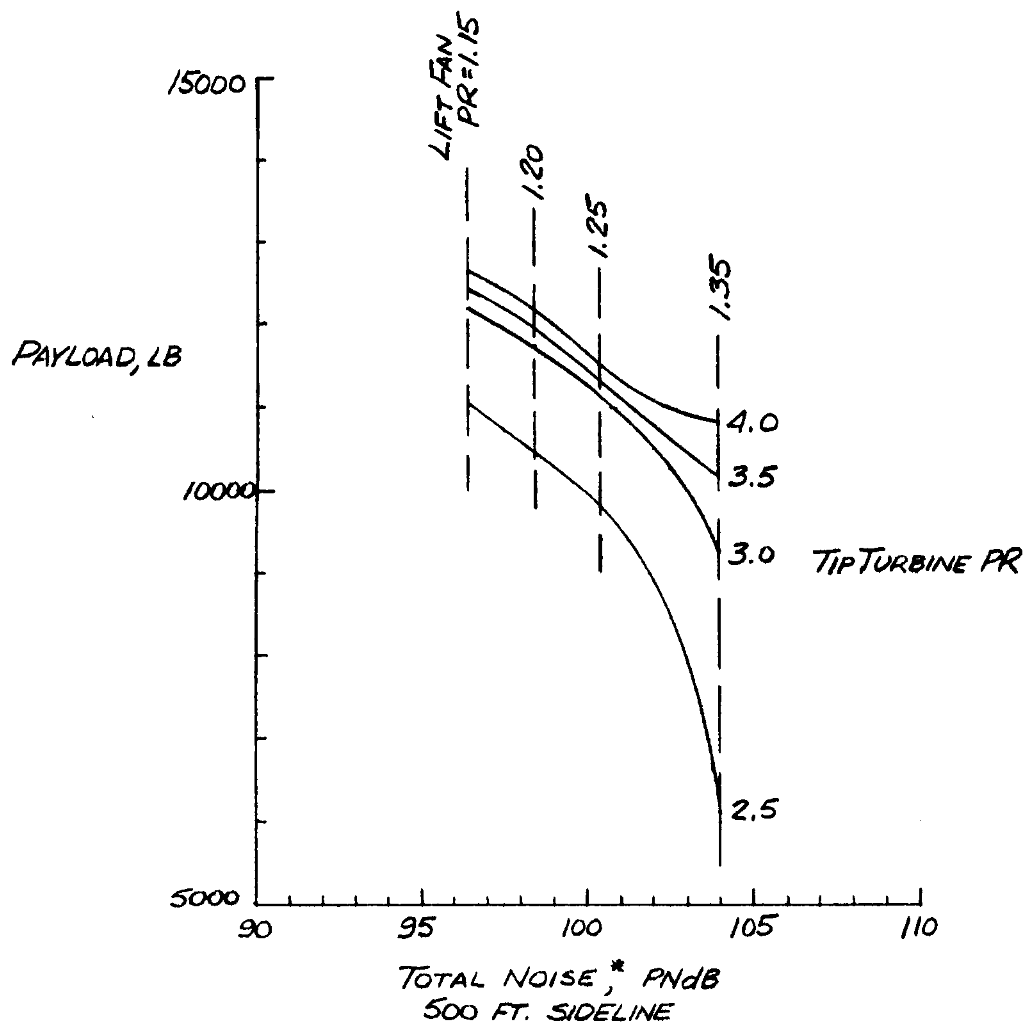

FIGURE 8.— PERFORMANCE-NOISE TRADEOFF. $(L/D)_{CR.} = 10$.

*ASSUMING 5 PNdB MACHINERY NOISE SOURCE REDUCTION & 10 PNdB SUPPRESSION.

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