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INTRODUCTION

Two programs now exist with the aim of making commercial supersonic travel a reality - one in Europe and one in the United States. The subject of propulsion for such supersonic aircraft has been a popular one and with good reason. The economics of the aircraft are strongly tied to the aircraft gross weight, and 60 percent or more of the aircraft gross weight is comprised of the propulsion system and its fuel. References 1 to 13 are among the many papers that have been written during the past several years on the subject of propulsion for supersonic transports. In these reports a variety of topics are discussed such as (1) why existing military engines should not be used, (2) the effects of engine design variables on engine performance, (3) why one engine type is to be preferred over another, and (4) numerous specific problem areas like the importance of matching engine flow to inlet flow.

The objective of this paper is to survey four types of gas turbine engines that are deemed suitable for powering a Mach 3 supersonic transport: dry turbojets, afterburning turbojets, duct-burning nonmixed-flow turbofans, and afterburning mixed-flow turbofans. Desirable features of each engine type are evolved, and the level of engine technology required to result in an attractive ratio of payload to aircraft gross weight is estimated. Other topics considered in the paper are engine sizing criteria, the effect of sonic boom limits on engine size and aircraft gross weight, inlet and exhaust nozzle performance, airflow scheduling in turbofan engines, and the use of variable turbine stators in turbojet engines.

METHOD OF ANALYSIS

The four types of gas turbine engines considered are shown in Fig. 1. The dry turbojet and the afterburning turbojet are one-spool engines, while the duct-burning turbofan and the afterburning turbofan are two-spool engines. Except where noted in the study, the duct-burning turbofan engine has a fixed primary nozzle downstream of the turbine and a variable primary nozzle downstream of the duct burner. In the afterburning turbofan, the air flow from the fan is mixed with the gas flow from the turbine prior to augmentation of the total flow in the afterburner. The geometry of the mixer is considered to be fixed.

Engine performance and weight are calculated for many engines with each characterized by specific design values of turbine inlet temperature (1800° to 2500° F), overall compressor pressure ratio (6 to 13), augmentation temperature (2740° to 3100° F), fan pressure ratio (2 to 3), and bypass ratio (0.5 to 1.5). A fixed-wing aircraft powered by four podded engines and carrying a payload of 26,000 pounds is flown over a specified mission with a 3200-nautical-mile range. On each flight the engines are sized to result in a minimum value of aircraft takeoff gross weight, which is considered to be the figure of merit in evaluating the different engines.

In calculating the design and off-design performance of each engine type, the engine components are matched so as to satisfy the relations involving continuity of flow, engine rotational speed, and power balance between the compressor or fan and its driving turbine. In the case of the afterburning turbofan engine, the fan air flow and turbine gas flow mix at equal static pressures. The procedures employed are similar to those discussed in reference 14.

Engine weight is calculated from empirical curves that relate installed engine weight to type of engine and design values of engine airflow, overall compressor pressure ratio, fan pressure ratio, bypass ratio, and turbine inlet temperature. For a turbine inlet temperature of 2100° F and near-optimum values of the remaining design parameters, the engine thrust-to-weight ratio ranges from 4.7 to 5.8 depending on the engine type. For comparison, General Electric's YJ93 afterburning turbojet engine, which will power the Mach 3 RS-70 aircraft for the United States Air Force, has a thrust-to-weight ratio of above 5.[15] In the term engine thrust-to-weight ratio, engine thrust is maximum thrust at sea-level static (SLS) conditions, and engine weight includes the gas generator, thrust reverser, and exhaust nozzle.

Aircraft takeoff gross weight (TOGW) is the sum of operating weight empty, fuel weight including reserves, and the fixed payload of 26,000 pounds. Operating weight empty less installed engine weight (expressed as percent of TOGW) was assumed to vary with TOGW from 36 percent at a TOGW of 308,000 pounds to 29 percent at a TOGW of 540,000 pounds.

A typical variation in maximum lift-to-drag ratio with flight Mach number for the fixed-wing aircraft used in this study is shown in Fig. 2. Also shown in Fig. 2 is the mission profile used in the study. The flight path up to the initial Mach 3 cruise altitude is fixed by scheduling flight Mach number with altitude. Some points along the path are Mach 1.05 and 40,000 feet, Mach 1.4 and 50,000 feet, and Mach 3 and 60,000 feet. The initial cruise altitude is greater than 60,000 feet and is selected in each case so as to minimize aircraft TOGW.

The Mach 3 cruise portion of the flight ends when a range of 2800 nautical miles is achieved. During letdown over the remaining 400 nautical miles, thrust setting and fuel consumption are at a low level. Fuel reserves are sufficient to allow for (1) an extension of supersonic cruise for a period equal to 10 percent of the elapsed time from takeoff to end of cruise, (2) cruise at Mach 0.9 for a distance of 250 nautical miles at the best altitude between 36,000 and 45,000 feet, and

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(3) holding at 1500 feet and 180 knots for 1/2 hour.

RESULTS AND DISCUSSION

Effect of Design Variables

Each of the four engine types is considered separately to determine the effects of the major engine design parameters on aircraft TOGW. In the figures of this section, aircraft TOGW is expressed as relative TOGW. Based on the input of this study, a relative TOGW of 100 corresponds to a payload fraction of $6\frac{1}{2}$ percent. A relative TOGW of 80 corresponds to a payload of slightly more than 8 percent and is adopted as a reasonable goal. In striving for the relative TOGW of 80, all the burden is placed on the engine; that is, no improvements in aircraft weight or aerodynamics are hypothesized.

Dry turbojets. - The principal design variables of a dry turbojet engine are considered to be design compressor pressure ratio, design turbine inlet temperature, and engine weight.

The effect of design compressor pressure ratio is shown in Fig. 3(a). Design compressor pressure ratio influences aircraft TOGW chiefly through its effect on engine weight and cruise specific fuel consumption (SFC). As design compressor pressure ratio increases from 6 to 13, engine weight increases continuously. Depending on the level of turbine inlet temperature, cruise SFC decreases continuously or else decreases, reaches a minimum, and then increases. In both cases there is a value of design compressor pressure ratio that minimizes aircraft TOGW. For any level of turbine inlet temperature in the range 1900° to 2500° F, a design pressure ratio of about 10 results in the minimum value of TOGW.

The desirability of being able to build reliable engines that operate at high values of turbine inlet temperature is illustrated in Fig. 3(b). As turbine inlet temperature increases from 1900° to 2500° F, both cruise SFC and engine weight decrease continuously. The reduction in engine weight comes about from the decrease in engine size that results from the higher values of thrust per unit airflow. At 1900° F relative TOGW is 150, while at 2500° F it has dropped to 115. Each of the dry turbojets had a near-optimum design compressor pressure ratio of 10. The solid line corresponds to a selected turbine cooling airflow schedule (2.6 percent of compressor airflow at 1900° F and 8.6 percent at 2500° F). The dashed line is for zero turbine cooling airflow and is of academic interest only since materials suitable for operation in this temperature range without cooling are not presently available. Notice that the required cooling airflow degrades the performance potential appreciably. At 2500° F, the cooling airflow requirement of 8.6 percent of compressor airflow is responsible for an increase in TOGW of about 9 percent.

Figure 3(c) shows the reduction in aircraft TOGW that would result from being able to build lighter dry turbojets. The results are for a dry turbojet having a near-optimum design compressor pressure ratio and a maximum turbine inlet temperature of 2500° F. Each 10-percent reduction in engine weight results in about a 5-percent reduction in aircraft TOGW. To achieve a relative TOGW of 80, an engine weight reduction of 55 percent is required. The corresponding value of SLS thrust to engine weight ratio is 9.3.

Afterburning turbojets. - In Fig. 4(a) is shown the effect of design compressor pressure ratio on the TOGW of aircraft powered by afterburning turbojet engines with a maximum augmentation temperature of 3100° F. Again, a design compressor pressure ratio of about 10 results in a minimum value of aircraft TOGW.

For engines with a near-optimum design compressor pressure ratio of 10, a design turbine inlet temperature of about 2300° F results in minimum aircraft gross weight (Fig. 4(b)). As turbine inlet temperature increases from 1900° to 2500° F, the amount of fuel decreases continuously. Engine weight, however, decreases, reaches a minimum around 2300° F, and then increases. The two factors that influence engine weight are the turbine inlet temperature and design airflow. Engine weight per unit design airflow increases continuously with rising turbine inlet temperature. Design airflow, however, decreases and then changes only slightly above about 2300° F with further increases in turbine inlet temperature. The combined effects of temperature and engine size at turbine inlet temperatures above 2300° F result in an increase in engine weight. The increase in engine weight overrides the decrease in fuel so that the net effect is an increase in TOGW.

At a turbine inlet temperature of 2300° F, the assumed 6.6-percent cooling air for the turbine accounts for an increase in TOGW of about 4 percent. The increase would be even more if the use of turbine cooling air results in less efficient turbine operation. An engine was considered in which the use of 6.6 percent of the compressor air to cool the turbine caused the turbine to operate at 81-percent efficiency. Data for this engine and an engine whose turbine operates at 88 percent efficiency with 6.6-percent turbine cooling air are presented in Table I. The drop in turbine efficiency degraded both thrust and specific fuel consumption throughout the flight range. The 7-percent drop in turbine efficiency caused TOGW to increase 9 percent. Engine and fuel weights are tabulated as percentages of TOGW. Engine weight remains the same, but total fuel weight increases. The breakdown in total fuel indicates increases in both useful fuel and reserve fuel. Most of the increase in reserve fuel is due to poor part-power performance during the 30-minute hold where specific fuel consumption increased about 11 percent. The increase in useful fuel is due mainly to higher fuel consumption prior to cruise. Specific fuel consumption is higher and the time required to climb and accelerate to the initial cruise conditions is longer because of the lower thrust level. The increase in TOGW that accompanied the drop in turbine efficiency illustrates that in order to realize the potential gains of high turbine temperature operation, turbine efficiency must not be degraded appreciably by the use of cooling air. Except for the case just described, no penalty in turbine efficiency was assessed for high temperature turbine operation.

The effect of engine weight reduction on afterburning turbojets is shown in Fig. 4(c). An engine weight reduction of 10 percent reduces aircraft TOGW about 4 percent. To attain a relative TOGW of 80, a weight reduction of 48 percent is required. The corresponding engine thrust-to-weight ratio is 11.3.

Afterburning turbofans. - In Fig. 5(a), afterburning turbofan engines having a design bypass ratio of 1.0 are considered. For a design turbine inlet temperature of 1800° F, a design overall compressor pressure ratio of about 11 results in minimum aircraft TOGW. At 2400° F, the optimum pressure ratio rises to about 13; however, at a pressure ratio of 11, TOGW is only 1/2 percent greater than minimum.

In Fig. 5(b), design overall compressor pressure ratio is fixed at 11. Aircraft gross weight is seen to be relatively insensitive to design bypass ratio.

The decrease in aircraft gross weight that results from operating afterburning turbofans at higher turbine inlet temperatures is shown in Fig. 5(c). Each engine considered has a design overall compressor pressure ratio of 11 and a design bypass ratio of 1.0. Raising turbine inlet temperature from 1800° to 2400° F reduced aircraft TOGW about 7 percent.

Engine weight reduction is considered in Fig. 5(d) for an afterburning turbofan having the following design values: overall compressor pressure ratio, 11; bypass ratio, 1; turbine inlet temperature, 2400° F; and afterburner temperature, 2740° F. An engine weight reduction of 10 percent results in about a $3\frac{1}{2}$-percent reduction in aircraft TOGW. A relative TOGW of 80 requires an engine weight reduction of about 40 percent. Such an engine would have a SLS thrust to engine weight ratio of 10.3.

<u>Duct-burning turbofans</u>. - In Fig. 6 the effects that the major design variables of duct-burning turbofans have on aircraft TOGW are shown. All engines in Fig. 6(a) have a design bypass ratio of 1, a design fan pressure ratio of 2.5, and a design duct-burner temperature of 3100° F. The optimum value of overall compressor pressure ratio is seen to increase from a value of about 8 at a design turbine inlet temperature of 1800° F to a value of about 11 at a turbine inlet temperature of 2400° F.

The engines of Fig. 6(b) have a design overall pressure ratio of 10 and a design bypass ratio of 1. The optimum value of fan pressure ratio is about 2.5 for turbine inlet temperatures in the range 1800° to 2400° F.

The engines of Fig. 6(c) have a design fan pressure ratio of 2.5 and a design overall pressure ratio of 10. The optimum design bypass ratio is about 1.2 for turbine inlet temperatures of 1800° and 2100° F. For a turbine inlet temperature of 2400° F, optimum design bypass ratio is about 1.

The effect of design turbine inlet temperature is shown in Fig. 6(d). Airplane weight drops 20 percent as turbine inlet temperature is raised from 1800° to 2400° F.

Figure 6(e) shows that for the specific duct-burning turbofan considered, a relative aircraft TOGW of 80 requires an engine weight reduction of about 35 percent. Such an engine would have a thrust-to-weight ratio of 9.6.

Engine Sizing Considerations

Each of the engines discussed in the previous section was sized to minimize aircraft TOGW. In sizing an engine for a supersonic transport, however, it is possible that design engine airflow will be dictated by something such as takeoff distance or noise. These and other criteria that could be critical in engine sizing are considered for the case of a specific afterburning turbofan (Fig. 7). From Fig. 7(a), the design engine airflow that minimizes aircraft TOGW is 460 pounds per second. If some other criterion requires a design engine airflow larger than 460 pounds per second, some increase in aircraft TOGW must be accepted.

In Figs. 7(b), the noise level 1000 feet from the runway is plotted against design engine airflow with afterburner setting as a parameter. The procedures of Ref. 16 were used to calculate engine noise. At Los Angeles International Airport, noise 1400 feet from the runway is limited to 120 perceived noise decibels (PNdb); at 1000 feet, the limit would be about 123 PNdb. To satisfy this limit on a hot day, the afterburner temperature during takeoff should not exceed about 1940° F. The value of design engine airflow has only a slight effect on runway noise. At the 3-nautical-mile point, however, it has an appreciable effect (Fig. 7(c)). This is because larger engines enable the aircraft to reach a higher altitude at the 3-nautical-mile point. On a hot day with the afterburner temperature set at 1940° F, the noise level at the 3-nautical-mile point can be limited to a value of 112 PNdb by installing engines with design airflows of 504 pounds per second. The lift-off distance on a hot day for this engine size and afterburner setting is 4300 feet or 45 percent of a 9500 foot balanced field length (Fig. 7(d)) and the lift-off speed is 165 knots. These values of lift-off speed and distance are considered to be acceptable.

The engine sizing considerations can be repeated for standard-day operation. To limit runway noise to 120 PNdb, afterburner temperature should not exceed about 1340° F (Fig. 7(b)). With this power setting, noise at the 3-nautical-mile point can be limited to 112 PNdb by selecting design engine airflow per engine to be 486 pounds per second (Fig. 7(c)). Lift-off speed would be 165 knots and lift-off distance 4400 feet (Fig. 7(d)). Standard-day operation is less critical than hot-day operation, so the hot-day engine size of 504 pounds per second is selected to test two other possible sizing criteria.

In Fig. 7(e), the climb path angle after an engine failure is plotted against design engine airflow per engine. The Civil Air Regulation lower limit on second-segment climb gradient is 0.03, which corresponds to a climb path angle of 1.72°. For a design engine airflow of 504 pounds per second, the climb path angle is 3.95°. Thus, the tentative engine size satisfies the one-engine out-climb requirement. There is no regulation governing minimum transonic thrust margin, but it has been suggested that the minimum thrust margin should be 0.3 on a standard day in order that adequate thrust be available for hot-day acceleration to cruise speed in a reasonable time. From Fig. 7(f), minimum transonic thrust margin on a standard day is 0.46 for a design engine airflow of 504 pounds per second. For this particular afterburning turbofan engine, then, the critical engine sizing criterion was that noise level at the 3-nautical-mile point on a hot day should not exceed 112 PNdb. This required an engine about 10 percent larger than that for minimum TOGW, and the resultant penalty in TOGW was about 1/2 percent (Fig. 7(a)).

Effect of Sonic Boom Limits

The calculations presented thus far are for a fixed schedule of altitude with flight Mach number during climb up to initial Mach 3 cruise conditions. As a result, the maximum sonic boom associated with climb varied for each aircraft/engine combination. For a TOGW of 400,000 pounds, maximum sonic boom during climb and acceleration to initial cruise conditions was found to be about 2 pounds per square foot (PSF). For a TOGW of 320,000 pounds, the maximum sonic boom was about 1.8 PSF. During Mach 3 cruise, the maximum sonic boom occurs at the beginning of cruise. It ranged from 1.5 to 1.7 PSF for aircraft having a TOGW of 400,000 pounds, and from 1.4 to 1.6 PSF for aircraft having a TOGW of 320,000 pounds. These values of sonic boom are 20 to 28 percent greater than the values that would be obtained for a rubberized aircraft configuration having an optimum combination of lift and volume at each flight condition.[17]

If a specific engine is selected and the climb path is varied from its nominal schedule of altitude with Mach number, engine size, aircraft TOGW, and maximum climb sonic boom, all will vary. The results of such a calculation for a specific duct-burning turbofan engine are shown in Fig. 8.

In Fig. 8(a), design engine airflow is plotted against maximum sonic boom overpressure. For a sonic boom of 2.2 PSF, design engine airflow is 440 pounds per second. For a lower sonic boom, the altitude flown by the aircraft must be raised, and this demands a larger engine. For a maximum sonic boom of 2.0 PSF, design engine airflow has increased to 550 pounds per second. As engine size and weight increase, the aircraft TOGW also increases (Fig. 8(b)). This increase in aircraft weight tends to increase sonic boom. Thus, installing bigger engines to fly at higher altitudes becomes less and less effective in reducing maximum sonic boom overpressure. Figure 8(b) shows that the sonic boom of this particular aircraft cannot be lowered beyond about 1.95 PSF. This example illustrates the very major effect that allowable sonic boom overpressure has on the propulsion system and the TOGW of the aircraft.

Inlet and Exhaust Nozzle Performance

The effect of inlet pressure recovery on the TOGW of aircraft powered by duct-burning turbofan engines is shown in Fig. 9. Three schedules of inlet pressure ratio with flight Mach number are shown. In schedule A, which is used as a reference, recovery is 95 percent at takeoff and 85 percent during Mach 3 cruise. In schedule B, recovery during Mach 3 cruise was raised to 90 percent. The effect of this change on aircraft gross weight is shown on the right. The decrease in TOGW is less than 1 percent. The third recovery schedule is characterized by a pressure ratio of 1.0 at takeoff and 92 percent during Mach 3 cruise. With such an inlet, aircraft gross weight decreased over 5 percent. This was due principally to a decrease in the amount of fuel consumed prior to cruise. Although specific fuel consumption changed only slightly, the time required to reach cruise conditions decreased appreciably. This resulted from the higher thrust levels attained with the higher recovery inlet.

The sizable effect that exhaust nozzle performance can have an aircraft gross weight is shown in Fig. 10. The schedule of gross thrust coefficient with flight Mach number is representative of a high performance exhaust nozzle. If the gross thrust coefficient at each flight condition could be increased 0.01, aircraft gross weight could be reduced an impressive 5 percent. While such a gain is indeed enticing, this extreme sensitivity of aircraft gross weight to exhaust nozzle performance is a reminder of the serious consequences that would result from falling short in developing a high performance exhaust nozzle. For the case considered here, if the exhaust nozzle gross thrust coefficient is decreased by 0.01 at each flight condition, the effect on aircraft TOGW is an increase of $5\frac{1}{2}$ percent.

Airflow Scheduling in Turbofan Engines

One of the choices open to the turbofan engine designer is the location of the engine operating line on the fan performance map. In Fig. 11, the fan performance map of a duct-burning turbofan engine is shown with three arbitrarily selected engine operating lines - A, B, and C. The variation in aircraft TOGW is seen to be less than 2 percent. Operating line A resulted in the minimum value of TOGW. In generating engine performance for the many duct-burning turbofan engines of this study, no attempt was made to select the optimum fan operating line for each engine. Instead, a fan operating line was drawn for each engine so that it resembled operating line A in Fig. 11.

Similar considerations were given to the choice of engine operating line on the fan performance map of the afterburning turbofan engine.

The duct-burning turbofan engines of the study have a fixed primary nozzle downstream of the turbine. As a result, engine airflow is not well matched with inlet airflow and spillage drag is quite high during operation in the transonic speed range. A scheme for improving the inlet-engine airflow match is to incorporate a variable area nozzle downstream of the turbine. With such an engine, the engine airflow can be reduced at high flight Mach numbers. This results in better inlet engine airflow matching throughout the flight speed range.

In Fig. 12, two duct-burning turbofan engines are compared. They are alike in most respects but differ in the type of nozzle downstream of the turbine. Engine A has a fixed-area nozzle that results in an engine airflow schedule designated base flow. Engine B has a variable-area nozzle that results in an engine airflow schedule designated low flow. Up to flight Mach numbers of 2.5 the two engine airflow schedules are identical. Above Mach 2.5 the low-flow engine demands less airflow than the base-flow engine. At Mach 3, the difference in airflow is 20 percent.

Since the inlet is sized by the Mach 3 cruise condition, the low-flow engine has a smaller lighter inlet, but more nacelle wave drag. This is shown at the left of Fig. 12 where the installation drag coefficient is plotted against the flight Mach number. Over most of the speed range, however, the low-flow engine has a lower engine drag. This is because the reduction in spillage drag more than compensates for the increase in wave drag. The figure on the right shows that aircraft TOGW is reduced about $3\frac{1}{2}$ percent by using the low-flow turbofan rather than the base-flow turbofan. This gain must be weighed against the complication of building and controlling the engine with a variable nozzle downstream of the turbine.

Variable Turbine Stators in Turbojet Engines

For subsonic flight, the turbofan engine cycle gives lower fuel consumption than the turbojet engine cycle. This is relevant to the two reserve requirements calling for subsonic flight to an alternate airport and holding prior to landing. In most cases, the weight of reserve fuel for these requirements equaled or exceeded the weight of the payload.

One means for improving the fuel consumption of the turbojet engine during subsonic flight is to incorporate variable turbine stators. The improvement that this can lead to is illustrated in Fig. 13. Engine performance for the hold flight condition is shown for two turbojet engines: one with fixed turbine stators and the other with variable turbine stators. The required level of thrust is such that the variable turbine stator engine has a 7-percent lower specific fuel consumption. A similar advantage prevails during subsonic cruise to an alternate airport. The effect on aircraft gross weight is shown on the right of Fig. 13. By powering the aircraft with turbojet engines having variable turbine stators, aircraft gross weight was reduced about $2\frac{1}{2}$ percent. Much larger benefits would result from the use of variable turbine stators if airline operations required considerable flying time at subsonic speeds. Thus, the incentive for developing the variable turbine stator concept depends very much on airline operational requirements.

SUMMARY

A Mach 3 transport aircraft with a fixed payload and powered by various turbojet and turbofan engines was flown on a 3200-nautical-mile mission. Minimum aircraft takeoff gross weight (TOGW) was used to indicate desirable values of engine design parameters. For both dry and afterburning turbojet engines, a design compressor pressure ratio of about 10 resulted in minimum TOGW. For the afterburning turbofan engine, the optimum overall compressor pressure ratio ranged from 11 to 13, while for the duct-burning turbofan engine, the range was from 8 to 11. Near optimum design values of bypass ratio and fan pressure ratio were 1.0 and 2.5, respectively.

Engine weight reduction and high values of turbine inlet temperature resulted in lighter aircraft to carry the fixed payload. With each of the four engine types, a payload equal to about 8 percent of the TOGW was attainable. The gas turbine engines had engine thrust-to-weight ratios in the range 9.3 to 11.3 and operated at turbine inlet temperatures in the range 2300° to 2500° F. To realize the potential gains from high turbine temperature operation, the turbine must be adequately cooled with only modest amounts of cooling airflow, and the turbine efficiency must not be degraded appreciably by the cooling airflow.

The effect of allowable sonic boom overpressure on engine size and aircraft TOGW was such that sonic booms below a certain level were not attainable; improvements in the propulsion system and/or the aircraft would be required to lower the limiting value of sonic boom overpressure.

It is concluded that worthwhile benefits to the concept of supersonic commercial air travel will result if the gas turbine engine technology continues to improve. The magnitude of the possible gains indicates that research efforts in propulsion should be continued and intensified.

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TABLE I. - EFFECT OF TURBINE EFFICIENCY

[Afterburning turbojet design values: compressor pressure ratio, 10; turbine inlet temperature, 2300° F; afterburner temperature, 3100° F.]

Turbine efficiency	88	81
Relative TOGW	99.5	108.3
Weight, percent TOGW		
Engine	9.56	9.56
Total fuel	51.66	53.13
Useful fuel	42.02	43.03
Reserve fuel	9.64	10.10

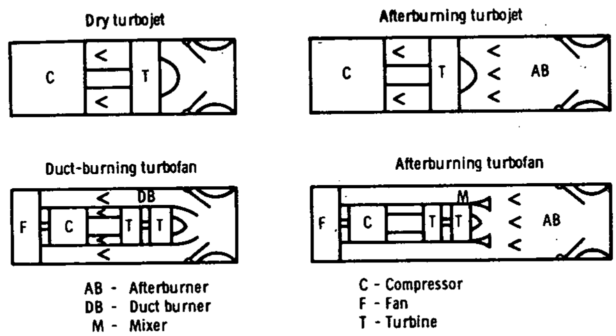


Figure 1. - Gas turbine engines.

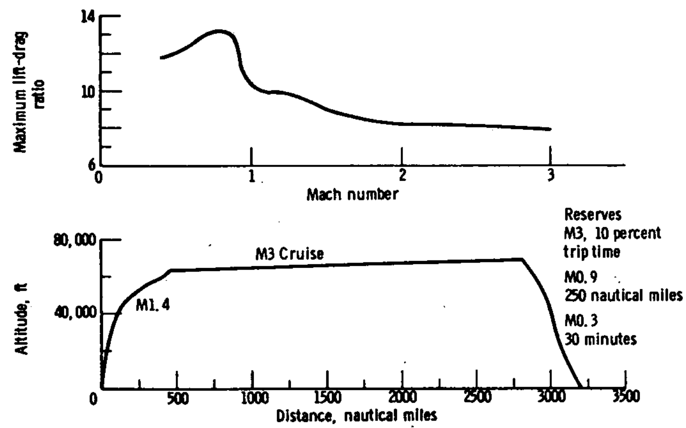
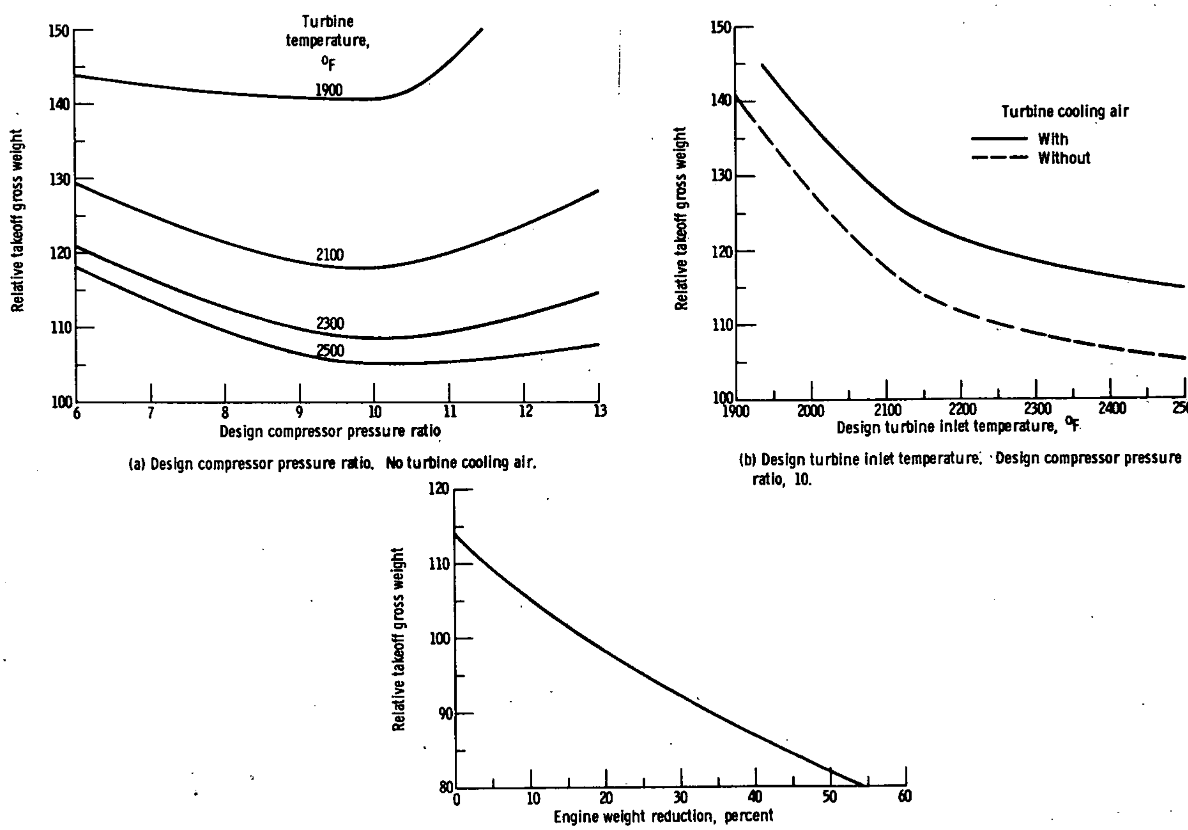
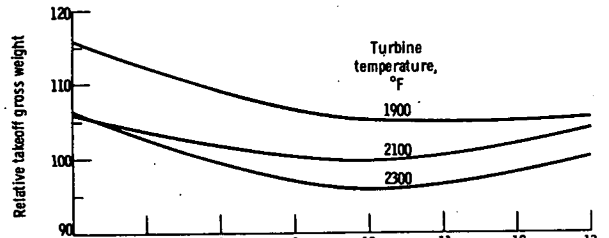


Figure 2. - Assumed aerodynamic performance and standard mission profile.

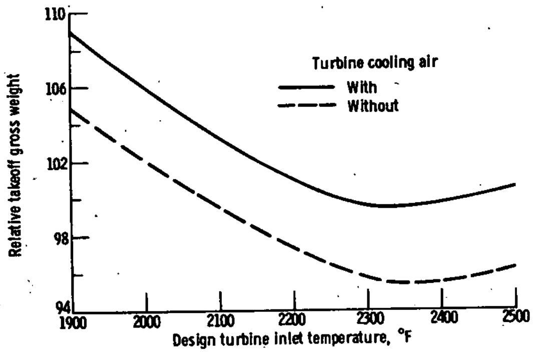


(c) Engine weight. Design values: compressor pressure ratio, 10; turbine inlet temperature, 2500° F.

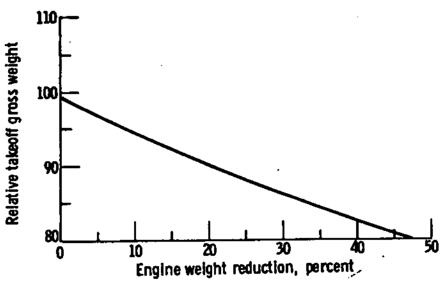
Figure 3. - Effect of design variables for dry turbojet.



(a) Design compressor pressure ratio. No turbine cooling air.

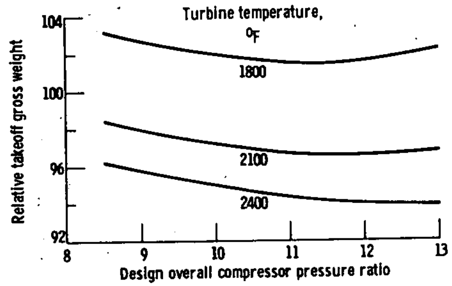


(b) Design turbine inlet temperature. Design values: compressor pressure ratio, 10; afterburner temperature, 3100° F.

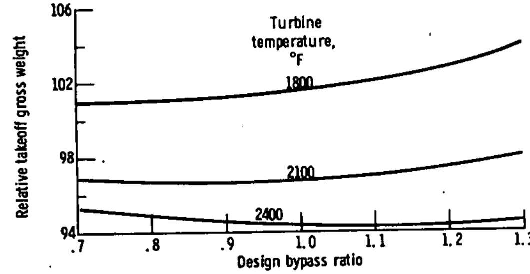


(c) Engine weight. Design values: compressor ratio, 10; turbine inlet temperature, 2300° F; afterburner temperature, 3100° F.

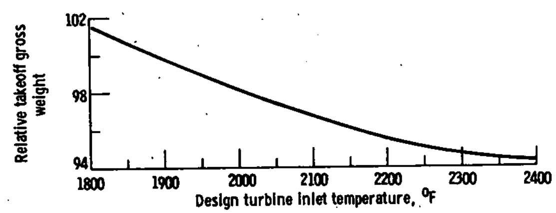
Figure 4. - Effect of design variables for afterburning turbojet.



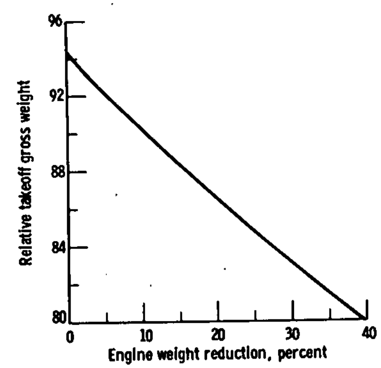
(a) Design overall compressor pressure ratio. Design values: bypass ratio, 1.0; afterburner temperature, 2740° F.



(b) Design bypass ratio. Design values: overall compressor pressure ratio, 11; afterburner temperature, 2740° F.

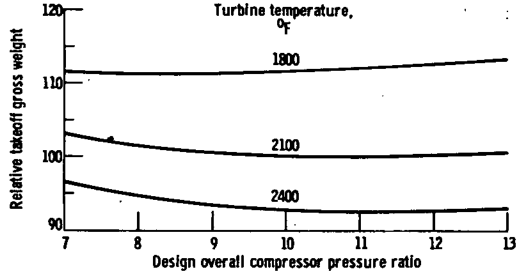


(c) Design turbine inlet temperature. Design values: overall compressor pressure ratio, 11; bypass ratio, 1.0; afterburner temperature, 2740° F.

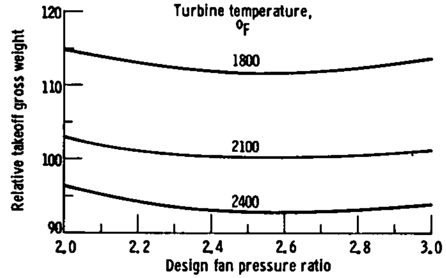


(d) Engine weight. Design values: overall compressor pressure ratio, 11; bypass ratio, 1.0; turbine inlet temperature, 2400° F; afterburner temperature, 2740° F.

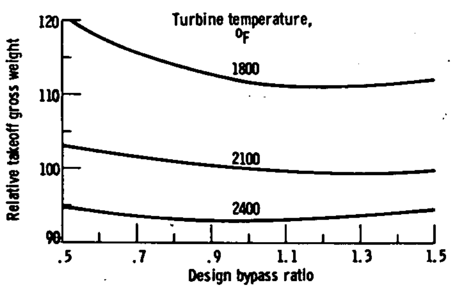
Figure 5. - Effect of design variables for afterburning turbofan.



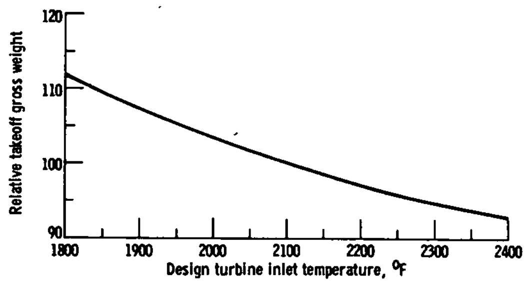
(a) Design overall compressor pressure ratio. Design values: fan pressure ratio, 2.5; bypass ratio, 1.0; duct-burner temperature, 3100° F.



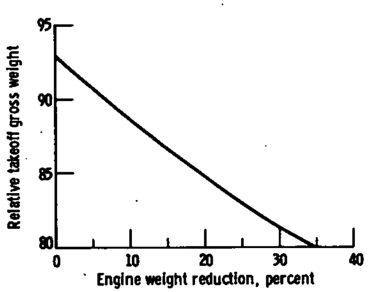
(b) Design fan pressure ratio. Design values: overall compressor pressure ratio, 10; bypass ratio, 1.0; duct-burner temperature; 3100° F.



(c) Design bypass ratio. Design values: overall compressor pressure ratio, 10; fan pressure ratio, 2.5; duct-burner temperature, 3100° F.

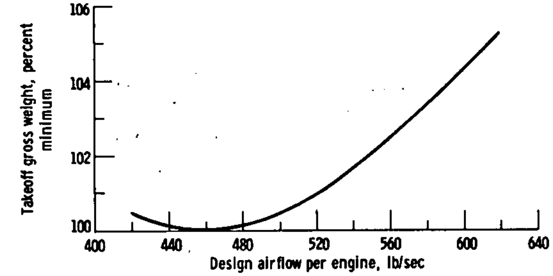


(d) Design turbine inlet temperature. Design values: overall compressor pressure ratio, 10; fan pressure ratio, 2.5; bypass ratio, 1.0; duct-burner temperature, 3100° F.

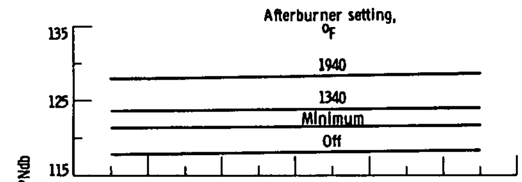


(e) Engine weight. Design values: overall compressor pressure ratio, 10; fan pressure ratio, 2.5; bypass ratio, 1.0; turbine inlet temperature, 2400° F, duct-burner temperature, 3100° F.

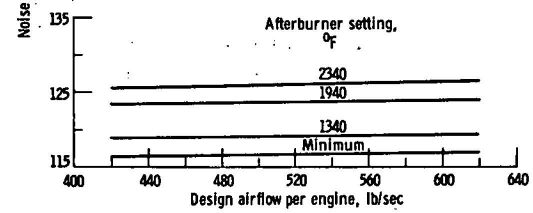
Figure 6. - Effect of design variables for duct-burning turbofan.



(a) Takeoff gross weight.



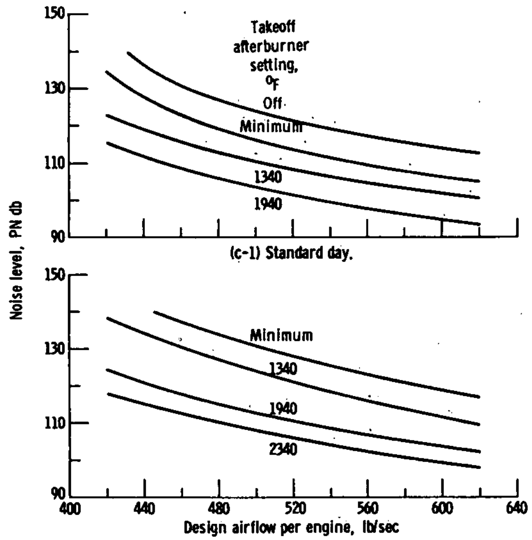
(b-1) Standard day.



(b-2) Hot day.

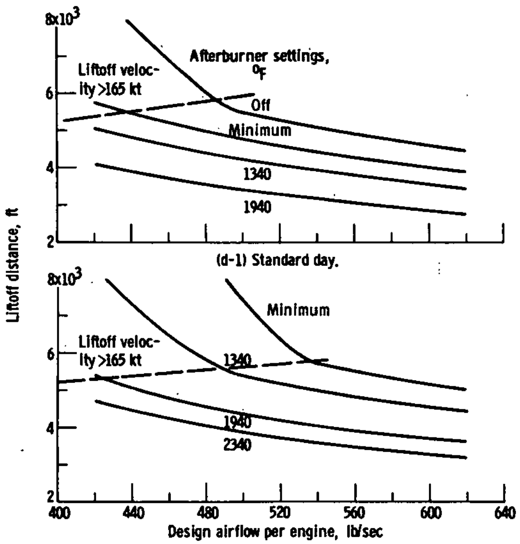
(b) Takeoff noise 1000 feet from runway.

Figure 7. - Engine sizing criteria. Afterburning turbofan design values: overall compressor pressure ratio, 11; bypass ratio, 1.0; turbine inlet temperature, 2100° F; afterburner temperature, 2740° F.



(c-2) Hot day.

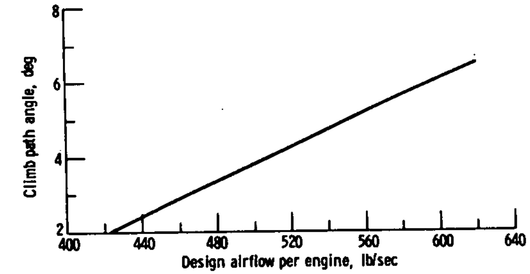
(c) Noise under flight path at 3 nautical miles from start of takeoff roll. Engine thrust is set to maintain climb at 500 feet per minute.



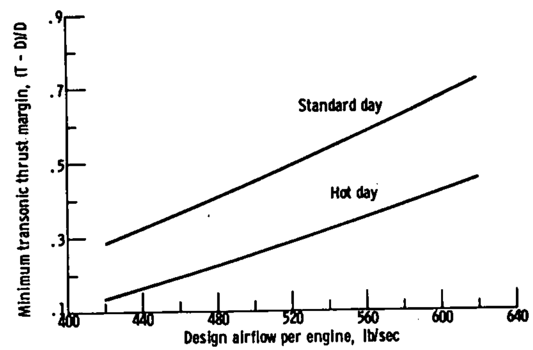
(d-2) Hot day.

(d) Liftoff distance.

Figure 7. - Continued. Engine sizing criteria. Afterburning turbofan design values: overall compressor pressure ratio, 11; bypass ratio, 1.0; turbine inlet temperature, 2100^0 F; afterburner temperature, 2740^0 F.

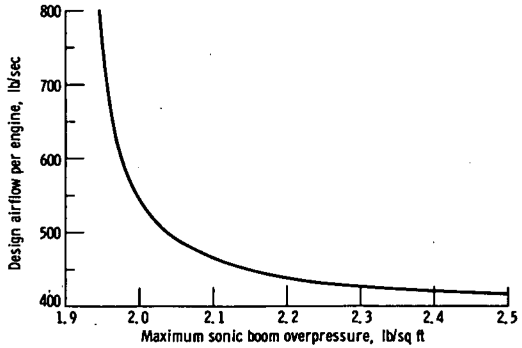


(e) Climb path angle. Thrust from one engine is lost at Mach 0.3 and 2000 feet on a hot day. Thrust of remaining engines is maximum augmented value.

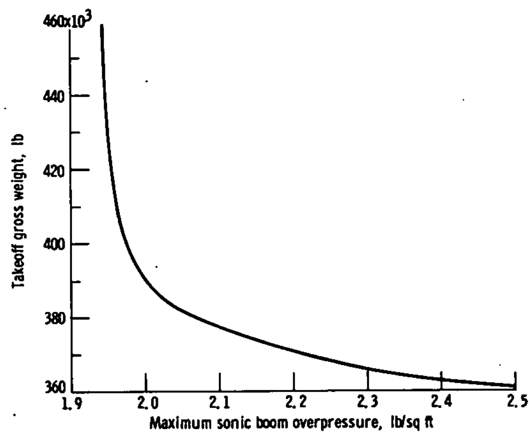


(f) Minimum transonic thrust margin.

Figure 7. - Concluded. Engine sizing criteria. Afterburning turbofan design values: overall compressor pressure ratio, 11; bypass ratio, 1.0; turbine inlet temperature, 2100^0 F; afterburner temperature, 2740^0 F.



(a) Effect on engine size.



(b) Effect on aircraft weight.

Figure 8. - Effect of maximum sonic boom on engine size and aircraft weight for duct-burning turbofan. Design values: overall compressor pressure ratio, 10; fan pressure ratio, 2.5; bypass ratio, 1.0; turbine inlet temperature, 2100° F; duct-burner temperature, 3100° F.

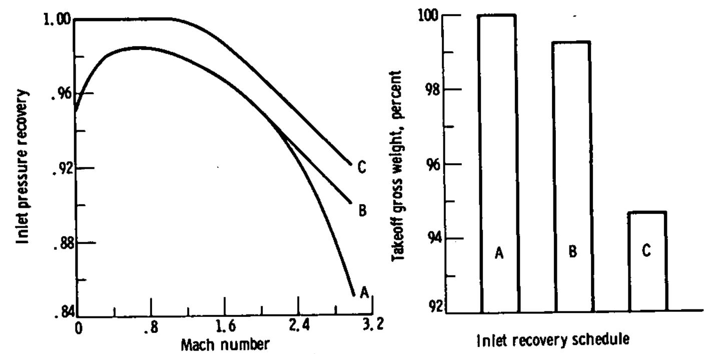


Figure 9. - Effect of inlet pressure recovery. Duct-burning turbofan design values: overall compressor pressure ratio, 10; fan pressure ratio, 2; bypass ratio, 1.5; turbine inlet temperature, 1940° F; duct burner temperature, 3040° F.

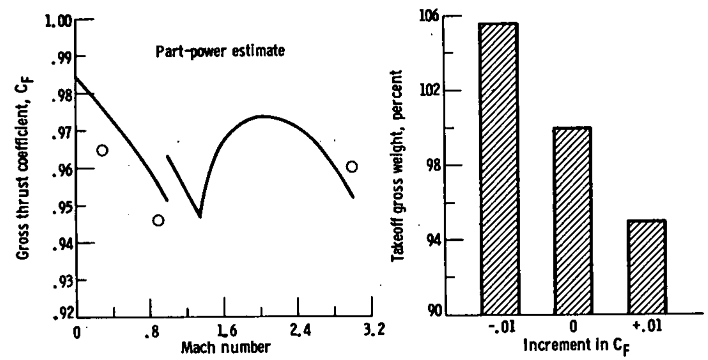


Figure 10. - Effect of exhaust nozzle performance. Afterburning turbojet design values: compressor pressure ratio, 10; turbine inlet temperature, 2300° F; afterburner temperature, 3100° F.

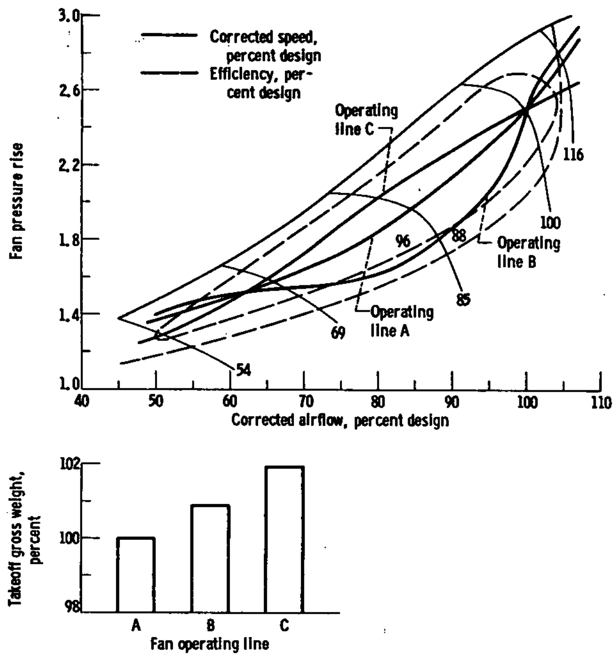


Figure 11. - Effect of fan operating line. Duct-burning turbofan design values: overall compressor pressure ratio, 10; fan pressure ratio, 2.5; bypass ratio, 1.0; turbine inlet temperature, 2100° F; duct-burner temperature, 3100° F.

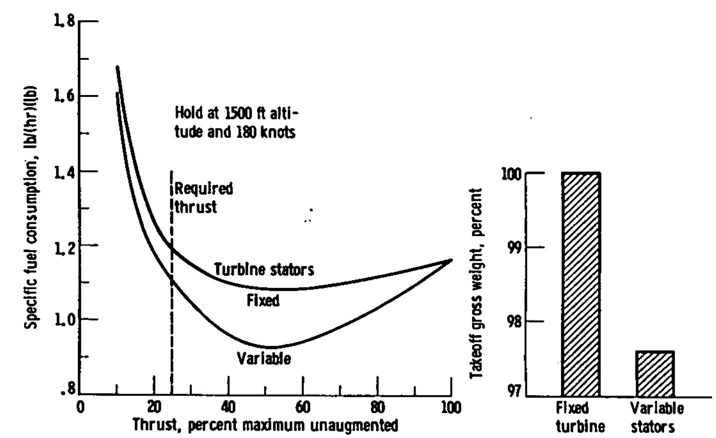


Figure 13. - Effect of variable turbine stators. Afterburning turbojet design values: compressor pressure ratio, 10; turbine inlet temperature, 2300° F; afterburner temperature, 3100° F.

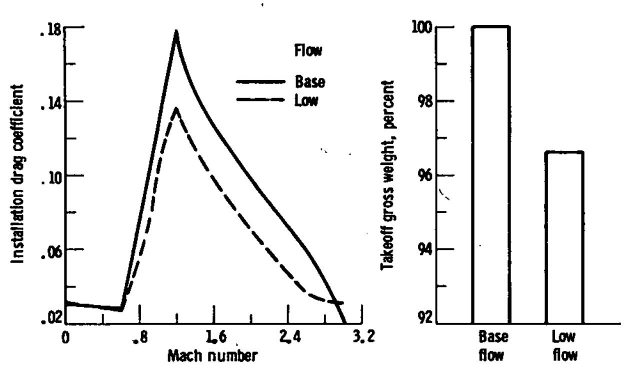


Figure 12. - Effect of low flowing. Duct-burning turbofan design values: overall compressor pressure ratio, 10; fan pressure ratio, 2; bypass ratio, 1.5; turbine inlet temperature, 1940° F; duct-burner temperature, 3040° F.