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PRELIMINARY STUDY OF TURBOJETS WITH ROTARY FLOW INDUCTORS FOR A LOW-NOISE SUPERSONIC TRANSPORT

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ABSTRACT

In a simplified airplane-mission study for a Mach 2.61 supersonic transport, dry turbojets with and without real suppressors and dry turbojets with ideal rotary flow inductors were studied for sideline noise levels as low as FAR 36-20. Compressor pressure ratio was varied from 5 to 30 and turbine temperature from 1800° to 3000° F. For no noise constraint and without a suppressor, the best dry turbojet gave a payload of 9.0 percent of gross weight and a sideline noise of 126 effective perceived noise decibels. Payload dropped rapidly for lower noise goals, becoming 6.3 percent of gross weight at FAR 36. At FAR 36, the turbojet with suppressor gave a payload of 8.3 percent and the turbojet with ideal rotary flow inductor, 7.3 percent. Below FAR 36, the ideal inductor was far superior to the real suppressor, giving payloads of 6.6 percent at FAR 36-10 and 5.7 percent at FAR 36-20.

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SUMMARY

In a simplified airplane-mission study for a Mach 2.61 supersonic transport, dry turbojets with and without real suppressors and dry turbojets with ideal rotary flow inductors were studied for sideline noise levels as low as FAR 36-20. Compressor pressure ratio was varied from 5 to 30 and turbine temperature from 1800° to 3000° F. For no noise constraint and without a suppressor, the best dry turbojet gave a payload of 9.0 percent of gross weight and a sideline noise of 126 effective perceived noise decibels. Payload dropped rapidly for lower noise goals, becoming 6.3 percent of gross weight at FAR 36. At FAR 36, the turbojet with suppressor gave a payload of 8.3 percent and the turbojet with ideal rotary flow inductor, 7.3 percent. Below FAR 36, the ideal inductor was far superior to the real suppressor, giving payloads to 6.6 percent at FAR 36-10 and 5.7 percent at FAR 36-20.

INTRODUCTION

A major problem in the design of supersonic transports is the avoidance of excessive sideline noise. A number of approaches have been suggested to reduce the sideline noise, at least to the requirement set forth in Federal Air Regulation (FAR) Part 36 for new subsonic transports. Sideline noise at 0.35 nautical mile is not to exceed 108 effective perceived noise decibels (EPNdB) for a gross weight of 600 000 pounds or heavier according to FAR 36. Naturally, a lower noise is desirable. The CARD study, reference 1, suggests that airplane noise be reduced 10 decibels per decade until the background noise level is reached (about 85 dB).

A turbojet engine provides very good cruise performance for an SST. Its major deficiency is excessive takeoff noise. Some device is desired that will result in acceptable noise with a minimum penalty in weight and drag. A jet noise suppressor is a candidate device, but all efforts so far have resulted in an excessive airplane performance penalty for noise goals below FAR 36.

In reference 2, the sideline noise is alleviated by oversizing turbojet engines and taking off at less than maximum thrust to reduce the jet velocity (and hence noise) while still maintaining an adequate performance margin. It was found that this approach could reduce sideline noise almost 7 EPNdB for a range penalty of 3.4 percent. However, the performance penalty became very large for noise levels much below FAR 36. When the American SST effort was terminated, oversized dry turbojets with noise suppressors and augmented turbofans were being considered for the American production SST to solve the sideline noise problem.

An aft-fan concept that combines the low-noise and high-thrust characteristics of a turbofan at takeoff with the high efficiency of a turbojet at supersonic cruise was studied in reference 3. With this concept it was possible to achieve the FAR 36 noise level with a range penalty of 0 to 280 nautical miles, the minimum range penalty being achieved from maximum usage of the better specific impulse of the turbofan mode of operation. A more detailed analysis is required to determine whether the overall performance of this concept is superior to other techniques for noise alleviation, such as oversized turbojets or jet noise suppressors.

Other variable-cycle engines were proposed in reference 4 for use in a supersonic transport. It is claimed that their use could save 61 000 pounds in equivalent weight which is equivalent to the entire design payload of the SST. These data indicate the maximum potential gain, which would be reduced because the variable-cycle engine would occupy more volume than the turbojet engine and may be heavier. Rather than improve SST performance, variable-cycle engines may be used to achieve lower noise levels. For example, a preliminary mission study was made of the range and jet noise of an advanced supersonic transport (AST) employing an augmentor wing and four duct-burning turbofan engines (ref. 5). The study showed that an augmentor wing can reduce the bypass jet noise sufficiently so that total noise levels below FAR 36 can be attained without significant range penalties if the augmentor wing can be designed without severe weight and performance penalties.

Another device which has the potential of reducing takeoff noise is a rotary flow inductor. It consists of a conical spinner with several jet nozzles mounted at the turbine exit and a cylindrical shroud larger in diameter than the turbojet. The exhaust from the turbine flows into the spinner and out the jet nozzles which are canted to rotate the spinner. The resultant cork screw flow from the spinner induces an airflow through the shroud which has a length to diameter ratio of 1 to 2. Thrust augmentation of the primary flow is achieved with a large airflow and low exit velocity and hence low noise. Some analytical and experimental studies of rotary flow inductors are reported in references 6 to 8.

In the present study, the ideal rotary flow inductor is combined with the dry turbojet in order to reduce sideline noise of a Mach 2.61 SST. Turbojets with and without noise suppressors are studied to maximize payload fraction in a simplified airplane-mission analysis for design compressor pressure ratios from 5 to 30 and design turbine inlet temperatures from 1800° to 3000° F. Results are presented for the case of no noise restraint and for noise levels down to FAR 36-20. The engine and inductor parameters of a turbojet with ideal rotary flow inductor are optimized to maximize airplane payload for a range of sideline noise levels. The variation of payload with sideline noise is compared with that achieved with suppressed dry turbojets.

ANALYSIS

Mission and Airframe

A total range of 3800 nautical miles is selected, of which 3350 nautical miles is supersonic cruise range (250 n mi are allowed for climb to initial cruise and 200 n mi for let down range). The cruise Mach number is 2.61 and initial cruise altitude is 60 000 feet. The cruise Mach number is slightly less than that of the cancelled Boeing 2707-300.

The airframe aerodynamics and weight fractions are from reference 2 and are based on the Boeing 2707-300 design. Takeoff gross weight is 750 000 pounds and cruise L/D is 8.0. (All symbols are defined in the appendix.) At takeoff, the ratio of engine thrust to airplane gross weight is 0.32. The following weight percentages are from reference 2:

	% TOGW
OWE less podded engines	31.71
Fuel up to cruise	12.96
Fuel design letdown	1.14
Reserve fuel	7.40
	53.21

This weight percentage is held constant in the analysis. Payload percentage is calculated from:

$$\mathrm{Pay} = 100 - 53.21 - W_{E+F} = 46.79 - W_{E+F}$$

To obtain fuel weight, a curve of SFC versus thrust at Mach 2.61 and 60 000 feet was calculated for each engine design. Cruise SFC was read from the curve at the required thrust level. Cruise fuel was calculated using the Breguet range equation.

Engine and Noise

Turbojet. - Engine performance was calculated from reference 9 and bare engine weight for 1974 year of first flight from reference 10. The podded engine weight is the sum of the weights of bare engine, inlet, nozzle, noise suppressor, nacelle, and mountings. The weight of inlet, nozzle, nacelle, and mountings was calculated from:

$$W_p = 160 \sqrt{\dot{W}}$$

This relation was obtained from some recent unpublished engine company studies of propulsion systems for an advanced supersonic transport. Turbojet engine parameters are as follows:

Design, P_2/P_1	5 to 30	
Design, T_3^0, ^oF	1800 to 3000	
Flight Mach number	0	2.61
Inlet P_1/P_0	0.95	0.85
η_C	0.85	varies
η_T	0.90	0.90
$(\Delta P/P)_{comb}$	0.05	0.05
CFN	0.97	0.97

Zero turbine cooling airflow was assumed. The nondimensional compressor map used in the analysis is shown in figure 1. It was derived from a compressor having a design pressure ratio of about 12 so that it is a good simulation of performance for compressors having design pressure ratios from about 8 to 16. It is a poorer simulation, especially as regards flow variation with equivalent speed, for the extremes in design compressor pressure ratio, 5 and 30.

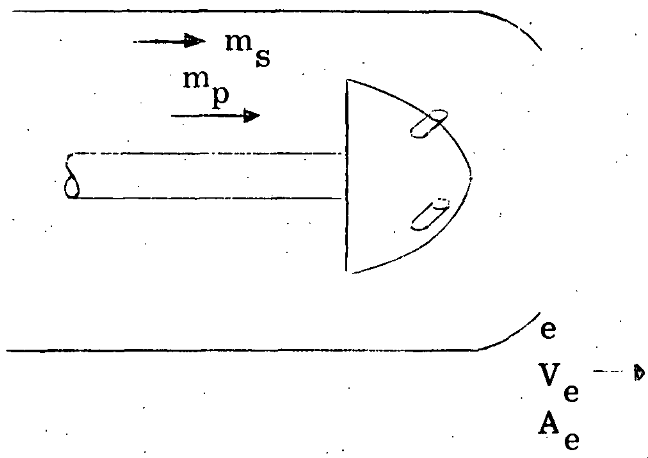
For the case of no noise constraint, the turbojet engines were sized for cruise and operated at part power for takeoff to meet the takeoff thrust requirement and reduce sideline noise. To obtain lower noise levels, the turbojets were oversized and operated at still lower part-power settings. The turbojets with rotary flow inductors were sized for takeoff and operated at part power during cruise. Part-power operation was at constant equivalent speed and reduced turbine-inlet temperature thus requiring a variable primary exhaust nozzle throat area.

The assumed performance of jet suppressors is shown in figure 2. Suppression and thrust loss are plotted against jet velocity. No one suppressor configuration has been found which can provide good performance over the entire jet relative-velocity spectrum. The curves in the region below 2000 feet per second (dashed curves) represent the best of the results obtained from many suppressor configurations. Above 2000 feet per second, the curves (solid curves) are for the Boeing 61-tube suppressor (NSC-119B) which is being investigated under the DOT/SST Technology Program. The Boeing suppressor provides a peak suppression of 18 PNdB at about 2600 feet per second. The data shown are based mainly on model tests at static conditions so there is a high degree of uncertainty as to whether the level shown is representative of a real application. The suppressor is retracted after takeoff with no thrust loss assumed during acceleration or cruise.

The weight of the suppressor was equal to 38 pounds per square foot of jet exit area. Some recent unpublished engine company studies suggest that suppressor weight equals $30\sqrt{\dot{W}}$. Suppressor weight, as calculated in this report, is about 50 percent heavier than that estimated in the engine company study.

Rotary flow inductor. - Another way of meeting a noise constraint and satisfying the takeoff thrust requirement is to combine the dry turbojet with some form of ejector. The usual induction of secondary flow by shear forces between primary jets and a secondary gas, as in a simple ejector, is a simple though rather inefficient pumping and jet thrust augmentation method, and is particularly inefficient at elevated primary gas temperatures. So far, the successful application of simple ejectors to jet or rocket propulsion has been limited by this low efficiency and by the bulky mixing ducts required in spite of their attractiveness from the point of view of mechanical simplicity. This situation may well change in the future with the introduction of rotary jets which transfer part of their energy and momentum to the secondary flow by interface pressure forces rather than by shear forces. This process also is inherently simple but has the potential of largely increased efficiency and greatly reduced flow interaction length. Analysis shows that the rotary jet flow inductor with isentropic flow deflection followed by constant-area mixing is capable of substantially better performance than the ideal ejector with the same geometry (ref. 6). Performance improvements from rotary jets over ejector performance are shown to be especially significant if the primary gas temperature is much higher than the secondary gas temperature, a condition that is always satisfied in a jet propulsion system.

A sketch of a rotary flow inductor is shown below:



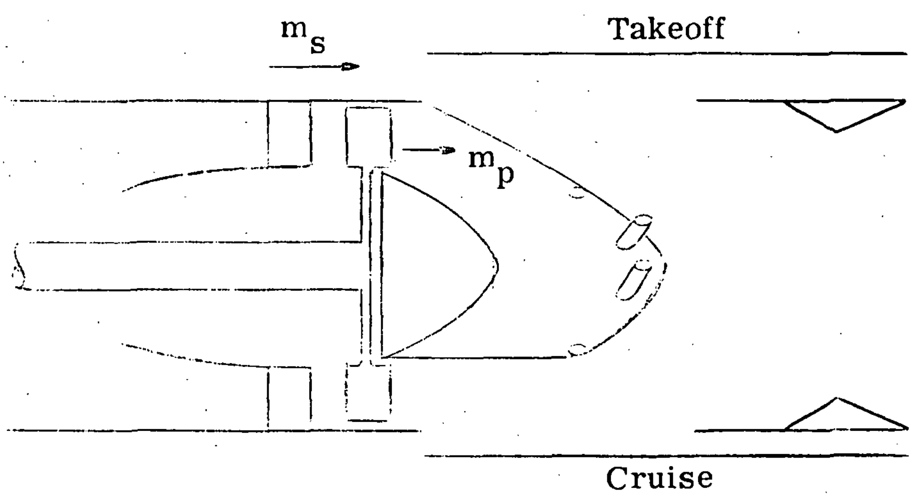
When mounted behind a dry turbojet, the flow from the turbine constitutes the primary flow, m_p. It exits the spinner through two or more canted nozzles. The resultant corkscrew flow induces a secondary flow, m_s. The rotating primary jets interact with the secondary flow in a flow pattern that is steady in a rotating frame of reference, whereby part of the axial momentum and energy transfer from the primary jets to the secondary flow is accomplished through fluid interface pressure forces rather than solely through shear forces as in an ejector.

For each turbojet with a rotary flow inductor, the values of $\overline{A}_e$ and $\overline{m}_s$ were selected to give a desired exit velocity. Airflow was selected to give the required takeoff thrust. It was found that maximum payload resulted when the $\overline{A}_e$ and $\overline{m}_s$ values required the engine to cruise at maximum thrust. Assuming that there is no heat exchange between the flows and the environment during the time that they pass through the inductor, the average exit velocity v_e can be related to the exit area A_e and the mass flow ratio m_s/m_p, in an equation which is valid no matter what the mechanism or the efficiency of the energy transfer between the two flows. Exit velocity was calculated from:

$$\overline{V}_e^2\overline{m}\left(\overline{T}_{pi}^o - 1\right) + \overline{V}_e\overline{A}_e = \overline{T}_{pi}^o + \overline{m}_s\overline{T}_{si}^o \qquad \text{(ref. 6)}$$

Nondimensional variables, indicated by a bar, are referred to the conditions of the primary flow when expanded isentropically to the exit static pressure. The analysis is based on the assumption that the flows in a rotor-fixed frame of reference are steady and isentropic and thus gives only an upper limit for the performance since the actual flows will not be exactly isentropic. Flow induction tests (ref. 6) with equal inlet temperatures of the primary and secondary flows confirm the trends of the analytical results. The reduction in performance as compared to the ideal device is probably mainly caused by the neglected jet dissipation during flow deflection. It will be assumed herein that the excellent ideal performance of the rotary inductor can be obtained in practice. (This is in optimistic contrast to the case of a simple ejector, whose actual performance is generally far below its ideal potential.)

Inductor weight was 38 pounds per square foot of jet exit area, assuming an inductor could be designed for about the same weight as a noise suppressor.



Sketch-rotary flow inductor during takeoff and cruise

During takeoff, shown in the top half of the sketch, the inductor shroud is deployed to admit secondary air. The hinged leaves of the spinner are expanded so that turbine gas flows into the spinner. During cruise the spinner leaves are contracted, as shown in the bottom half of the sketch, so that the turbine gas flows into the exhaust nozzle. The shroud is also contracted to avoid a drag penalty.

Noise. - Jet noise was assumed to be the predominant noise source and was calculated according to the procedures of references 11 and 12. Scrubbing and internal noise was assumed to be absorbed by acoustic lining on the surface of the shroud. Peak sideline noise (as per FAR 36) was calculated after lift-off on a 0.35 nautical mile sideline with the airplane at an 800-foot altitude. The peak sideline noise occurs at this altitude because it is the lowest at which there is no significant extra ground attentuation. When the angle of elevation from the observer is 20° or more, extra ground attentuation is insignificant, according to reference 13. EPNdB and PNdB were assumed to be equal at the sideline condition. The EPNdB scale attempts to correct the PNdB scale for subjective response to maximum pure tone and duration of the noise heard by the observer (ref. 14).

RESULTS

Dry Turbojets

No noise constraint. - The performance of dry turbojets for the condition of no noise constraint is shown in figure 3. The weight of engine plus fuel is seen to decrease as turbine temperature increases (fig. 3(a)). Weight of fuel decreases because SFC improves at higher turbine temperature providing the proper value of compressor pressure ratio is selected. The major decrease, however, is in engine weight. Higher turbine temperature yields higher values of specific thrust and hence smaller engines.

The trends of payload and noise as turbine temperature increases are shown in figure 3(b). Payload fraction increases to 9.0 percent of gross weight at a turbine temperature of 3000° F. In all cases, the engines were sized for cruise, which gave more than enough thrust for takeoff. For full-power takeoff (dashed line), sideline noise was about 130 EPNdB at all turbine temperatures. Throttling back during takeoff to just the required thrust level reduces the sideline noise (solid line of fig. 3(b)) but not enough to achieve FAR 36. The optimum compressor pressure ratio increases with turbine temperature to a value of 16.5 for 3000° F, figure 3(c). Increasing turbine temperature and higher compressor pressure ratio tend to increase engine weight, but the decreasing design airflow shown in figure 3(d) results in an engine weight decrease as turbine temperature increases.

Noise level of 106 EPNdB. - The performance of dry turbojets constrained to a noise level of 106 EPNdB is shown in figure 4. The noise is reduced below that of figure 3 by means of enlarging the engine so that more throttling is permissible during takeoff. Now, lower design turbine temperature is required to reduce weight of engine plus fuel, figure 4(a). Fuel weight is fairly constant since cruise SFC is almost constant when compressor pressure ratio is optimized to minimize weight of engine and fuel. Airflow is constant so that the decreasing turbine temperature and compressor pressure ratio cause engine weight to decrease. A maximum payload of 6.2 percent of gross weight was obtained at 2000° F (fig. 4(b)). At lower turbine temperature, cruise thrust was inadequate. While sideline noise is 2 EPNdB below FAR 36, the payload fraction is probably too low for an economically viable SST.

Payload versus noise. - The tradeoff between payload fraction and sideline noise level is shown in figure 5 for the engines that give the highest payload fraction for a given noise level. The solid line is for turbojets without noise suppressors. The highest payload shown (9.0% of gross weight) is attractive but the accompanying sideline noise level of 125.6 EPNdB is unacceptable. At FAR 36, the payload of 6.3 percent of gross weight is probably too low while at FAR 36-10, payload is only 4.5 percent of gross weight.

The results with jet noise suppressors are shown by the dashed line. At FAR 36, the payload fraction of 8.3 percent of gross weight is quite attractive while at FAR 36-10 the payload fraction of 4.8 percent is definitely unattractive. The large benefit of using a noise suppressor at FAR 36 and the small benefit at FAR 36-10 reflect the nature of the suppression dependence on relative jet velocity, figure 2.

Turbojet with Rotary Flow Inductor

For turbine temperatures of 2200°, 2600°, and 3000° F, the values of exit area and compressor pressure ratio were optimized to maximize the payload fraction for two arbitrary sideline noise levels, 114 and 101 EPNdB. The payload fraction increases as turbine temperature increases, figure 6. The engine parameters for a sideline noise level of 101 EPNdB are shown below:

Design T_3^{o}, ^{o}F	2200	2600	3000
Design P_2/P_1	10	14	16
$\overline{A}_e$	6.47	8.70	10.95
Inductor A_e, ft^2	93.62	94.74	97.67
V_e, ft/sec	1199	1301	1200
$\dot{W}$, lb/sec	6445	6435	6443
$\dot{W}_p$, lb/sec	1055	865	710
Pay, % gross weight	5.02	6.25	6.89

Optimum compressor pressure ratio increases from a value of 10 for 2200° F turbine temperature to a value of 16 for a turbine temperature of 3000° F. The exit diameter is 11.15 feet for a turbine temperature of 3000° F while compressor diameter is only 5.08 feet. No drag penalty was assessed for the large diameter shroud of the rotary flow inductor. Perhaps the shroud can be designed to be collapsible in order to minimize drag penalty.

Payload versus sideline noise is shown in figure 7 for turbojet with ideal rotary flow inductor (solid line) and for turbojet with real jet noise suppressor (dashed line). The maximum payload for no noise constraint is also shown to indicate the penalty in payload for achieving noise gals of FAR 36, -10, and -20. At FAR 36, the real suppressor is superior to the idealized inductor and payload is 8.3 percent of gross weight. Below FAR 36, the idealized inductor is superior to the real suppressor. At FAR 36-10, payload is 6.6 percent of gross weight while at FAR 36-20, the payload using the turbojet with ideal rotary flow inductor is 5.7 percent. In making these comparisons it should be emphasized that the assumed noise suppressor, although of somewhat advanced technology, incorporates thrust losses and suppression characteristics that have been investigated in detail in the laboratory if not in flight. On the other hand, the noise of the rotary inductor has been calculated ignoring internal effects and the thrust calculation is very idealized. For example, no deterioration with flight speed has been considered, although this has been a major problem with ejectors. Thus, every effort has been made to present the inductors in a favorable light, in the absence of evidence to the contrary.

CONCLUDING REMARKS

In a simplified airplane-mission study for a Mach 2.61 supersonic transport, dry turbojets with and without real suppressors and dry turbojets with idealized rotary flow inductors were studied for sideline noise levels as low as FAR 36-20. Design compressor pressure ratio was varied from5 to 30 and design turbine temperature from 1800° to 3000° F. Without a noise constraint and without a suppressor, the dry turbojet gave an attractive payload (9.0% of GW) but an excessive sideline noise (126 ENdB). For FAR 36, payload dropped to 6.3 percent of gross weight while at FAR 36-10, payload was only 4.5 percent of gross weight.

With a real noise suppressor, the dry turbojet gave a payload of 8.3 percent of gross weight for a sideline noise meeting FAR 36. Thus, for this noise goal, a suppressed dry turbojet is a promising propulsion system. At lower noise levels, the payload was unattractive. For example, at FAR-10 payload was only 4.8 percent of gross weight.

At FAR 36, the turbojet with ideal rotary flow inductor gave a payload of 7.3 percent of gross weight making it inferior to the suppressed turbojet. At lower noise levels the ideal inductor is superior to the real suppressor.

At FAR 36-10, the ideal inductor payload was 6.6 percent of gross weight and at FAR 36-20, 5.7 percent. Thus, the turbojet with rotary flow inductor may be promising, expecially for noise goals of 10 and 20 decibels below FAR 36. More investigation of this propulsion system seems warranted. A reliable weight estimate is needed and an inductor design (possibly collapsible) which would minimize drag penalties (not considered in the present study). If these further studies confirm the system's promise, then experimental studies should be carried out to define the noise and performance characteristics of the rotary flow inductor including the effect of forward flight speed.

APPENDIX - SYMBOLS

A_e	exit area
CFN	exhaust nozzle gross thrust coefficient
GW	gross weight
L/D	lift to drag ratio
m	mass flow
N	rotational speed
OASPL	overall sound pressure level
OWE	operating weight empty
P	total pressure
Pay	payload
SFC	specific fuel consumption
T^o	total temperature
V	velocity
W	weight
$\dot{W}$	airflow
δ	ratio of total pressure to sea level pressure
η	efficiency
θ	ratio of total temperature to 519^o R
ρ_j	density of jet

Subscripts:

BE	basic engine
C	compressor
comb	combustor
E	engine

e	exit
F	fuel
IN	inlet
i	inlet station
N	nozzle
P	pod
p	primary
s	secondary
T	turbine
TJ	turbojet
0	ambient
1	compressor inlet
2	compressor exit
3	turbine inlet

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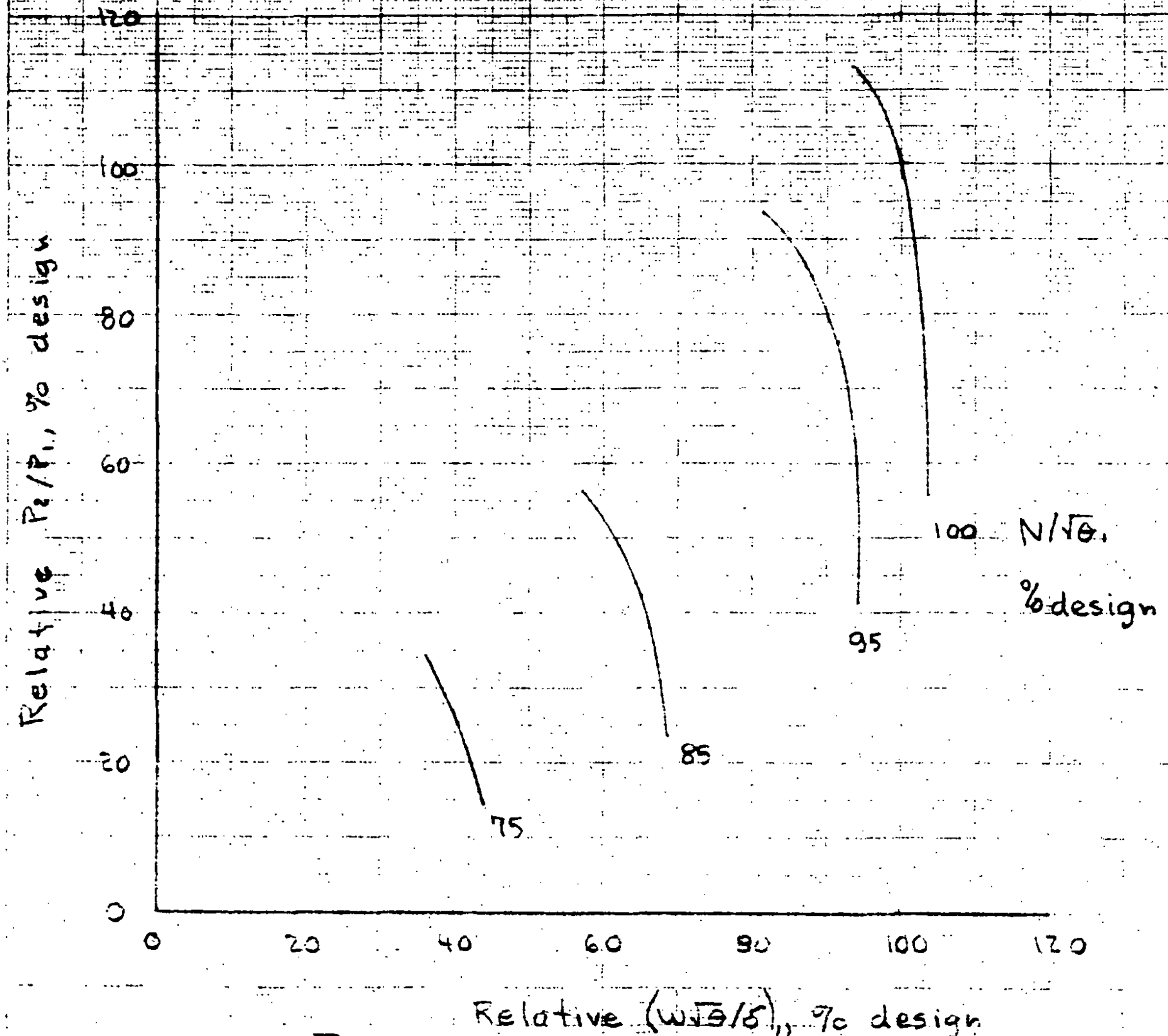
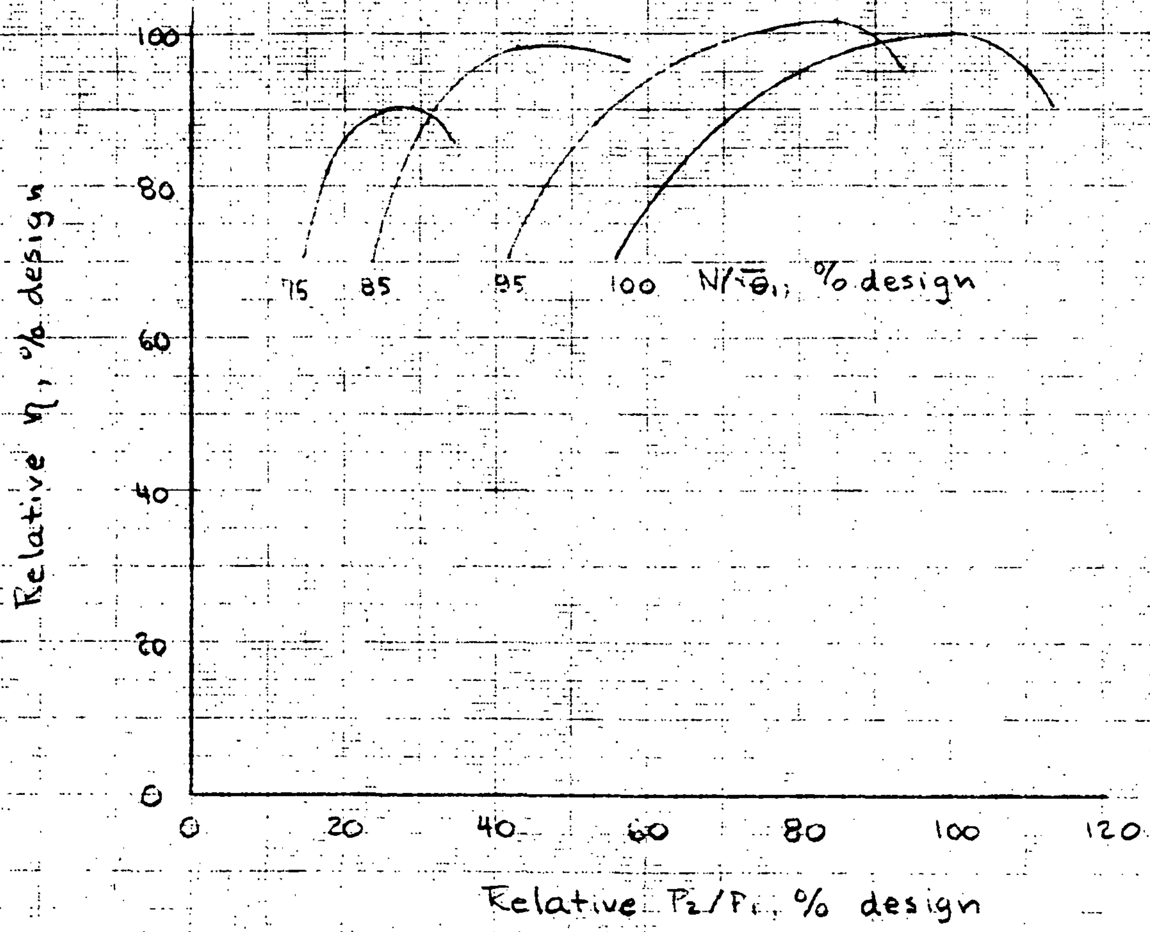


(a) Pressure ratio

Figure 1.- Compressor performance.



(b) Efficiency

Figure 1.- Concluded

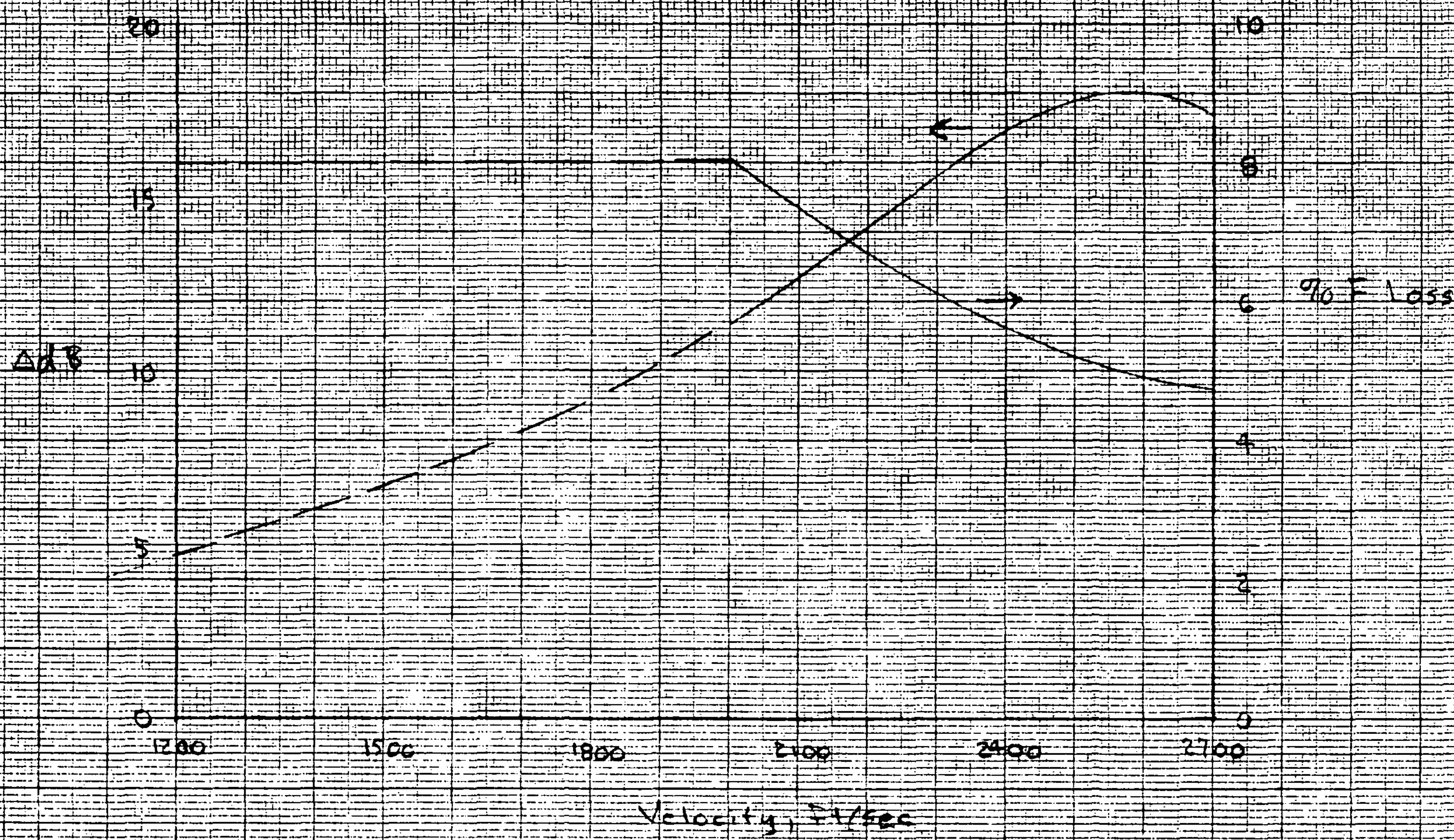
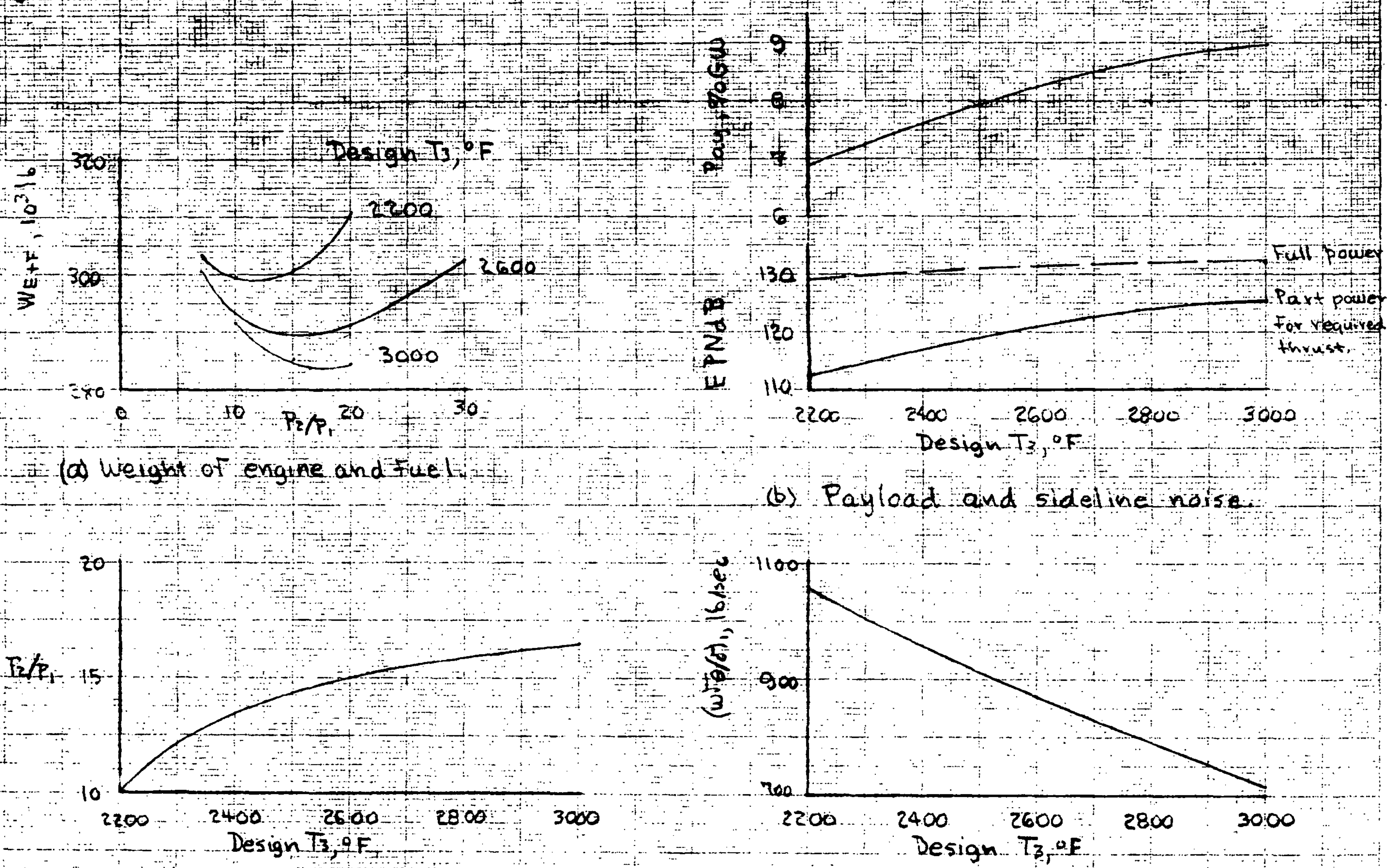


Figure - 2 Jet noise suppressor performance.

Figure 3.- Performance of dry turbojets. No noise constraint.



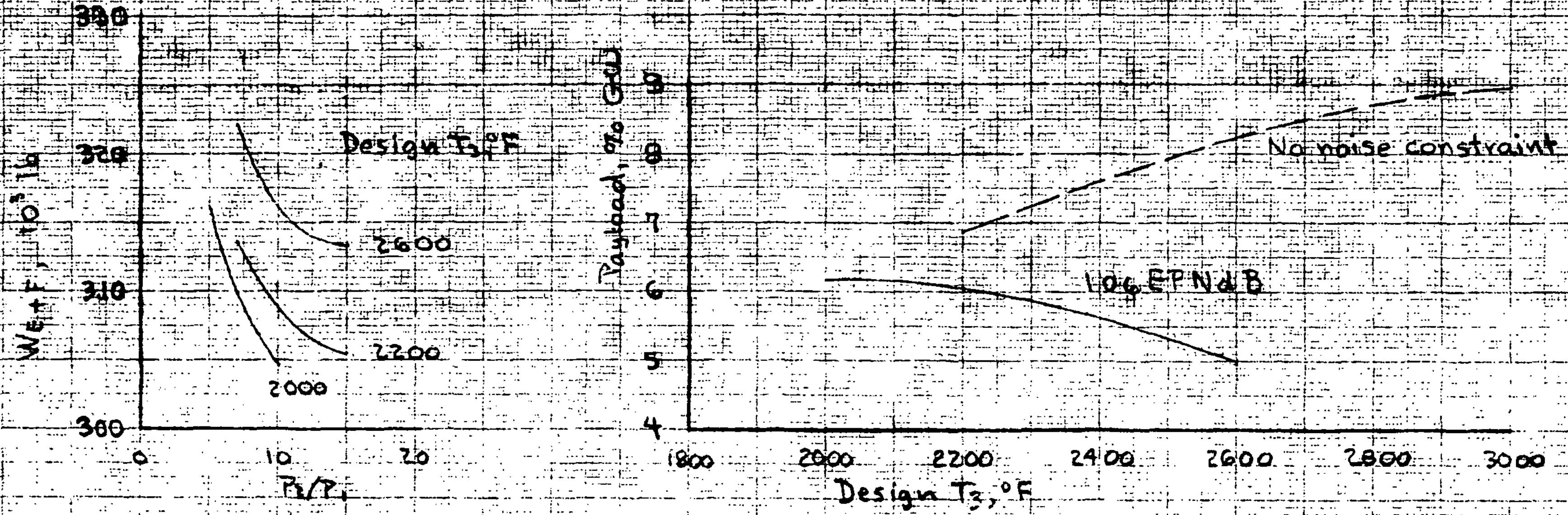
(a) Weight of engine and fuel.

(b) Payload and sideline noise.

(c) Pressure ratio.

(d) Engine airflow.

Figure 4 - Performance of dry turbojets. Sideline noise, 106 EPNdB. No suppressor.



(a) Weight of engine and fuel. (b) Payload

Figure 5.- Effect of sideline noise on payload. Dry turbojet.

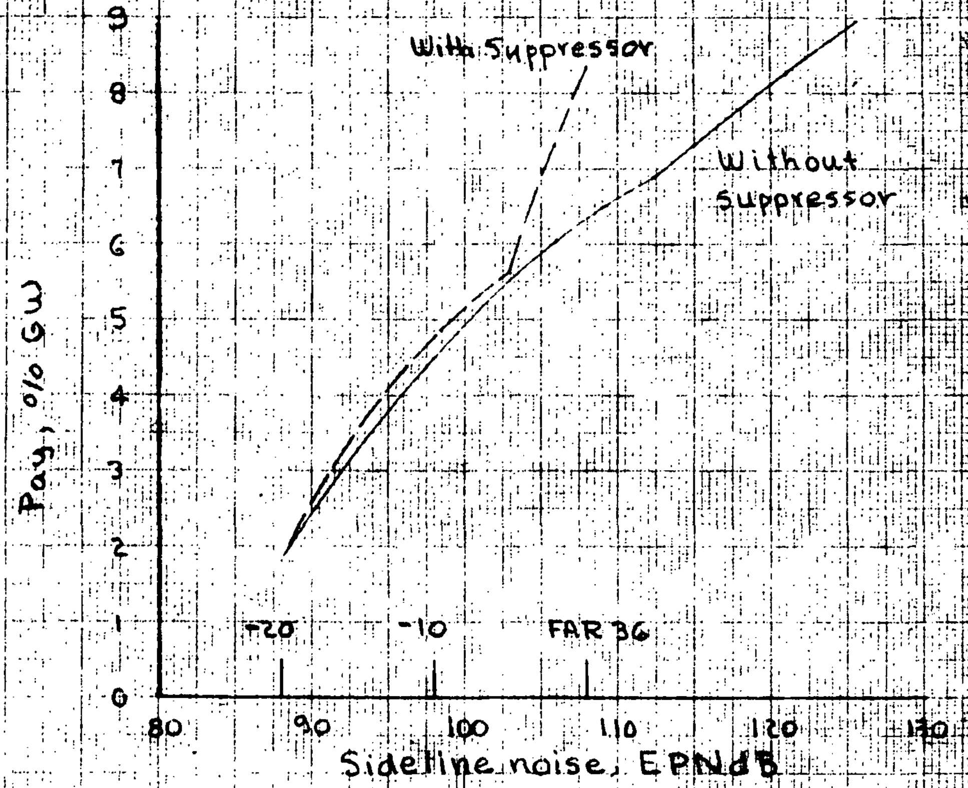
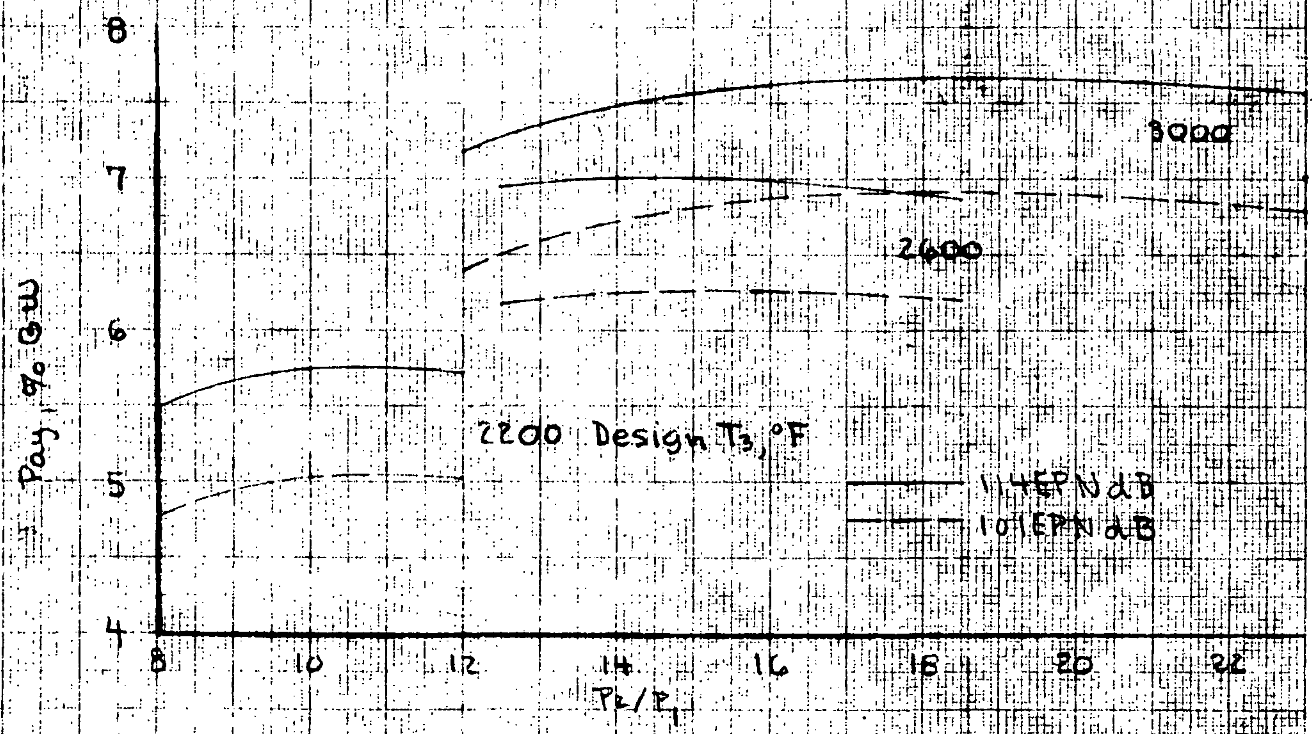


Figure 6. Performance of dry turbojet with ideal rotary Flow Inductor.



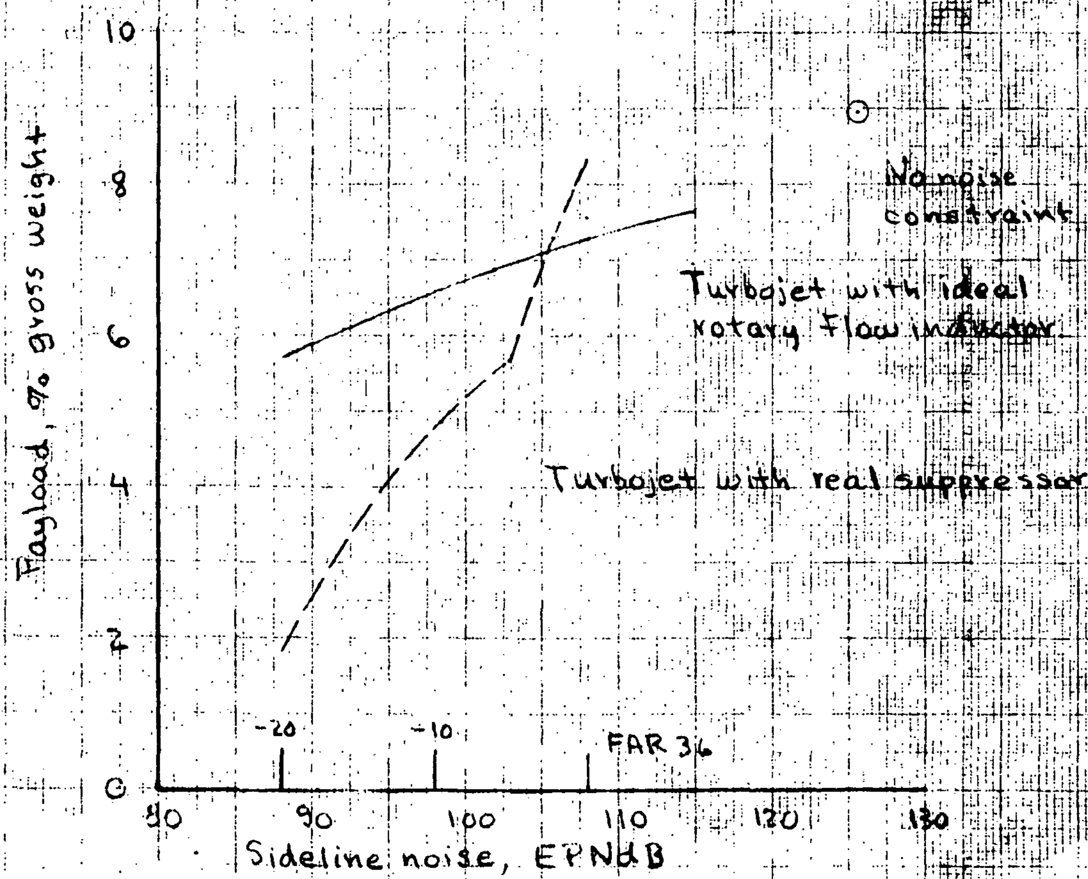


Figure 7. - Payload versus noise.