SURVEY PAPER ON VTOL PROPULSION COVERING RESEARCH PROBLEMS IN ATTAINING PROGRESSIVE TECHNOLOGICAL ADVANCEMENT

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SUMMARY

The main propulsion characteristics affecting the usefulness of Vertical Takeoff and Landing aircraft are similar to those of conventional aircraft, except their influence is stronger. The historic progress in Cruise Specific Fuel Consumption, Specific Weight and Specific Volume are examined, and predictions made for near future characteristics. The basic gas turbine engine component technology, and engine cycle improvements necessary to attain the engine performance progress are discussed in some detail. Some problems associated with VTOL propulsion system installation are also discussed.

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SURVEY PAPER ON VTOL PROPULSION COVERING RESEARCH PROBLEMS IN ATTAINING PROGRESSIVE TECHNOLOGICAL ADVANCEMENT

Michael B. Comberiate*

INTRODUCTION

There exists today an interest in aircraft that can takeoff and land vertically, and thereby minimize the dependency upon large prepared airfields. However, the seriousness of this interest is limited by the lack of success achieved to date in attaining a safe, reliable, and economical VTOL airplane. The most successful VTOL today is the gas turbine-powered helicopter, which is notorious for its low speed. The speed limitation is the result of the high rotor and hub drag, and the low power available for cruise. In surveying the field of VTOL aircraft, it is noted that for most VTOL types so much power is required for lift that there is an excess power for cruise. Among the VTOL aircraft types which appear to meet the need for high cruise speed, at a power condition compatible with good cruise specific fuel consumption for range, are the augmented engine types. In this category are the lift fan - cruise jet and lift jet - cruise jet engine propulsion system aircraft. Although these systems can be tailored to give VTOL aircraft speed and relative safety because there is so much powerplant, as compared with conventional aircraft, their basic performance characteristics such as specific fuel consumption, specific weight and specific volume, must be improved even further in order to meet the performance required for attractive VTOL operation. The challenge for vastly increased propulsion performance for desirable VTOL aircraft occurs at a time when gas turbine technology is in the midst of a great revival, spurred mainly by the international efforts for supersonic transports and jumbo jets. So now, with the increased level of technological effort, as evidenced by the increased expenditure of funds, and the availability of advanced mathematical analyzing techniques, computers, high temperature and rapid-response instrumentation, miniaturization of electronic measuring devices, and new large, complex wind tunnels, it appears that much more rapid advancements in technology can be expected in the near future. The resultant

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improved propulsion systems would enhance the attractiveness of VTOL aircraft, and go a long way toward establishing more serious interest.

The VTOL as a Propulsion Man's Aircraft

Vertical Takeoff and Landing aircraft are much more influenced by propulsion system characteristics than are conventional aircraft. This is true for two reasons: first, VTOL aircraft characteristics are more closely tied to the type propulsion system, and second VTOL aircraft require more power per pound of vehicle.

Although there are many different types of VTOL aircraft, their performance characteristics generalize remarkably well with the propulsion parameter, disc loading. Figure 1 is a plot of the whole spectrum of VTOL aircraft using disc loading as the primary identifier. On the ordinate, many aircraft performance characteristics could be laid out to show how they vary with disc loading for any VTOL. As indicated by the arrow in the extreme left hand side of the chart, lift efficiency (pounds per pound thrust), and time in lift varies indirectly with disc loading. The second arrow on the right indicates that cruise speed and downwash velocity varies directly disc loading. From the figure it is evident that, once the disc loading is selected, the essential qualitative performance characteristics of the particular type VTOL are established.

In Figure 2 is shown the classical mismatch of VTOL aircraft propulsion thrust loading requirements for vertical takeoff and for cruise, as shown by the lower edge of the cross-hatched band and for cruise plus the power loading for tactical maneuverability for military vehicles illustrated by the upper edge of the band. VTOL aircraft require three to four times as much thrust for vertical flight as required for cruise. The mismatch decreases as the airspeed and thrust requirements for maneuverability increase. Thus it is evident, that if the same unaugmented propulsion system, which is used for vertical takeoff were used for cruise, the engine would have to be operated in a highly throttled condition. Under such condition the specific fuel consumption of the engine would be relatively high, and this would give relatively poor range. From this it is evident that VTOL aircraft would benefit from a propulsion system which would do two things: first, give the high power needed for vertical takeoff, and second, operate in a cruise mode at a high percent power setting, where good specific fuel consumption would be attained.

The lift fan - cruise jet and the lift jet - cruise jet, or composite propulsion systems offer the high power needed for vertical takeoff, and good cruise specific fuel consumption, which is necessary for improved range or economy. In addition, these jet propulsion systems can give high power and low drag needed for high subsonic and supersonic speed. In order to show a further desirable characteristic of these augmented propulsion systems for VTOL, Figure 3 is shown. This figure shows mission radius for the spectrum of VTOL types as varying considerably from the helicopter, which has the shortest radius, to the composite jet which has the greatest radius. The curve for mission radius could be the reverse of one for time in lift, or hover time, if fuel weight were traded off for time in lift. However, if we did not consider making such trade, and were interested only in VTOL vehicles for their ton-mile capability, that is their ability to takeoff vertically with a load and carry it the most ton-miles, we would be able to show this by the second curve. This curve is quite interesting, in that it shows that all VTOL types have approximately the same capability as evidenced by the flatness of the curve. Since the load-carrying capability of the augmented propulsion system types is equal to that of other VTOL aircraft, their greater speed gives them greater potential for productivity, which is load-carrying capability per unit of time. Their potential for productivity makes the lift fan-jet engine and the lift engine - cruise engine VTOL aircraft very attractive. In addition, the higher power loadings of the jet propulsion system VTOL aircraft make them most likely to benefit from engine performance improvements resulting from the present increased efforts in gas turbine technology. Thinner lift fans and lower volume lift engines will contribute to improved drag characteristics of aircraft utilizing these concepts. The anticipated improvements in the basic engine performance characteristics: cruise fuel consumption, specific weight, and specific volume will be examined next.

Trends in the Primary Performance Characteristics of VTOL Engines

As shown previously, the most important characteristics for VTOL engines are specific fuel consumption, specific weight, and specific volume. For the composite jet VTOL systems, the cruise specific fuel consumption is the main factor influencing range. It is twice as influential as cruise engine weight, and even more than twice for lift system weight, or lift system specific fuel consumption. Figure 4 shows the trend for cruise thrust specific fuel consumption for large transport, or bomber, gas turbine engines as installed. The conditions selected are Mach 0.8, and 36,000 feet altitude, as representative of cruise for conventional jet transport aircraft, which is also representative of anticipated subsonic VTOL jet transports. During the past 20 years the cruise thrust specific fuel consumption was reduced from 1.2 to 0.6, a reduction of 50 percent. A portion of this improvement, the reduction from 0.8 to 0.6, which occurred during the past two or three years, was due to the use of the turbofan engines with bypass ratios up to 2. In the late 1968, it is believed that large cruise engines of bypass ratios up to 8 will be used which will have cruise thrust specific fuel consumptions of approximately 0.3 or 0.4. In the 1970's, it is believed that large cruise fans with bypass ratios of 15 will be available which will have cruise specific fuel consumptions as low as 0.25. These low values for the main influence factor for range makes the high bypass cruise fan and cruise engine very attractive for long range operation at high subsonic speeds.

Figure 5 shows the trends in VTOL engine thrust to weight ratio from 1953 to the present with a prediction for the near future. In 1955 gas turbine engine thrust weight ratio was in the order of 2 or 3 to 1. Improvements have given a steady rise to a present figure of approximately 6. This improvement is expected to continue steadily to 8 or 10 in the early 1970's. A separate relationship is shown for the lift fan and lift jet engines. Considerably higher thrust to weight values are ascribed to these engines. Lift jet engines and lift fans of 16 to 1 have been in evidence since 1964. It is anticipated that lift fans of 30 to 1 would not be unreasonable for the mid 1970's. The reasons for the distinct advantage in thrust-weight ratios for the lift fans and lift jet engines are, first, the lift fans are not complete engines. If the gas producer portion of the propulsion system were included, the thrust-weight ratio would probably be down on the lower leg of the curve. Second, the lift jet actually serves as a boost engine, and therefore does not have to be built to the same long-life criteria as the cruise engine, nor is the requirement for low specific fuel consumption as critical, since it operates only for a small part of the mission, i.e., take-off, and landing.

Another most important propulsion system characteristic for VTOL aircraft is thrust to volume ratio, for which the trends are shown in Figure 6. Since 1964, the thrust volume ratio for gas turbine engines has improved approximately 100 per cent in going from 200 to 400 pounds thrust per cubic foot. Some very large gains are predicted over the next few years: A 100 per cent improvement of the present values are predicted by the early 1970's. These large gains are expected to result from the great efforts being made to shorten and lighten engines. The details of how this is being done will be given next.

Gas Turbine Engine Technology

The efforts which are now being made to improve technology for aircraft gas turbine engines, in general, are directly applicable to VTOL gas turbine engines. Each of the major engine components, the compressor, combustor and turbine will be examined to see where and how progress is being made.

Compressors. One of the most effective ways to reduce engine size and weight is to reduce the size of the compressor by improving the stage loading. Figure 7 shows the effect of increasing compressor stage pressure ratio on decreasing the number of stages required to attain an overall compressor pressure ratio of 9. Present day axial flow compressor stages produce a pressure rise of approximately 1.3 at 1100 to 1200 feet per second tip speed. This corresponds to a blade loading factor of less than 0.4. At an average stage pressure ratio of 1.3, approximately 8 stages are necessary to produce a multistage compressor having an overall pressure ratio of 9. In the event that the pressure rise per stage is increased to 1.6, less than 5 stages would be needed for an overall pressure ratio of 9. The increased pressure rise per stage may be attained by either increasing the compressor tip speed, or by increasing the blade loading. There are several advantages to maintaining low tip speeds. First, the compressor noise is greatly affected by tip speed, and keeping the compressor noise levels down is an item of major importance, as will be mentioned later. Second, higher tip speed stages require materials of higher strength-density ratios. Stainless steel cannot be used for tip speeds much above 1000 feet per second because of the hub stresses. Titanium is satisfactory for tip speeds in the order of 1500 feet per second. In the near future, the potentials of beryllium to achieve 2000 feet per second, and of boron fiber-reinforced materials to attain 2400 feet per second may be realized.

Historical trends in axial flow compressor stage loadings are shown in Figure 8. The average stage pressure ratio, which, as stated previously, are in the area of 1.3 - 1.4, are expected to be increased to 1.8 - 2.0 in the early 1970's. In general, the improvements in stage pressure ratio will result from improved blade design achieved from further use of analytical methods and computers, and of special high speed flow cascade test facilities for checking blade performance. There is a sizeable effort underway to make improvements in compressor blade and vane stage loading by improved control of the boundary layer so as to prevent its separation from the airfoil suction surface at high angles of attack. Several methods to do this, which have been tested, are shown on Figure 9. Slots cut across the airfoil, at approximately mid-chord, allow higher pressure air to go through the airfoil and add energy to the suction surface boundary layer and thereby delay separation and loss of blade loading. This method has been shown to give increased lift coefficient and lowered wake losses at high incidence angles. The other two methods shown, blowing and bleeding, have been found to be effective, but not as readily adapted to rotating machinery as slotting. Another method, not illustrated here, increased airfoil cambering by use of hinged flaps, somewhat like that done on airplane wings, is also being investigated.

<u>Combustors</u>. The main objectives of combustor research are shown in Figure 10. The most desirable goal is high temperature rise. If this is achieved in a relatively short burning length the result is a lighter weight burner. One factor which will contribute to this is an efficient diffuser which can convert the high velocity air from the compressor into high pressure in a short length without flow separation from the walls. The burning must occur efficiently so that good performance and no hot spots are created. The hot gas leaving the combustor should have a uniform circumferential temperature and be tailored, radially, to promote long life of the burner and of the hot parts downstream. An estimate of burner heat release progression is shown on Figure 11. During the past ten years the burner heat release rate in millions of BTU per hour per cubic foot per atmosphere has tripled. It is expected that there will be an increase of almost double the present value of approximately 8 in the next decade. Higher heat release rates than those shown might readily be attained if low pressure drop and the desired temperature pattern and uniformity are not maintained. Under such conditions, combustor and other hot section parts life would be severely reduced.

One idea, which has great potential for making considerable reduction in burning length, and therefore is particularly attractive for lift engines, is the diluent stator combustor shown on Figure 12. Here the combustor is shortened by moving the turbine stator into the primary burning zone. Most of the secondary air mixes with the combustion air to cool it from the high stoichiometric temperatures, by passing first through the turbine stator which is porous or has large holes in the surfaces of its airfoil for this purpose. Careful selection of the size and location of these passages in the stator can cool the stator as well as the combustion gases down to the desired cycle temperature, and also control the shape of the radial temperature profile.

<u>Turbine</u>. The progression of gas turbine engine technology is closely associated with the increase in turbine inlet temperature (TIT). TIT is the maximum cycle temperature for a non-afterburning engine, and is the greatest single factor influencing all three of the engine performance characteristics: specific fuel consumption, specific weight, and

specific volume. Figure 13 shows the effect of turbine inlet temperature on thrust per pound of airflow of a non-after-burning engine. There is a dramatic increase in power output through increasing the turbine inlet temperature from 1600°F to 2700°F. Thrust per pound of air goes from 65 to 105, an increase of over 60%. The percentage improvement falls off somewhat at temperatures above 3500°F but is still quite large. Increasing turbine inlet temperature is not easily done as evidenced by the next figure.

Figure 14 shows the progression of turbine inlet temperature from 1946 to date, and an estimate of the improvements to be made in the next few years. In the fifteen year period from 1946 to 1961, the temperatures have been increased from approximately 1450°F to 1750°F an increase of only 300°. During the fifteen years from 1961 to 1976 it will be increasingly difficult to make a 300°F gain in turbine inlet temperatures. However, the great increase in effort in high temperature materials will probably be sufficient to make this gain. Practically speaking, cooling is used at temperatures above 1750°F, and the increases in turbine inlet temperatures estimated by 1976, based upon improved cooling techniques, as well as improved materials, is shown on Figure 14 to approach 3000°F.

An estimate of the advancement in turbine blade materials technology alone is shown in Figure 15. Here the material temperature that will produce rupture at 100 hours under a steady stress of 20,000 pounds per square inch is plotted against years. 20,000 pounds per square inch is considered a reasonable stress level for turbine blade materials. In the period from 1946 to 1966, the critical temperature has risen from 1400°F to 1800°F, which covers the same period and the same gains shown in Figure 14. Figure 15 shows the gains in twenty years to be only 400°F. It is anticipated that 2050°F will be reached by 1976, which would be relatively large gain, and the result of the great efforts which are now being made in oxidation resistant coatings.

The greatest gains in turbine inlet temperature will have to be made from turbine cooling techniques. Several methods of turbine blade and vane cooling are shown in Figure 16. These methods are shown in the order of effectiveness: convection cooling, impingement cooling, film cooling and transpiration cooling. Some cooling methods are better suited for certain portions of the blade. Convection cooling usually runs the length of the blade, passing over vertical fins on the inside walls to cool the midchord. Impingement cooling is very effective in reaching and cooling the leading edge. Film cooling can be effective to set up a film of cool air over the trailing edge, or of the section directly behind the leading edge. Figure 17 shows a combination of these three types of cooling used on a single turbine blade design which was derived analytically. Such combination of cooling is very effective in reducing blade material temperatures with the minimum quantity of cooling air flow, and to prevent thermal fatigue, which will be discussed later. Transpiration cooling has great effectiveness, and would likely be used where large amounts of cooling are needed. However, this method is susceptible to oxidation and clogging of the cooling flow passages.

VTOL Propulsion Operating Problems

The propulsion system operating problems which are particularly severe for VTOL aircraft are low cycle fatigue, inlet flow distortion and noise. About all that can be done in this short survey is to describe the problems, and make no pretension of solutions. The inlet distortion resulting from hot gas ingestion will be covered by others during this meeting, and will not be included in this discussion.

Low Cycle Fatigue is the result of high stresses from aerodynamic, or thermal loads suddenly applied and suddenly relieved on engine parts such as compressor and rotor blades, which even normally are highly stressed. This type of fatiguing occurs where many starts and stops per operating hour are required. An example of the cause for high thermal stressing during engine acceleration and deceleration is shown in Figure 18. The curves show the rate of change of temperature of two points on the blade cross section. Point (1) is on the leading edge of the blade, and point (2) is at the midchord point on the suction side of the blade. As the turbine inlet temperature increases during an acceleration, points (1) and (2) are heated up at different rates so that there can be a temperature differential between these points of as much as 900°F. During a deceleration the temperatures quickly approach each other, so that in another acceleration, the differential heating causes large temperature excursions. There are also large temperature differences between points along the span of the blade. Large temperature differences set up high thermal stresses. In operation where there are many starts, or much power cycling, such as in a VTOL lift engine, which is sometimes also used for stability and control, fatigue failure would be a problem. Several things can be done to reduce thermal fatigue failures. First, the stresses due to unequal heating of the different points on the turbine blades can be prevented from being even more aggravated by making the burner exit temperature profile, both radially and circumferentially, conform to more exacting specifications. Then, it would be possible to tailor the cooling air flow in the blade so as to reduce the temperature differential. The next thing to do is to use those materials, which by their better creep strength, and low coefficient of thermal expansion are better-suited for the thermal conditions encountered. Thoria-dispersed nickel and nickel chromium alloys are believed to have potential here.

Inlet Distortion in Cross-flow is a potential problem for lift fans and lift engines. The maximum inlet flow distortion will exist when the ratio of air inlet velocity to airspeed is lowest. Figure 19 shows the problem for lift fans; separation of the air flow on the upstream side of the rim and the hub. This causes a large performance loss, unloading and overspeeding of the fan, and severe vibration. The vibration would be quite similar to that experienced by propellers, called 1P vibration. The use of circular inlet vanes, vortex generators, and boundary layer control by bleeding or sucking in the area where separation occurs have been found to be very effective in recovering the losses.

Noise. Aircraft engine noise is a complex and difficult problem in general, but, for VTOL aircraft, the problem is particularly severe because they have proportionately more power for a given size aircraft, and takeoff and land closer to large groups of people. Figure 20 gives a comparison of the estimated noise levels for the spectrum of VTOL aircraft. The values are given in terms of PNdB, the standard units of noise measurement, and are for equal vehicle gross weights of 75,000 pounds, at a horizontal distance of 400 feet. An acceptable airport noise level is about 112 PNdB. VTOL aircraft would operate at smaller aiports where the acceptable level for commercial operation would be less than 100 PNdB. It is noted that noise level is another parameter that generalizes with disc loading. The higher disc loading vehicles are considerably noisier. One way to view the various VTOL types is according to their variations in bypass ratio. The higher the bypass ratio, the lower the noise. Rotorcraft have an equivalent bypass ratio of 150. The lift fan has a bypass ratio on the order of 8 to 15. One method to reduce jet noise is by increasing bypass ratio. As pointed out under compressors, another effective method of reducing compressor noise is by lowering tip speed. Another method is by adding sound absorption material in the compressor inlet ducts. This paper does not go into any detail on the various possibilities of noise suppression because to date noise has not been considered a major problem for the military which would warrant a performance trade-off to alleviate.

CONCLUSION

This survey has tried to show that there has been, and will very likely continue to be, great activity in gas turbine propulsion technology aimed toward improving cruise specific fuel consumption, specific weight and specific volume, which are necessary to achieve more useful VTOL aircraft in the near future. The lift fan cruise jet and lift jet-cruise jet composite VTOL types are considered most apt to benefit from the current technological programs, and are likely to yield attractive high speed vehicles for military and civilian use. Certain problems associated with the propulsion systems of these high speed VTOL types, such as inlet flow distortion from cross flow and hot gas reingestion, and low cycle fatigue appear to be amenable to resolution from the current technological activity. However, engine noise of the jet VTOL's is quite severe, and will take a greatly increased effort to ameliorate.

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GENERALIZATION OF VTOL AIRCRAFT PERFORMANCE CHARACTERISTICS WITH DISC LOADING

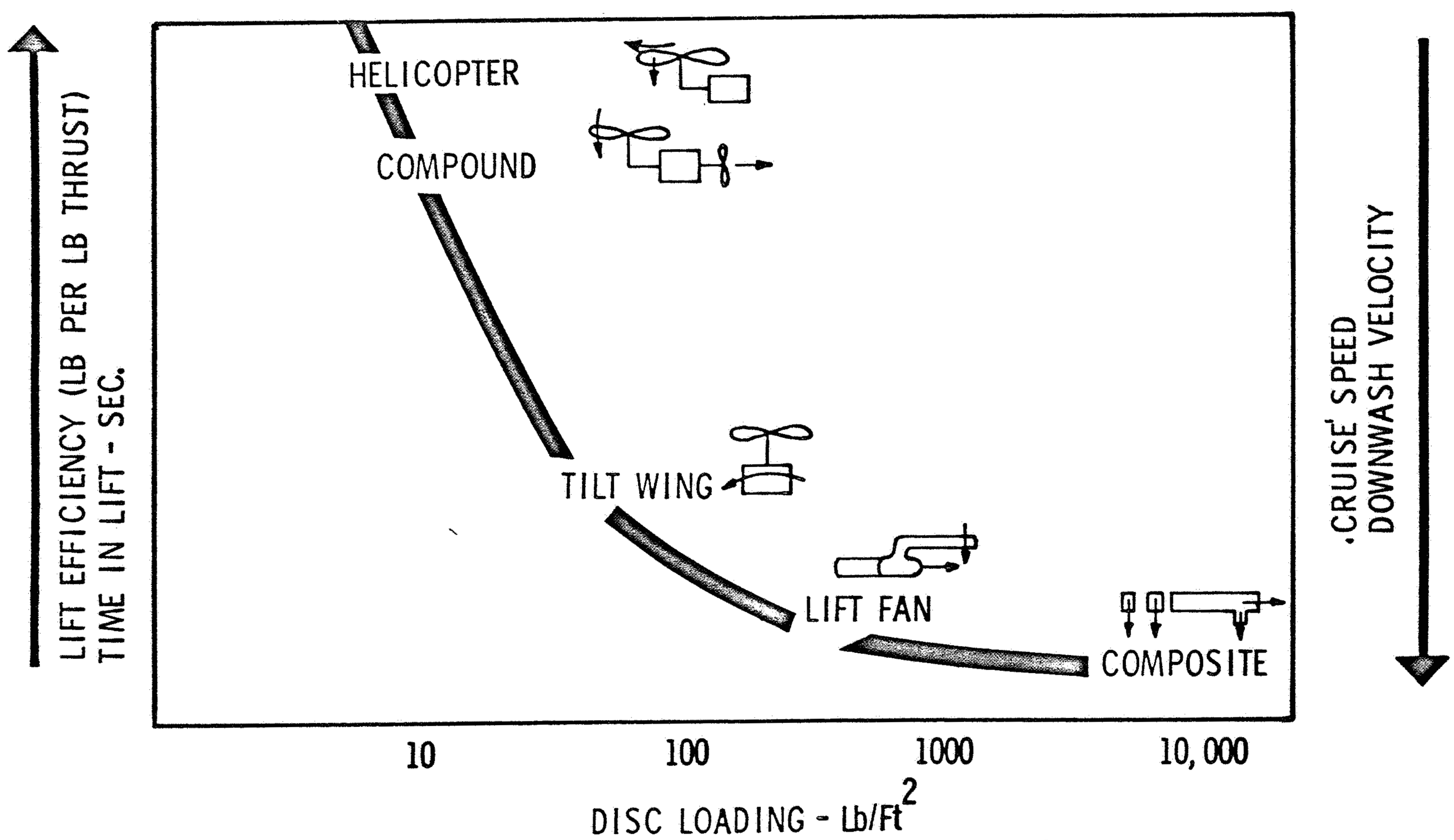

Figure 1.

COMPARISON OF TAKEOFF AND CRUISE THRUST

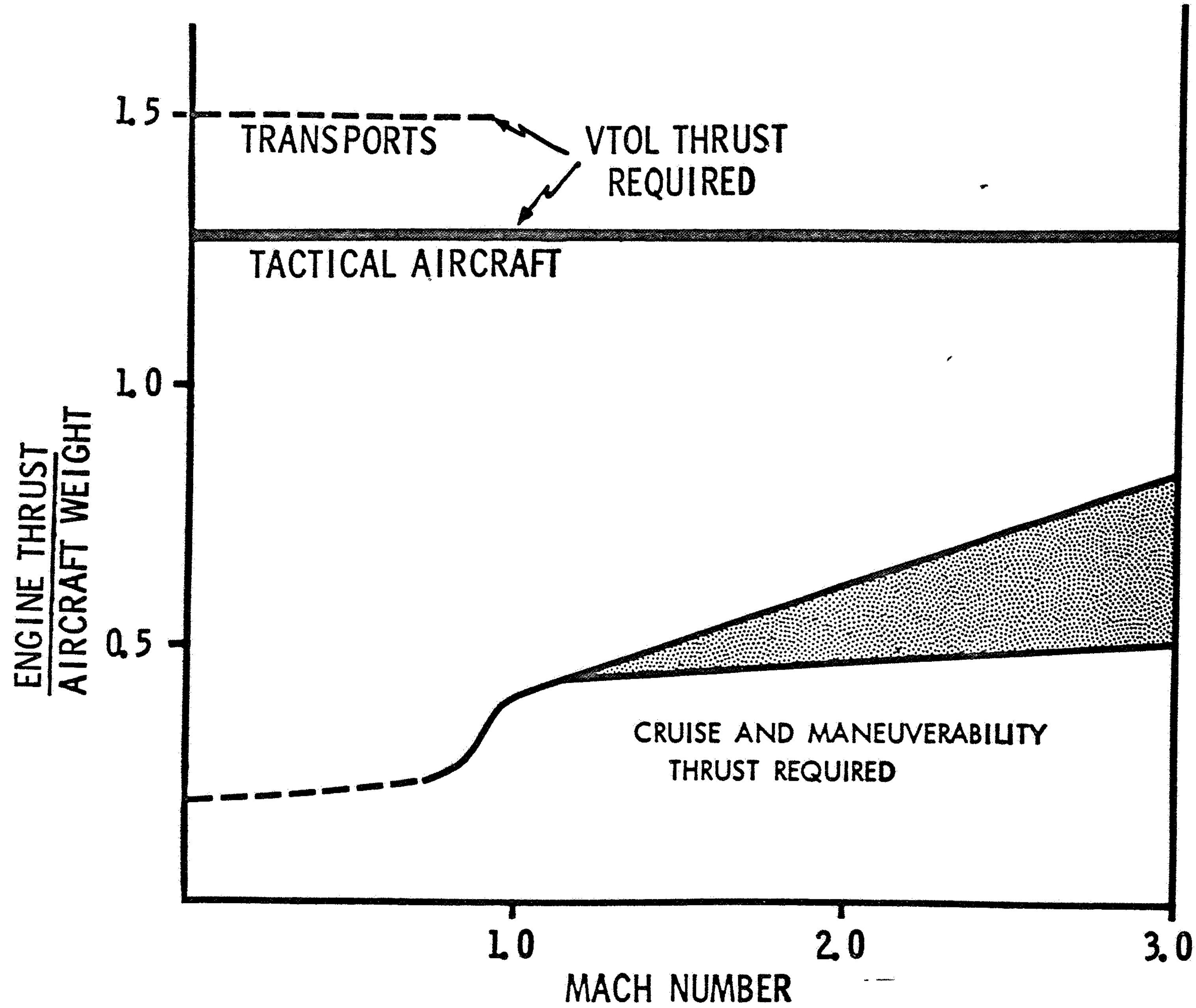

Figure 2.

RELATIVE MISSION PERFORMANCE OF VTOL AIRCRAFT
(Equal GW, 30,000 lb.)

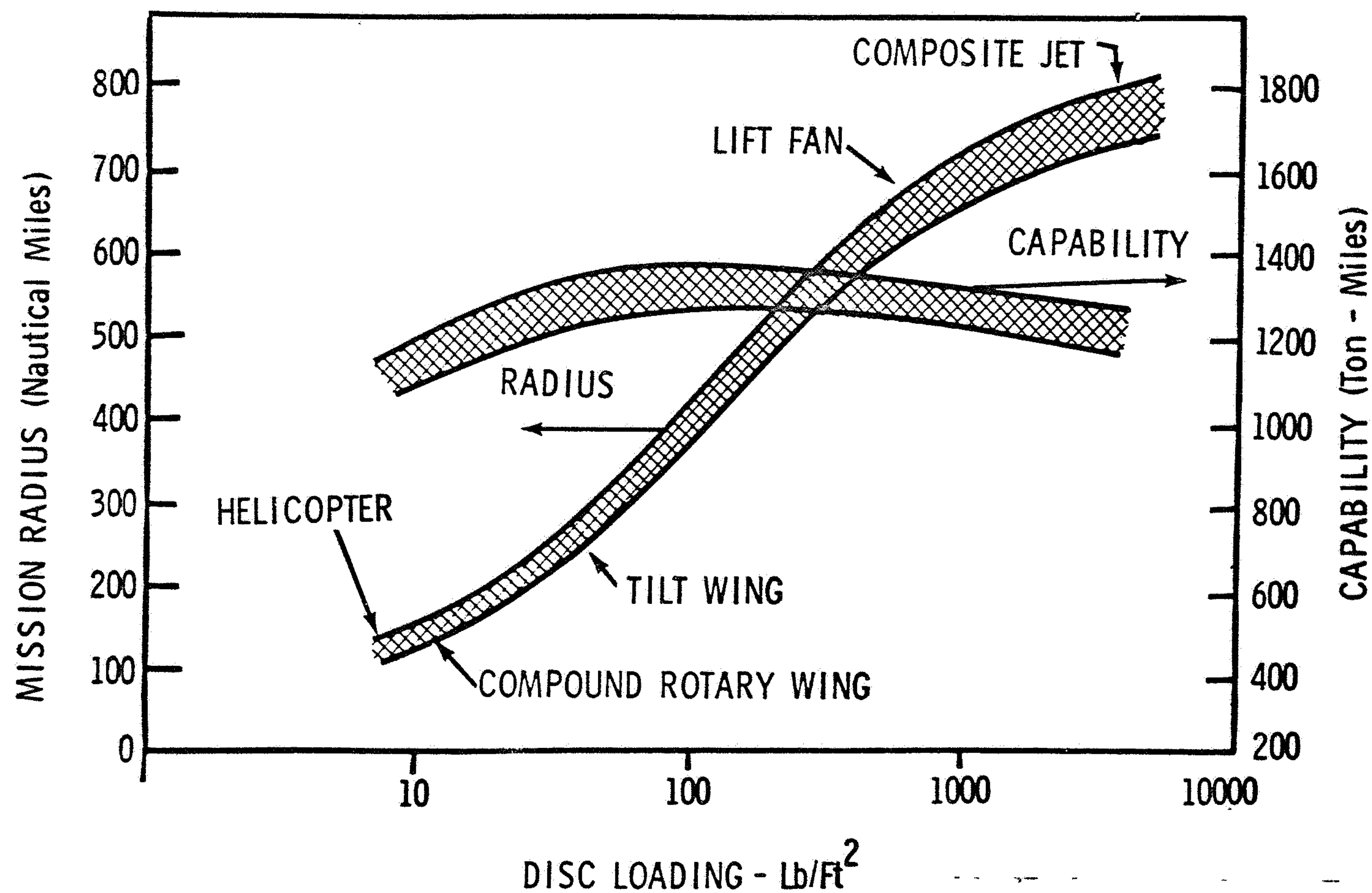

Figure 3

PERFORMANCE TREND FOR CRUISE TSFC

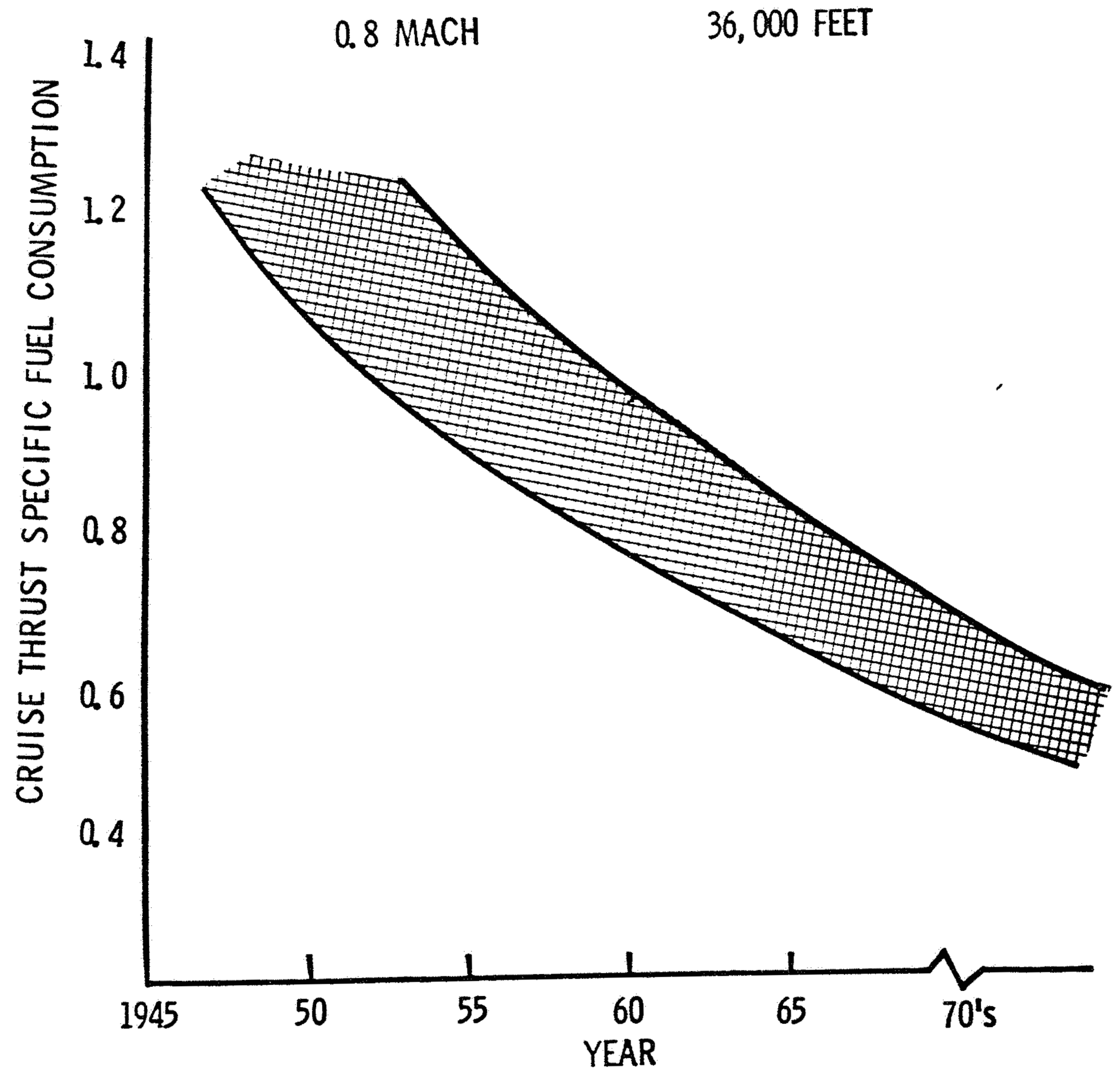

Figure 4

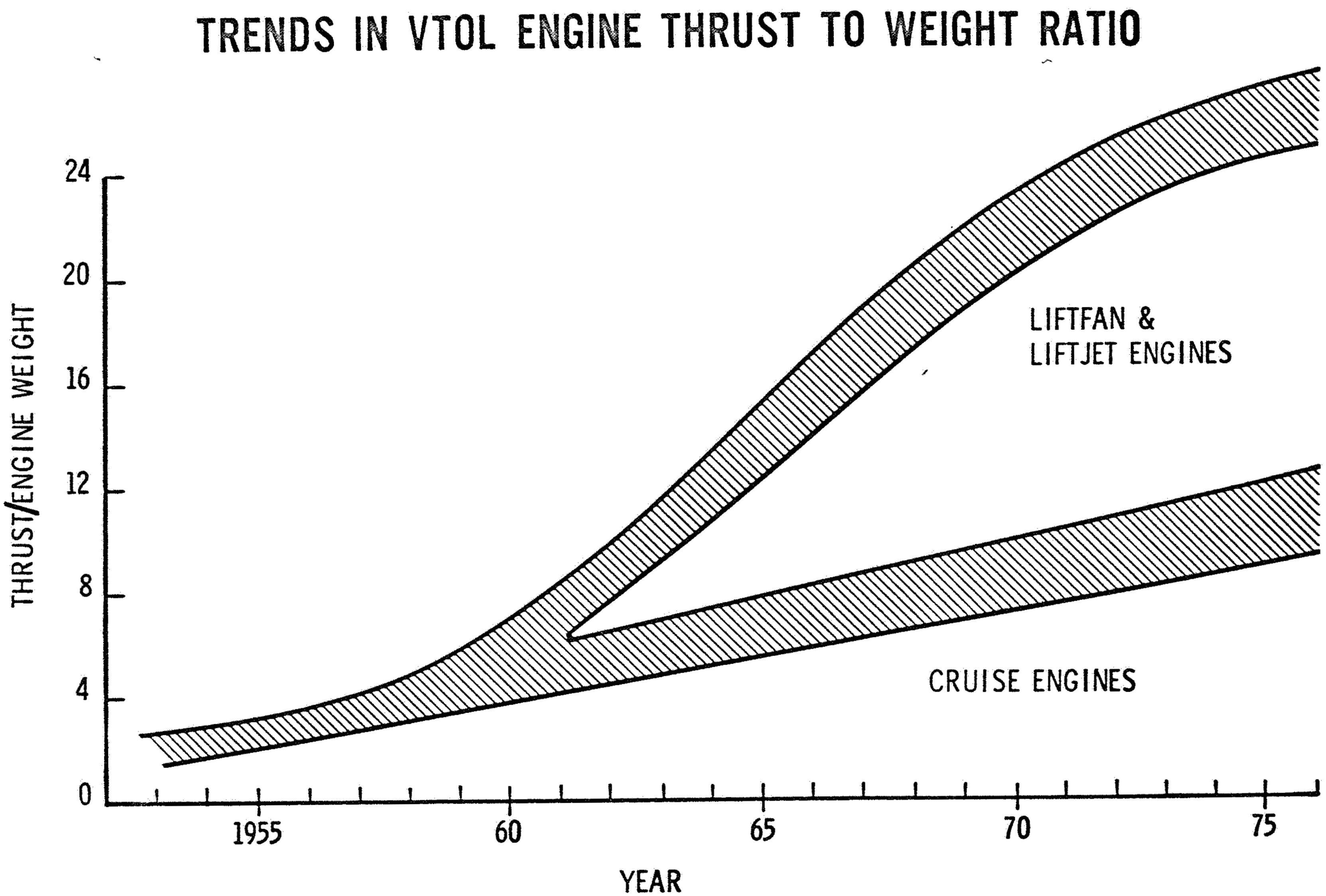
TRENDS IN VTOL ENGINE THRUST TO WEIGHT RATIO
THRUST/ENGINE WEIGHT
0
4
8
12
16
20
24
1955
60
65
70
75
YEAR
LIFTFAN &
LIFTJET ENGINES
CRUISE ENGINES

Figure 5

TRENDS IN VTOL ENGINE THRUST TO VOLUME RATIO

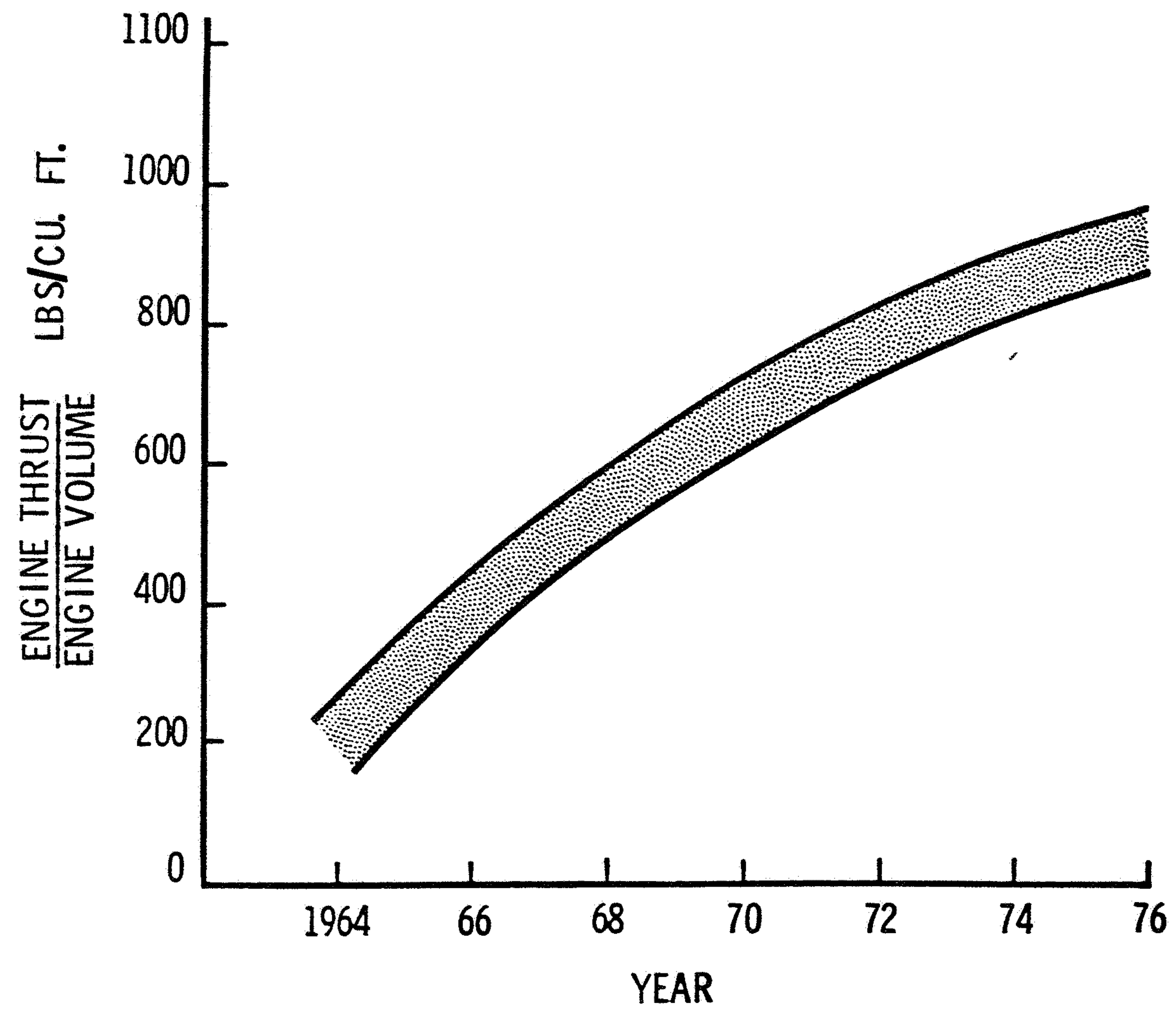

Figure 6

EFFECT OF INCREASING COMPRESSOR STAGE PRESSURE RATIO

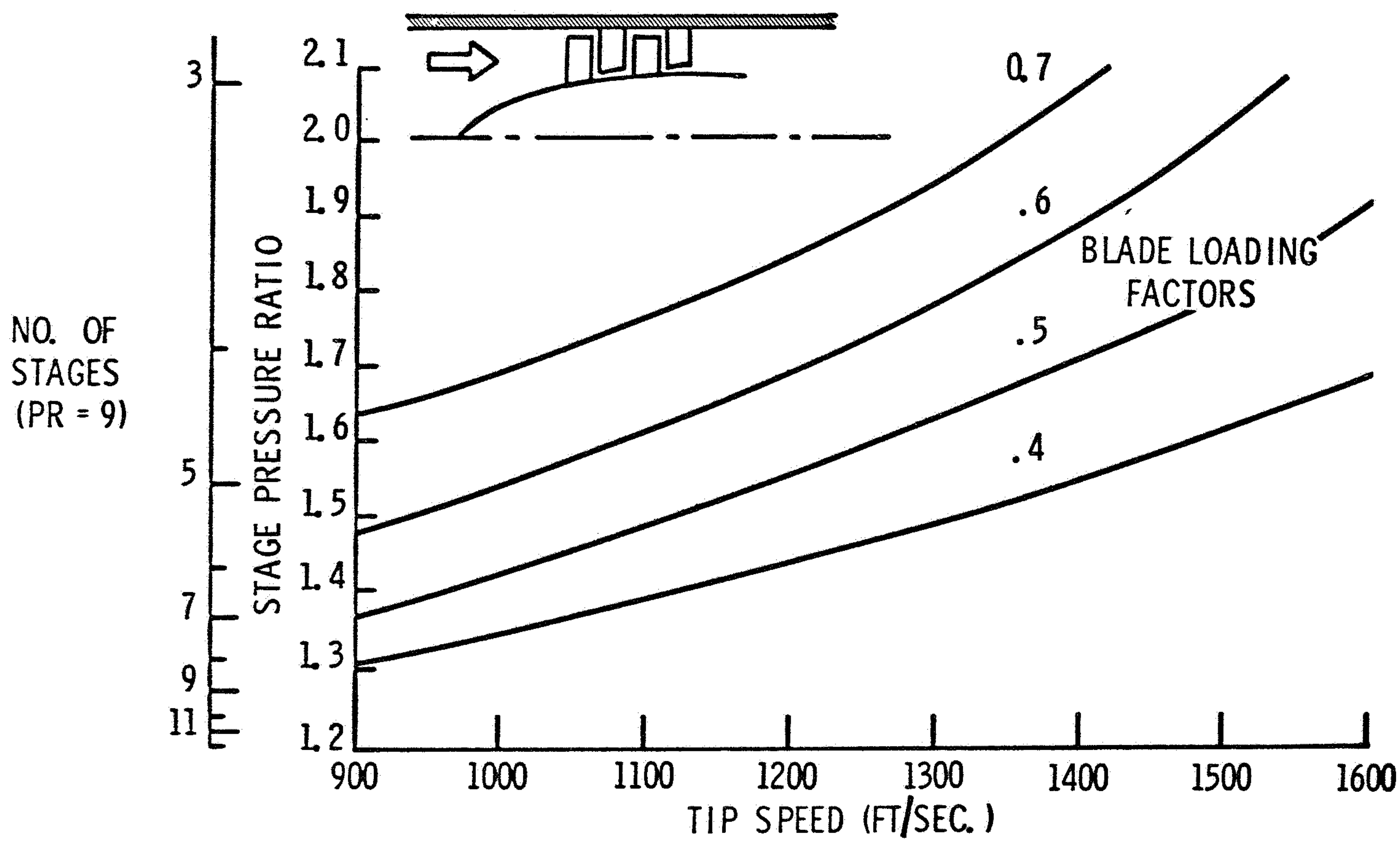

Figure 7

HISTORICAL TREND IN COMPRESSOR LOADING

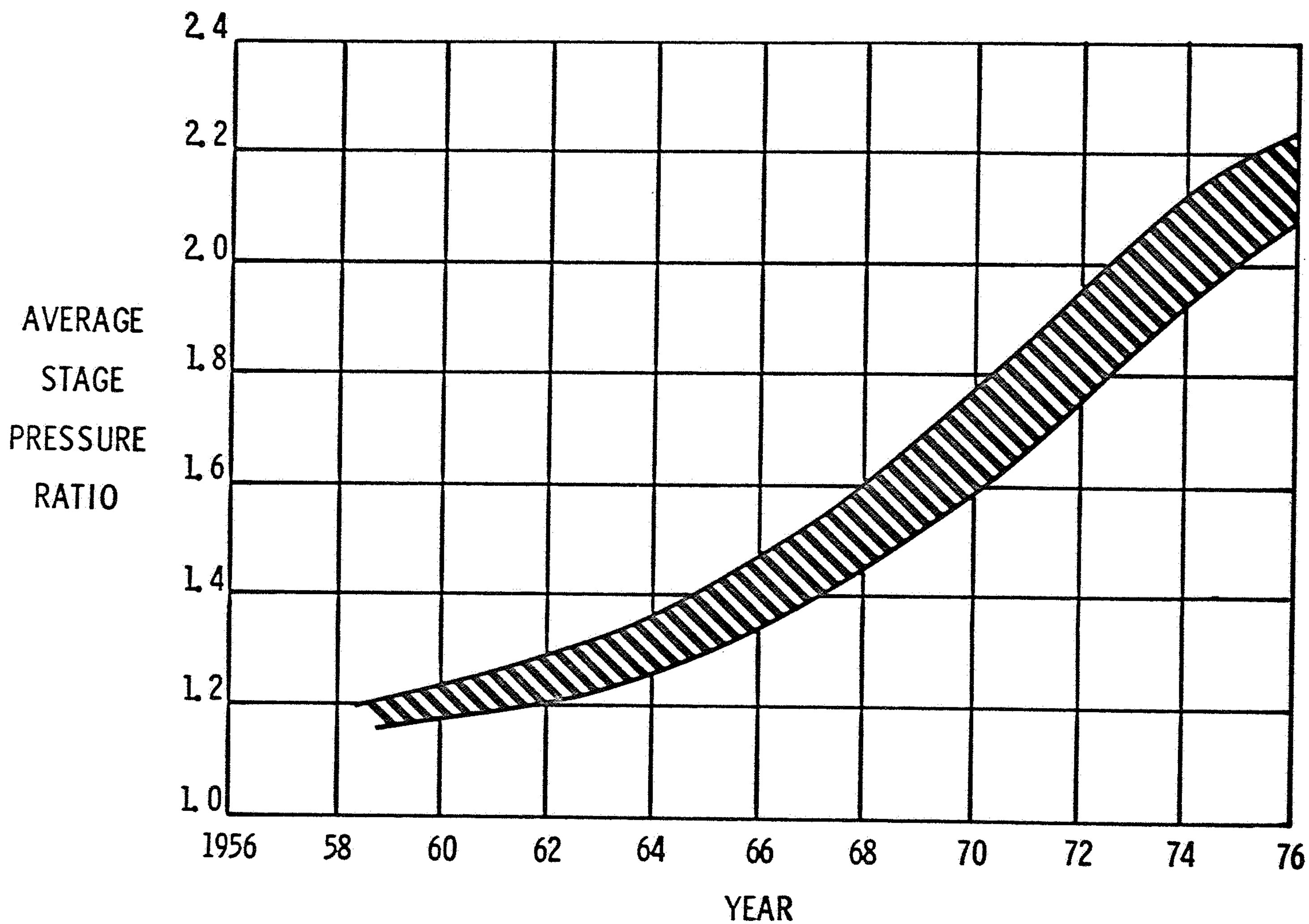

Figure 8

METHODS FOR INCREASING COMPRESSOR BLADE LOADING

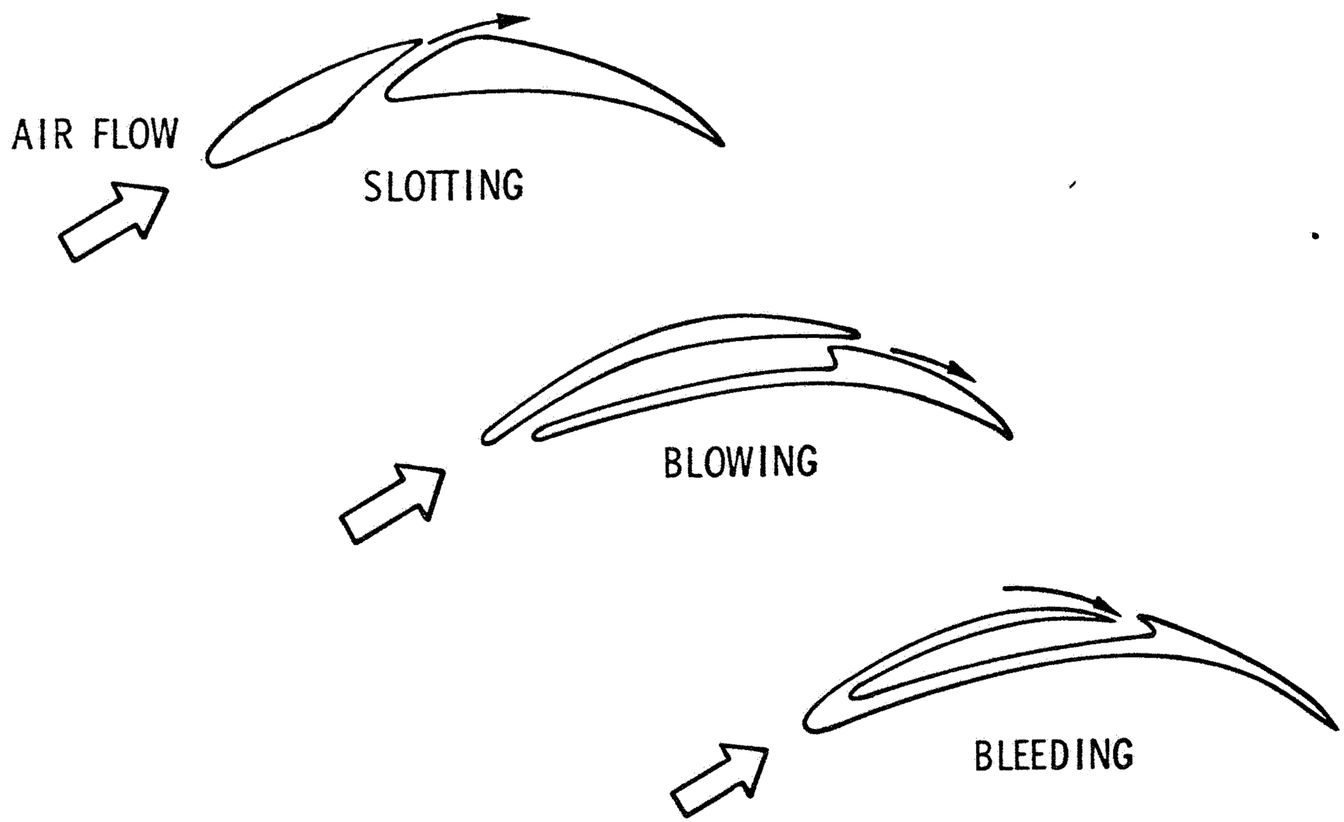

Figure 9

COMBUSTOR OBJECTIVES

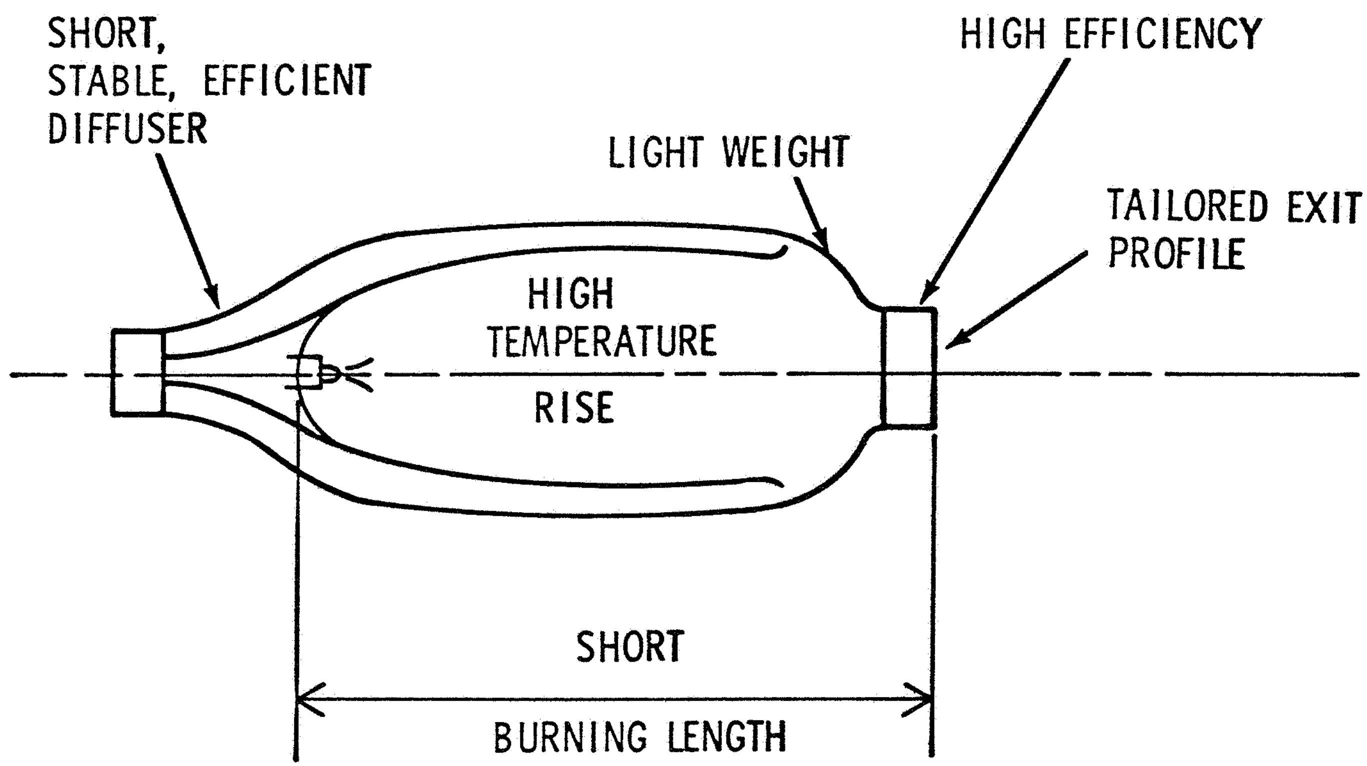

Figure 10

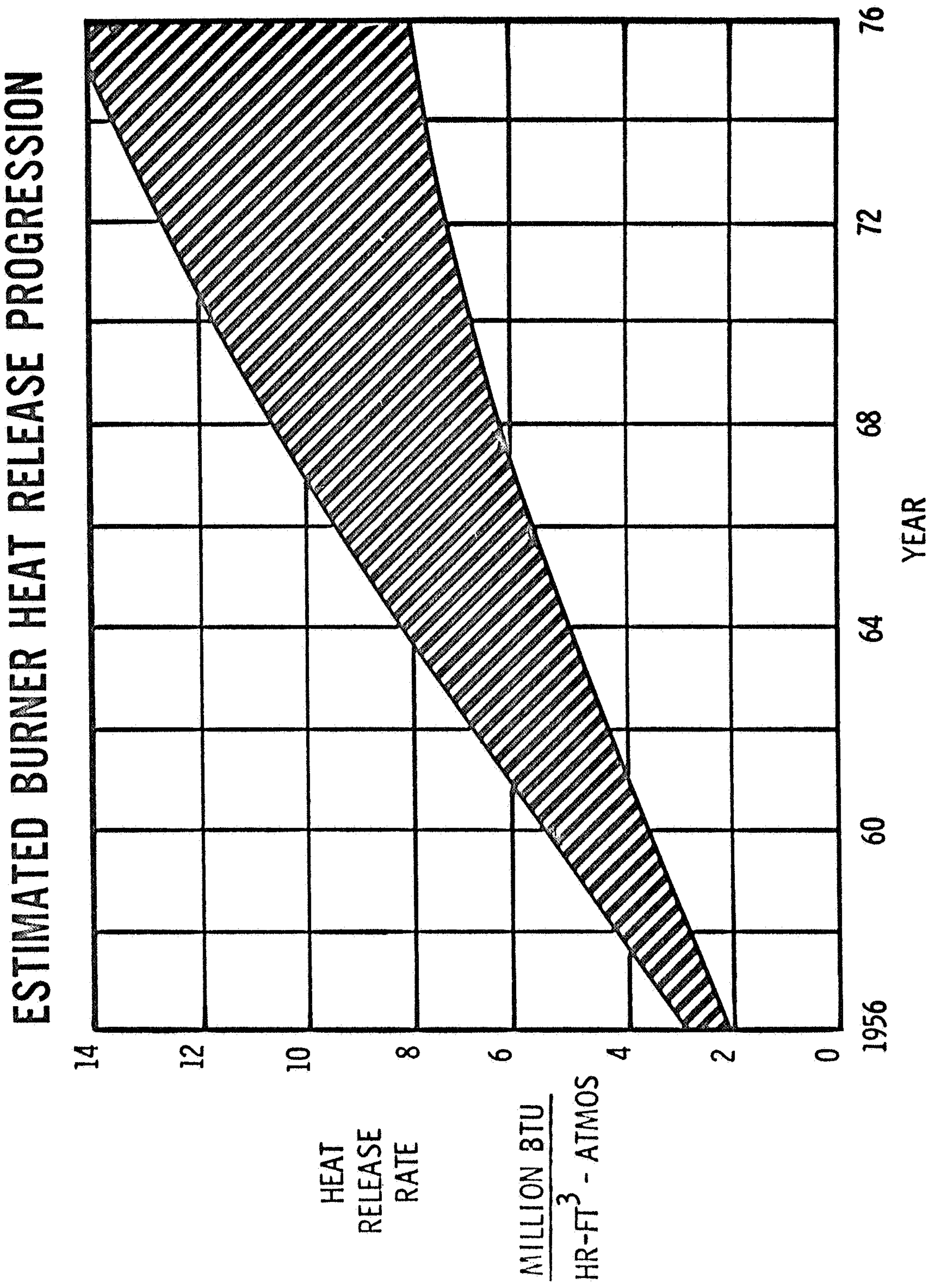
ESTIMATED BURNER HEAT RELEASE PROGRESSION
HEAT
RELEASE
RATE
MILLION BTU
HR-FT3 - ATMOS
14
12
10
8
6
4
2
0
1956
60
64
68
72
76
YEAR

Figure 11

DILUENT STATOR COMBUSTOR

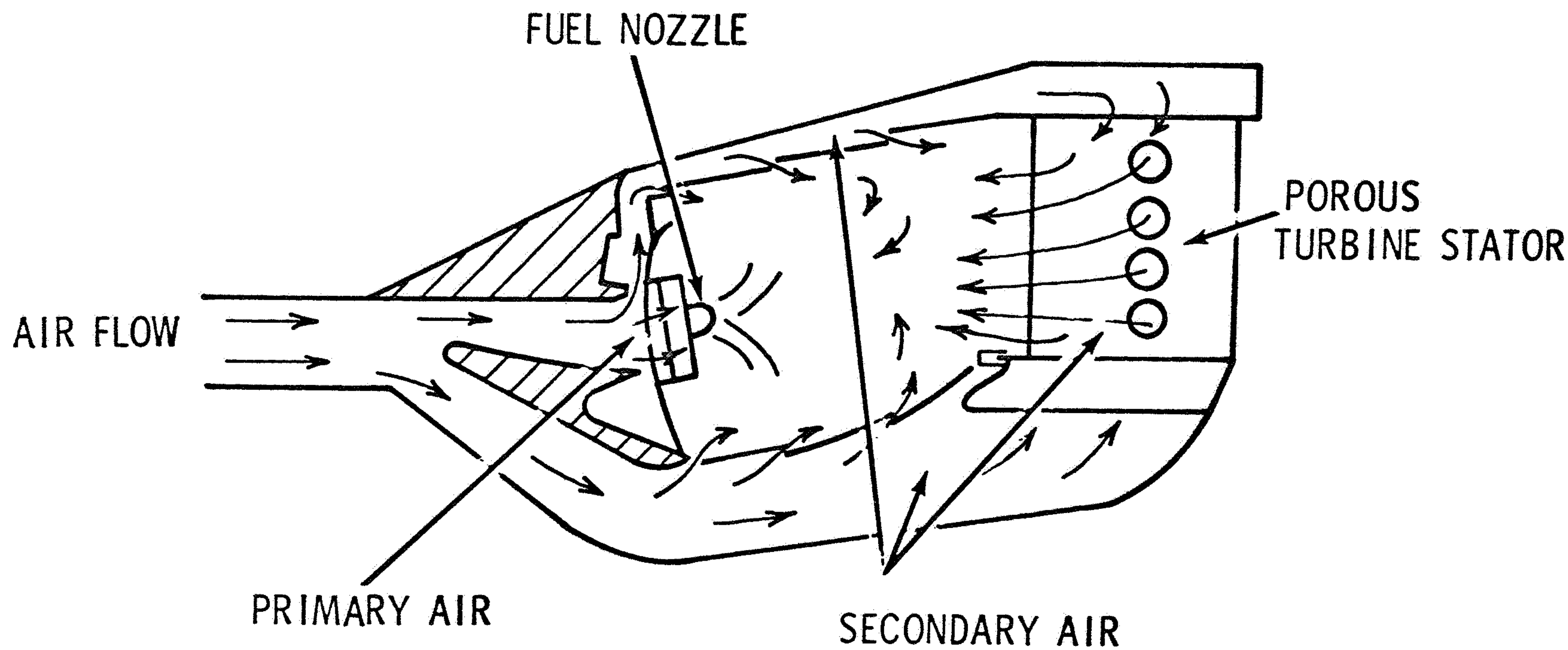

Figure 12

EFFECT OF TURBINE INLET TEMPERATURE ON THRUST PER POUND AIR FLOW

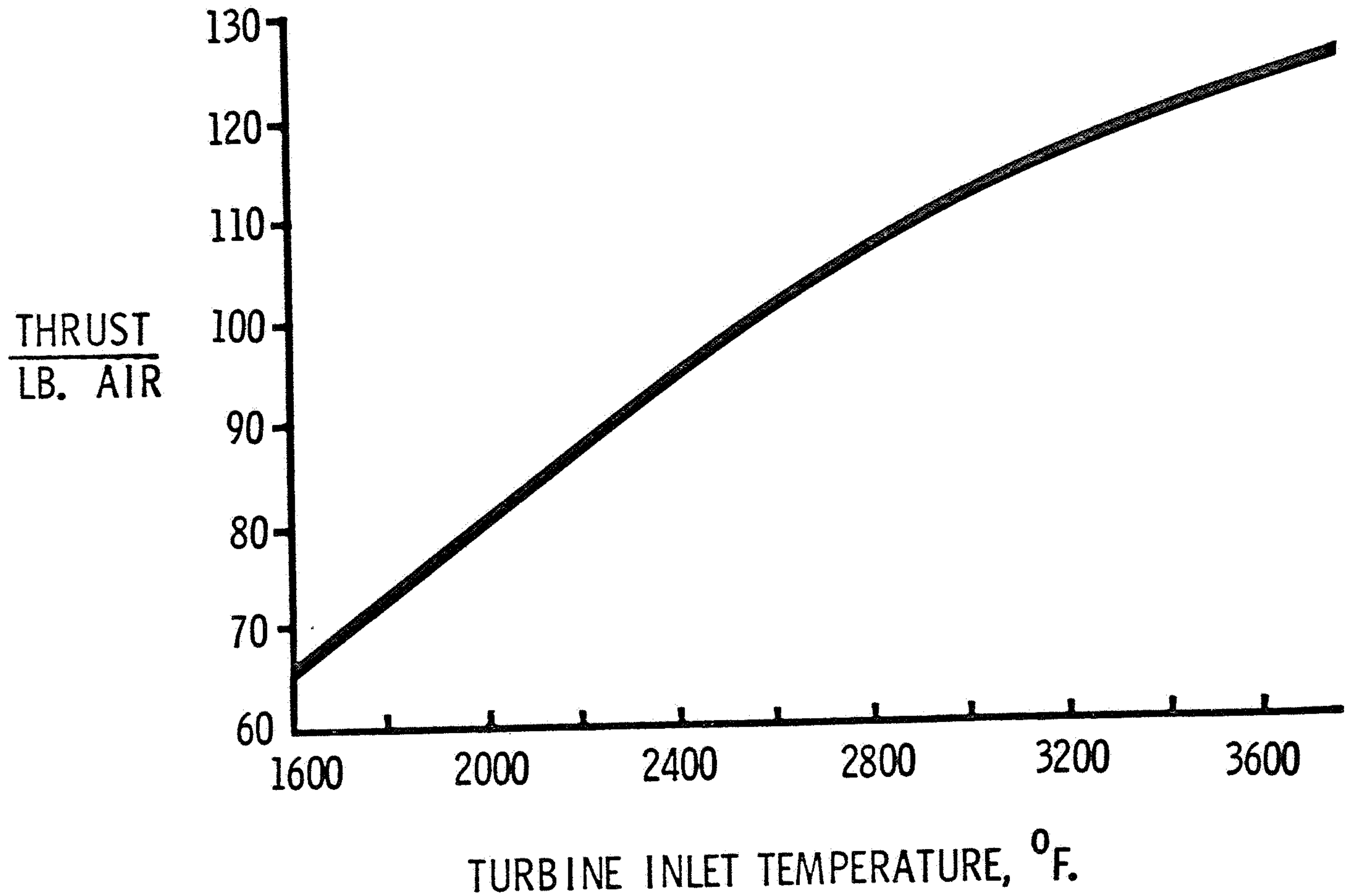

Figure 13

TURBINE INLET TEMPERATURE PROGRESSION ESTIMATE

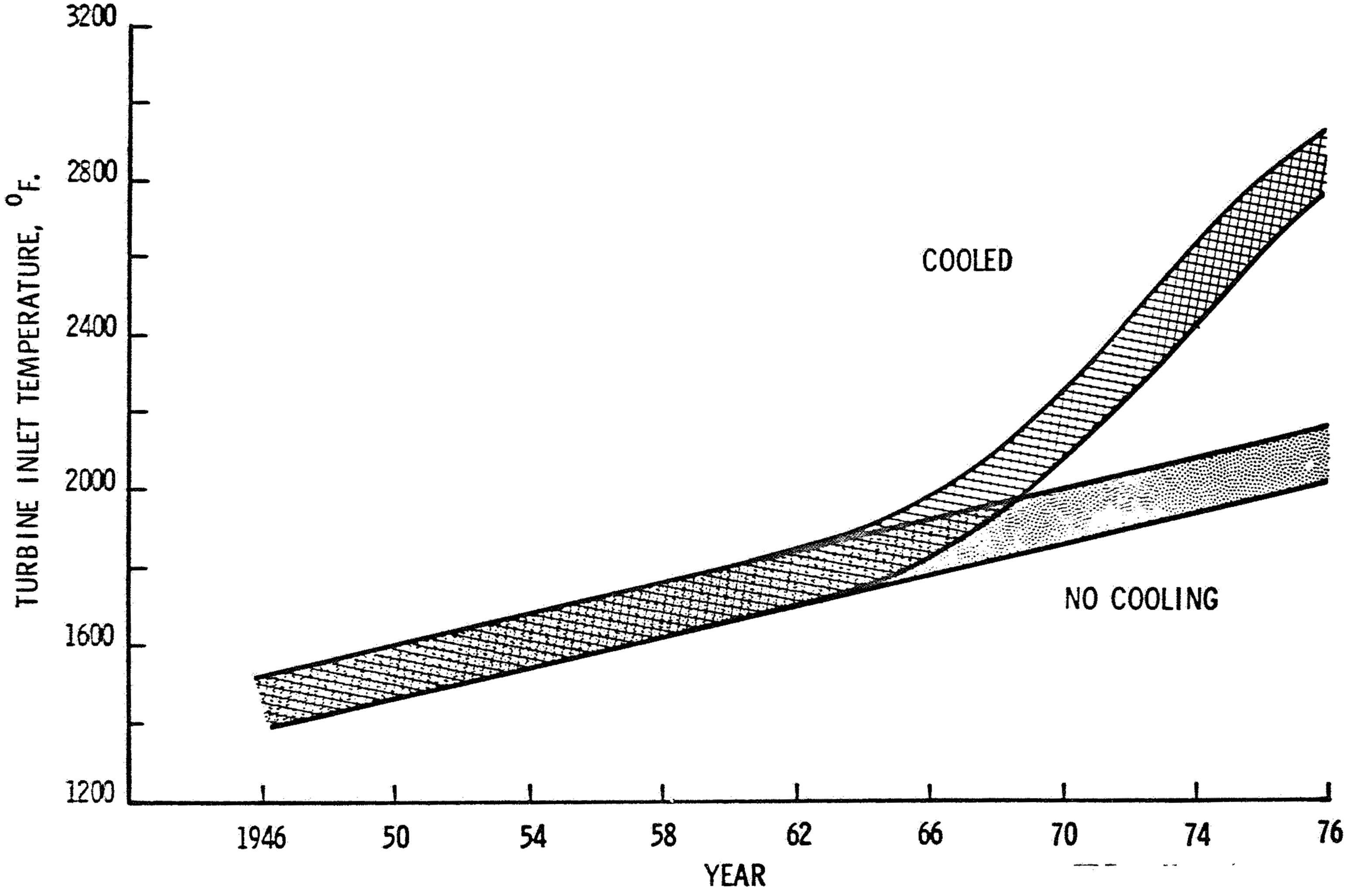

Figure 14

ESTIMATED ADVANCEMENT IN TURBINE BLADE MATERIALS

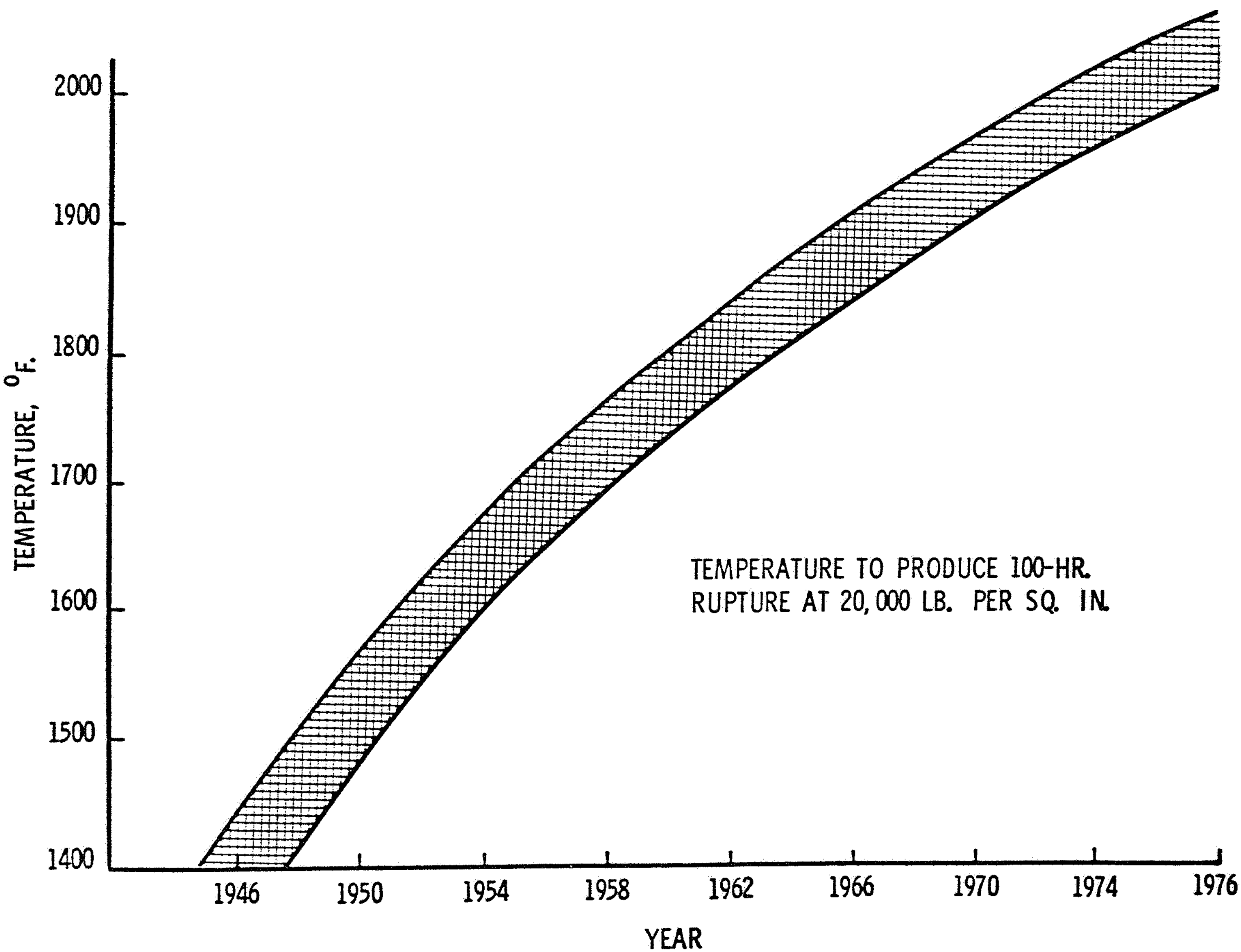

Figure 15

METHODS OF TURBINE BLADE COOLING

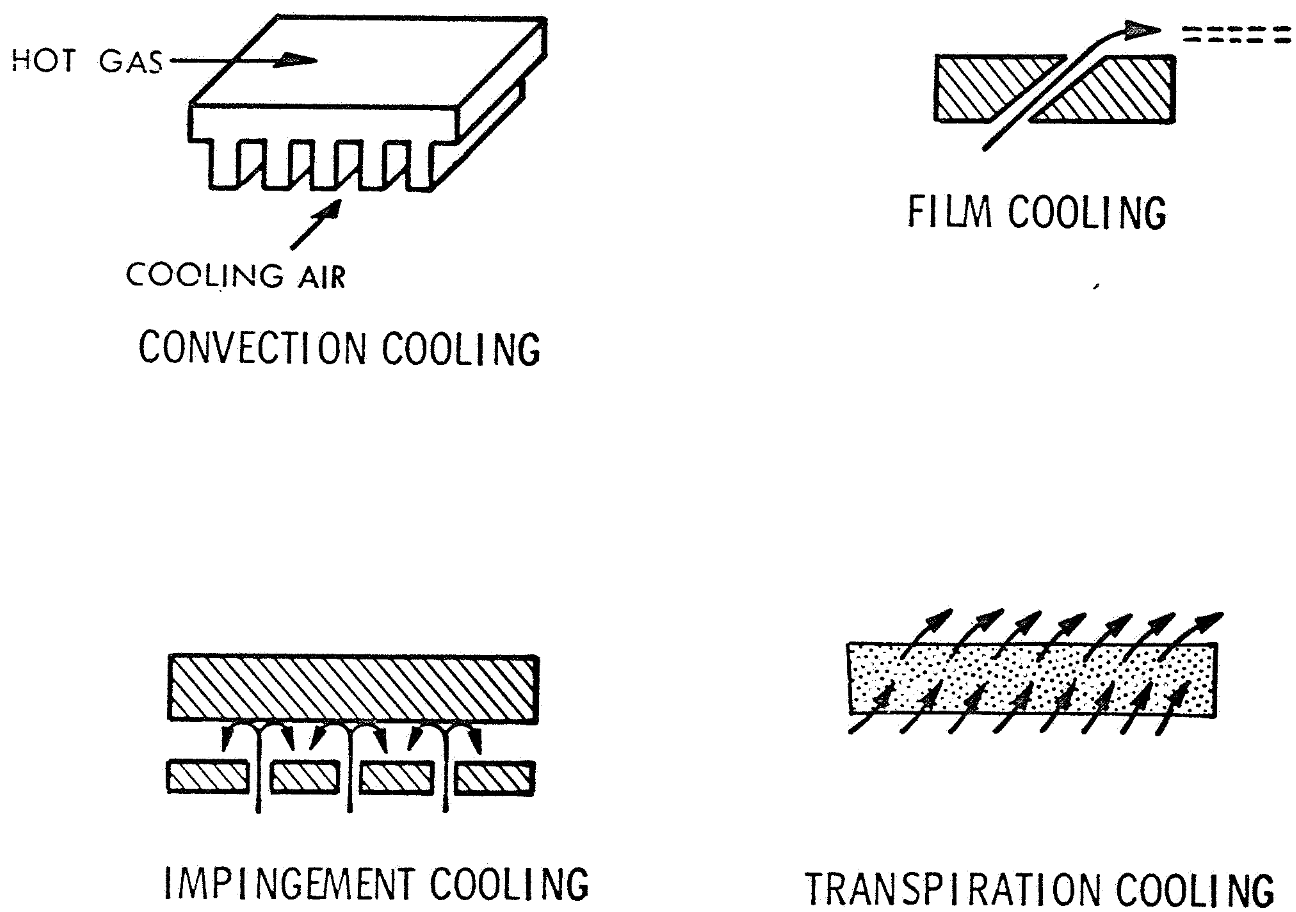

Figure 16

BLADE DESIGN DERIVED FROM ANALYSIS

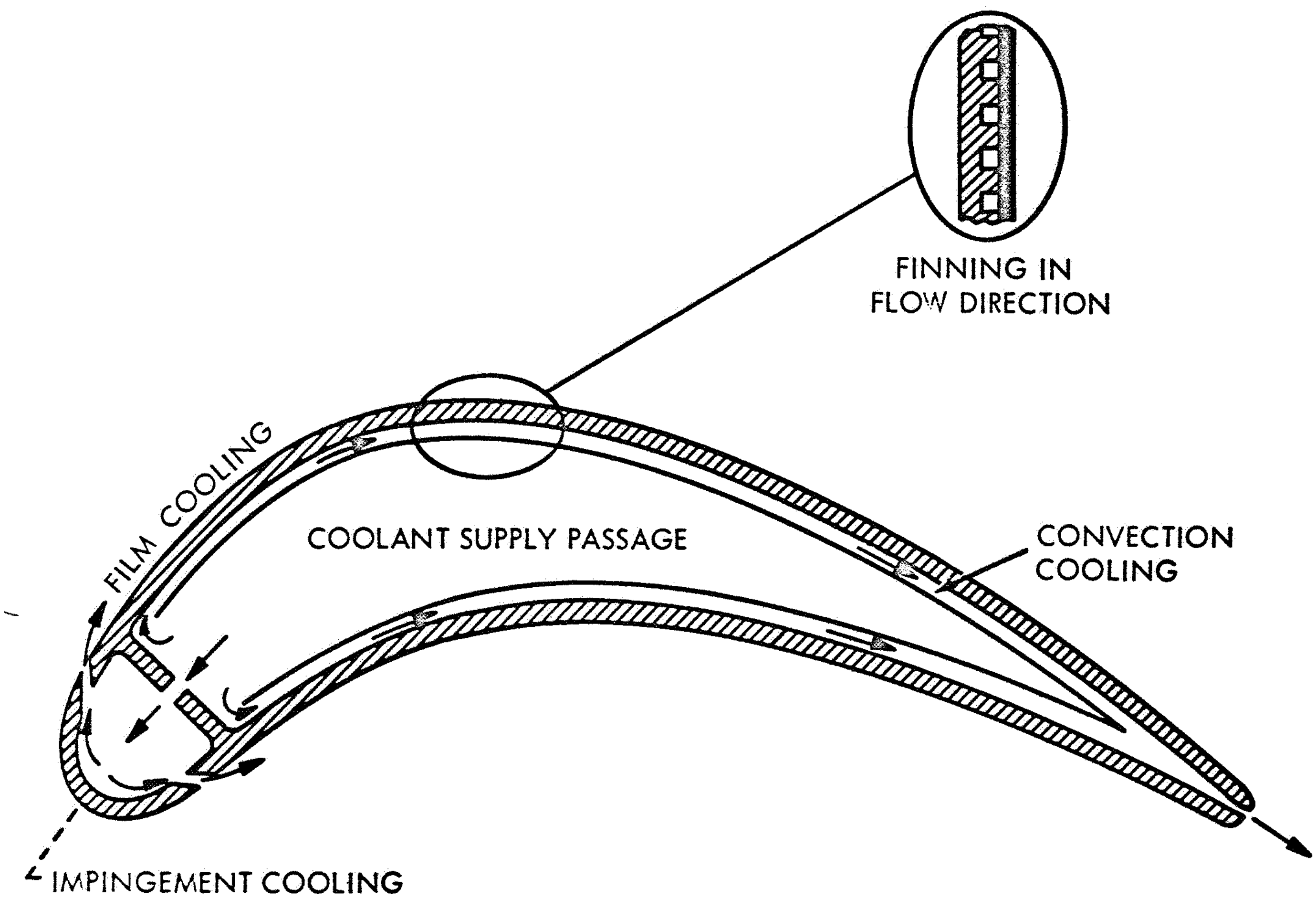

Figure 17

INSTANTANEOUS TURBINE BLADE MATERIAL TEMPERATURE DURING RAPID CYCLING

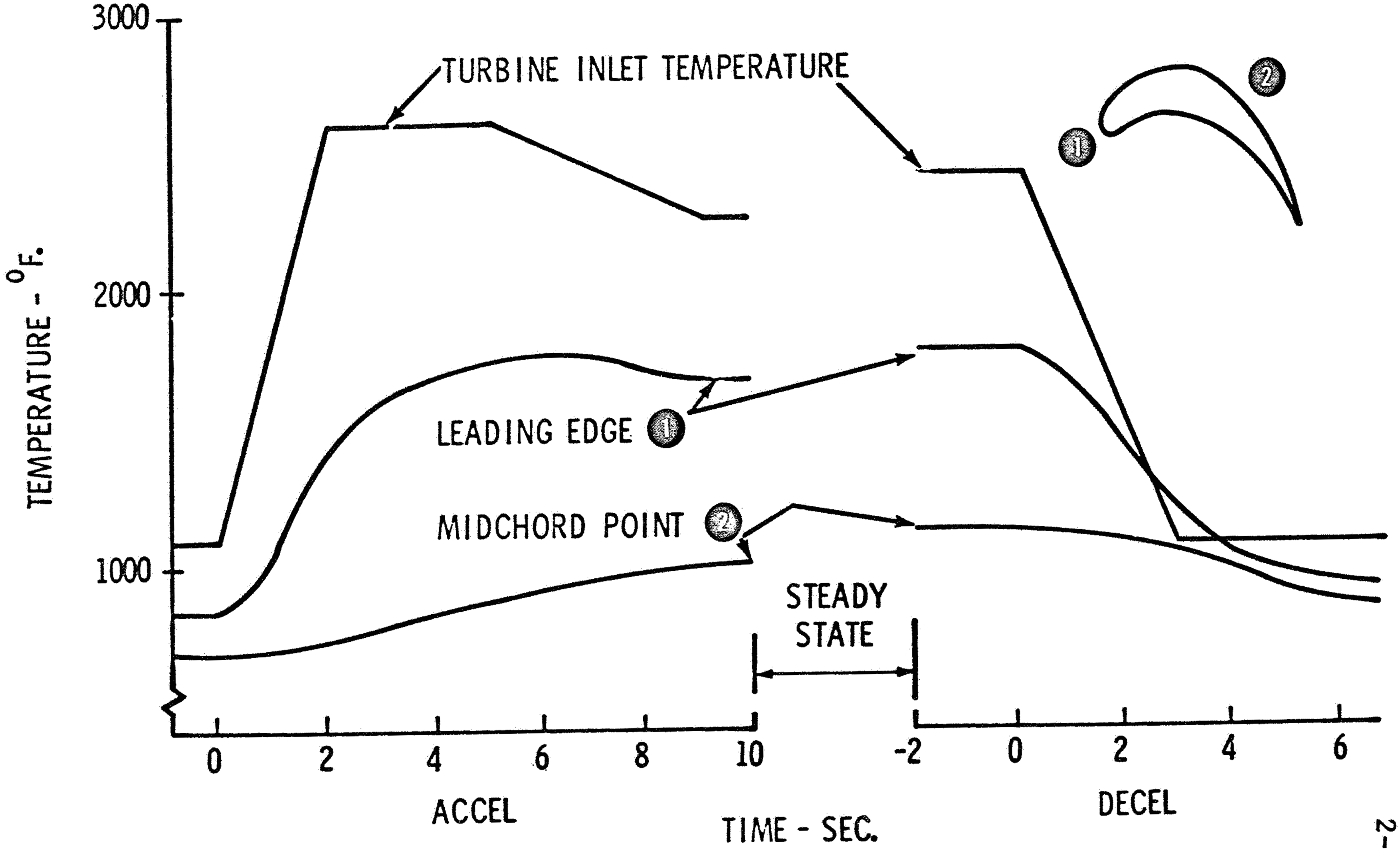

Figure 18

INLET FLOW DISTORTION ON LIFT FAN DURING TRANSITION

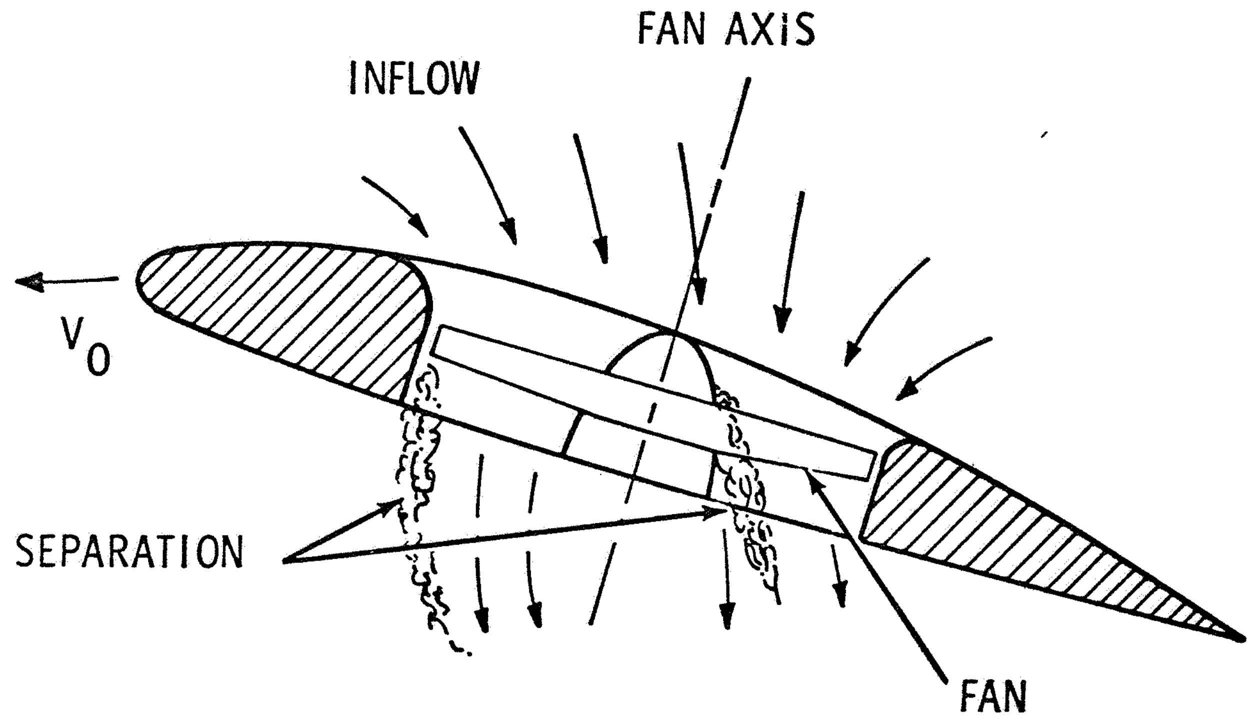

Figure 19

ESTIMATED NOISE LEVELS AT 400 FEET

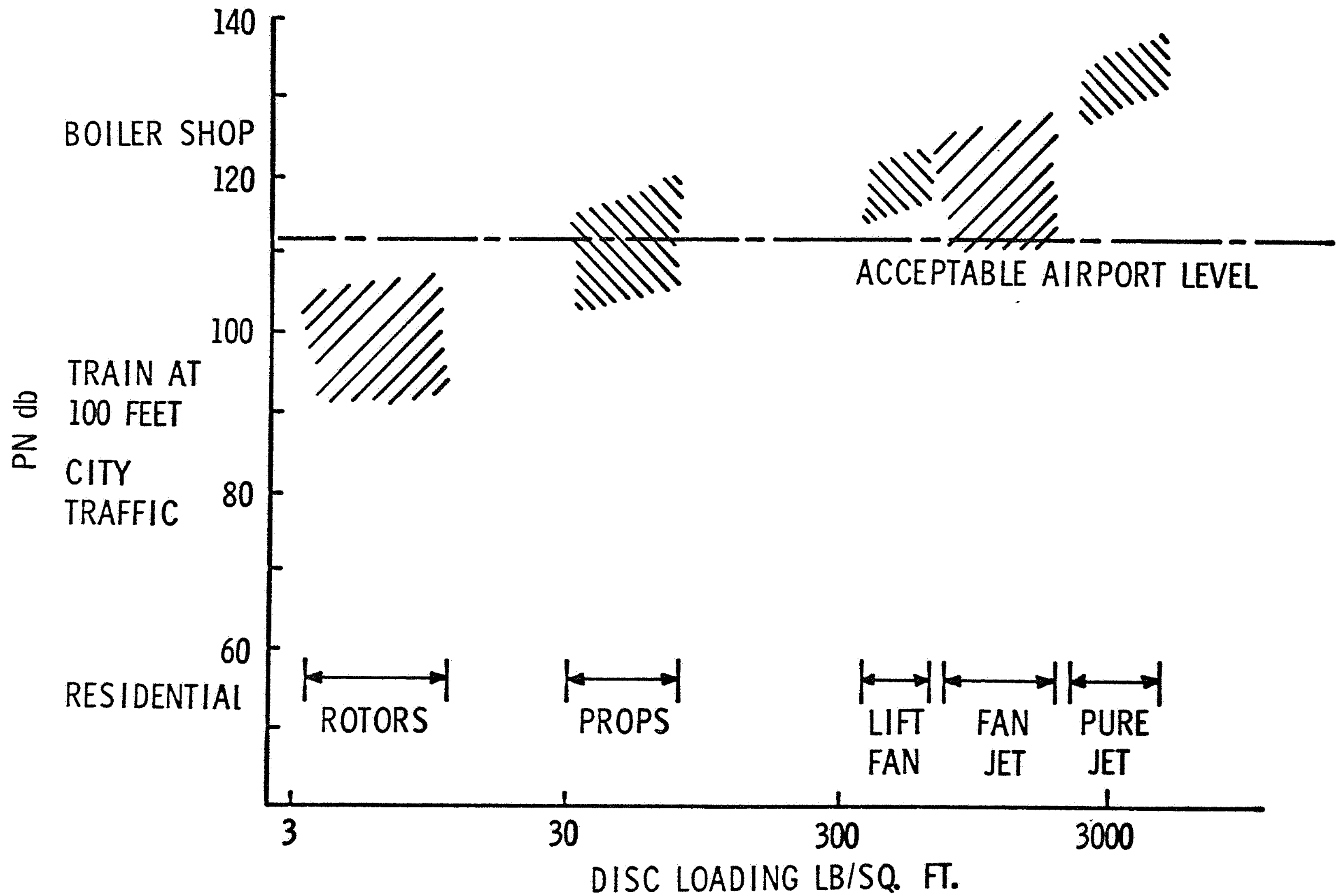

Figure 20