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A NASA Lewis Comparative Propulsion System Assessment for the High-Speed Civil Transport

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HSR Propulsion System Studies

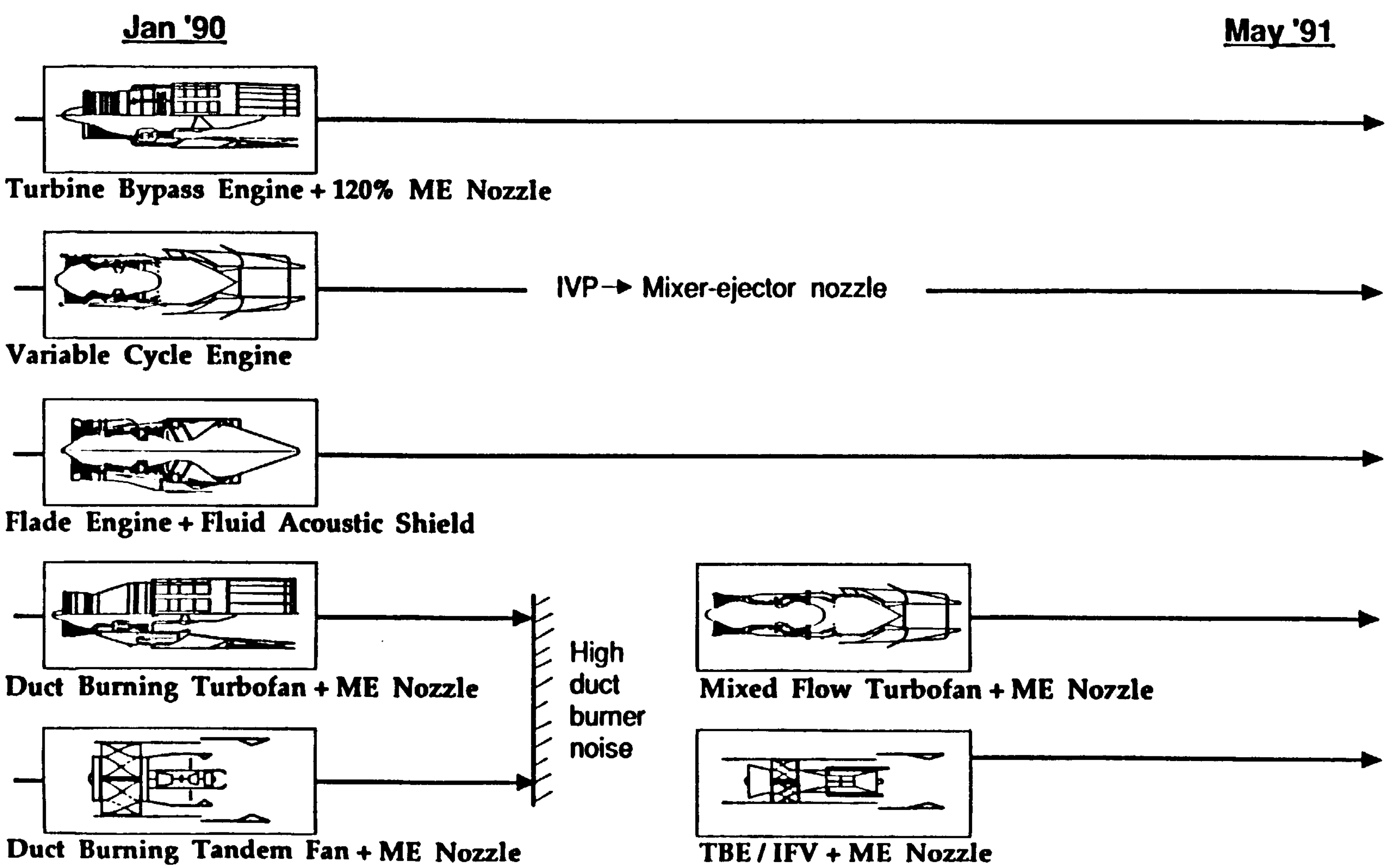
Concept Status

At the beginning of 1990, five engine concepts were under consideration for the HSCT propulsion system. The turbine bypass engine (TBE) was originated by Boeing during The Supersonic Cruise Research (SCR) studies of the 1970s. The variable cycle engine (VCE) with an inverted velocity profile (IVP) was General Electric's best engine during the same study. The IVP took the hot core stream and moved it to the outside and the fan flow was ducted to the center of the nozzle exhaust. This had been shown to give up to 6 dB noise suppression relative to a conic nozzle. The Flade engine is a VCE with an additional bypass stream added for use during takeoff. The variable stream control engine (VSCE) was Pratt & Whitney's best candidate engine during SCR. It used a duct burner to generate the IVP exhaust. The tandem fan approach was a means of greatly increasing airflow during takeoff to reduce the jet velocity and hence the noise.

The TBE concept with a suppressor nozzle (mixer-ejector (M-E)) is still attractive. The IVP nozzle on the VCE was attractive during SCR which had a noise goal of FAR36 Stage 2. The IVP alone, however, could not reduce the noise level to Stage 3, which is about 6 dB quieter. Therefore, it became necessary to also add a suppressor type nozzle which destroyed the IVP. This resulted in eliminating the crossover ducts in the VCE and adding a mixer-ejector nozzle for the current concept. The VSCE was dropped from consideration due to high duct burner noise and the inability for the IVP to meet Stage 3 requirements. The mixed flow turbofan with the M-E nozzle was added because of its inherently low exhaust velocity. The Flade engine also has low jet velocities and requires much less suppression in the nozzle. The tandem fan was only studied at Mach 3.2 and used heavy materials in the valve because of the high temperature at this cruise speed, and still may require a M-E nozzle. It also had excessive noise due to a duct burner placed in the bypass stream. This combination together with the higher weight and added nacelle length made it unattractive. However, at the lower temperatures of M2.0 to M2.4, lighter materials can be used and a valved version of the TBE is now being studied both at P&W and I-H at LeRC.

HSR Propulsion System Studies

Propulsion Concept Status



HSR Propulsion System Studies

Candidate Propulsion Concepts: LeRC Assessment

The Turbine Bypass Engine is a turbojet engine where compressor discharge air is bypassed around the combustor and the turbine at maximum power. As the turbine inlet temperature is reduced, the amount of air bypassed is reduced to maintain constant corrected flow ($W\sqrt{T}/P$) through the turbine. This keeps the airflow through the engine high and reduces both spillage and boattail drag at part power. Of the four engines shown here it is the only one that does not necessarily require an afterburner.

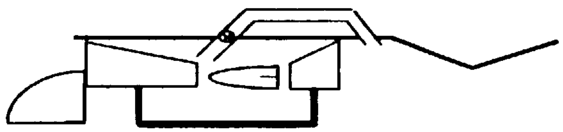
The mixed flow turbofan and variable cycle engine are very similar. The major difference is the addition of a valve in the front of the VCE which allows the bypass ratio to increase during takeoff. The Flade engine is a derivative of the VCE where an additional tip fan is added to the VCE front fan. This can be used to "high flow" the engine during takeoff to reduce the core velocity and lower the jet noise. In addition, this Flade flow can be collected and used to create a fluid acoustic shield on the bottom half of the engine. During supersonic cruise, the tip fan is unloaded by changing the angle of its inlet guide vanes.

Due to its recent inclusion in our studies, the tandem fan has not yet been investigated in great detail and is not presented in this analysis.

HSR Propulsion System Studies

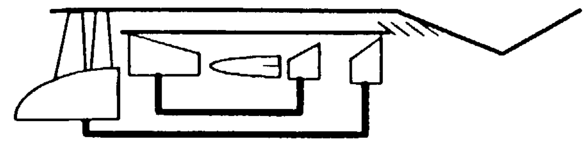
Candidate Propulsion Concepts: LeRC Assessment

Turbine bypass engine



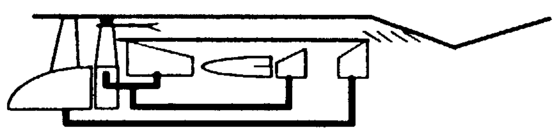
- Simple cycle
- Low cruise temperature

Mixed flow turbofan



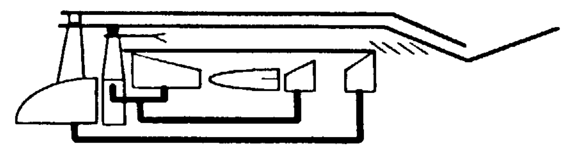
- Low jet velocity
- Good subsonic SFC

Variable cycle engine



- Variable bypass
- Good subsonic SFC

Flade engine



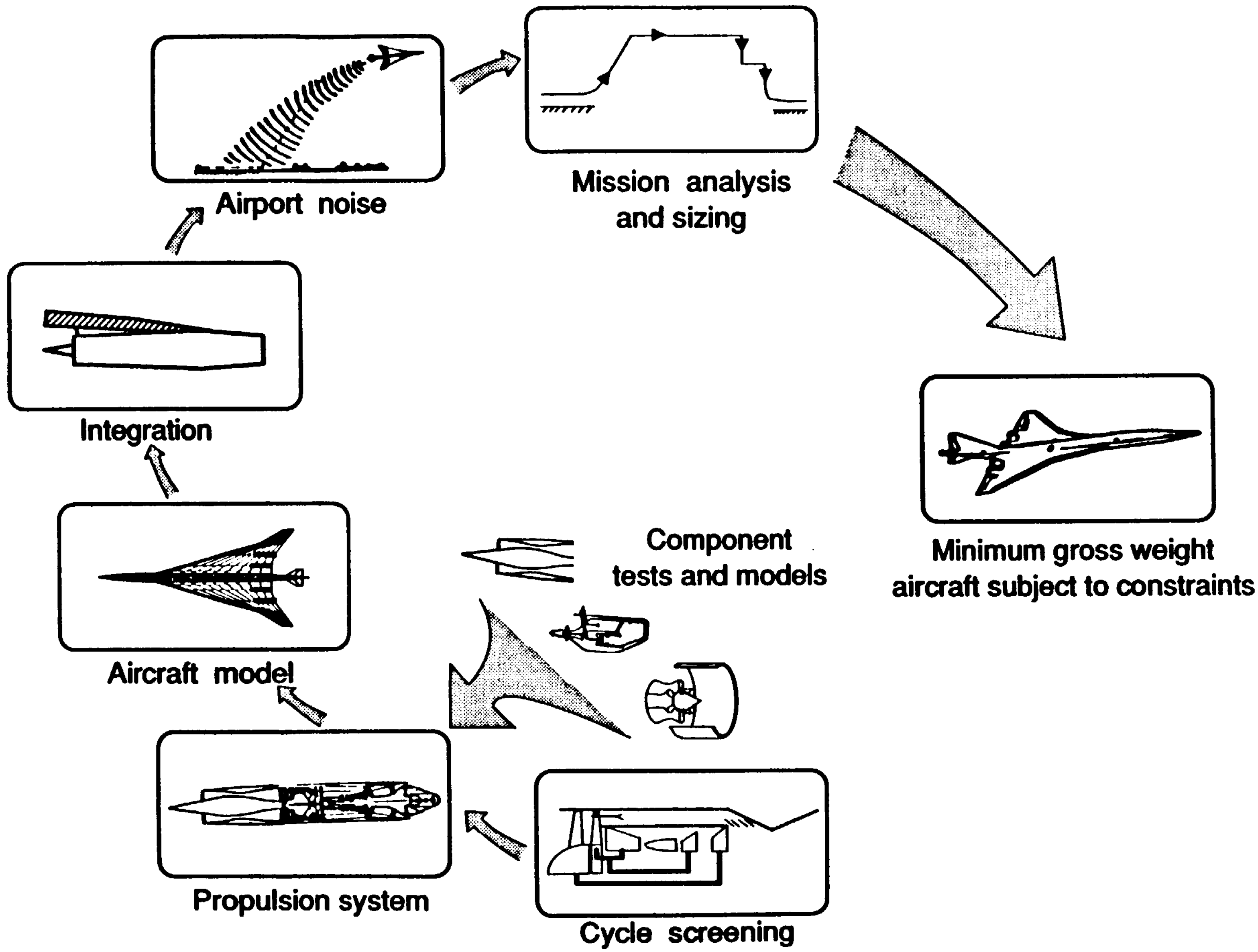
- Low jet noise
- Variable bypass
- Good subsonic SFC

HSR System Study Flowpath

A wide variety of engine cycle concepts of interest are modeled in the Navy/NASA Engine Program. The installation code uses component maps for the inlet and nozzle to generate installed (isolated nacelle) engine data. These data are supplied to a mission code along with an aircraft model (currently the Boeing Mach 2.4 model 1080-834). The propulsion system is installed on the wing (currently assuming no interference drag penalty based on results from other studies). The mission code is used to fly the aircraft over the mission and a noise code used to calculate the airport noise. A fuel balanced aircraft takeoff gross weight is then calculated which satisfies any constraints.

As better component data becomes available from tests and/or analytical studies by NASA and the contractors, the models in the computer codes are refined and the mission performance recalculated.

HSR System Study Flowpath



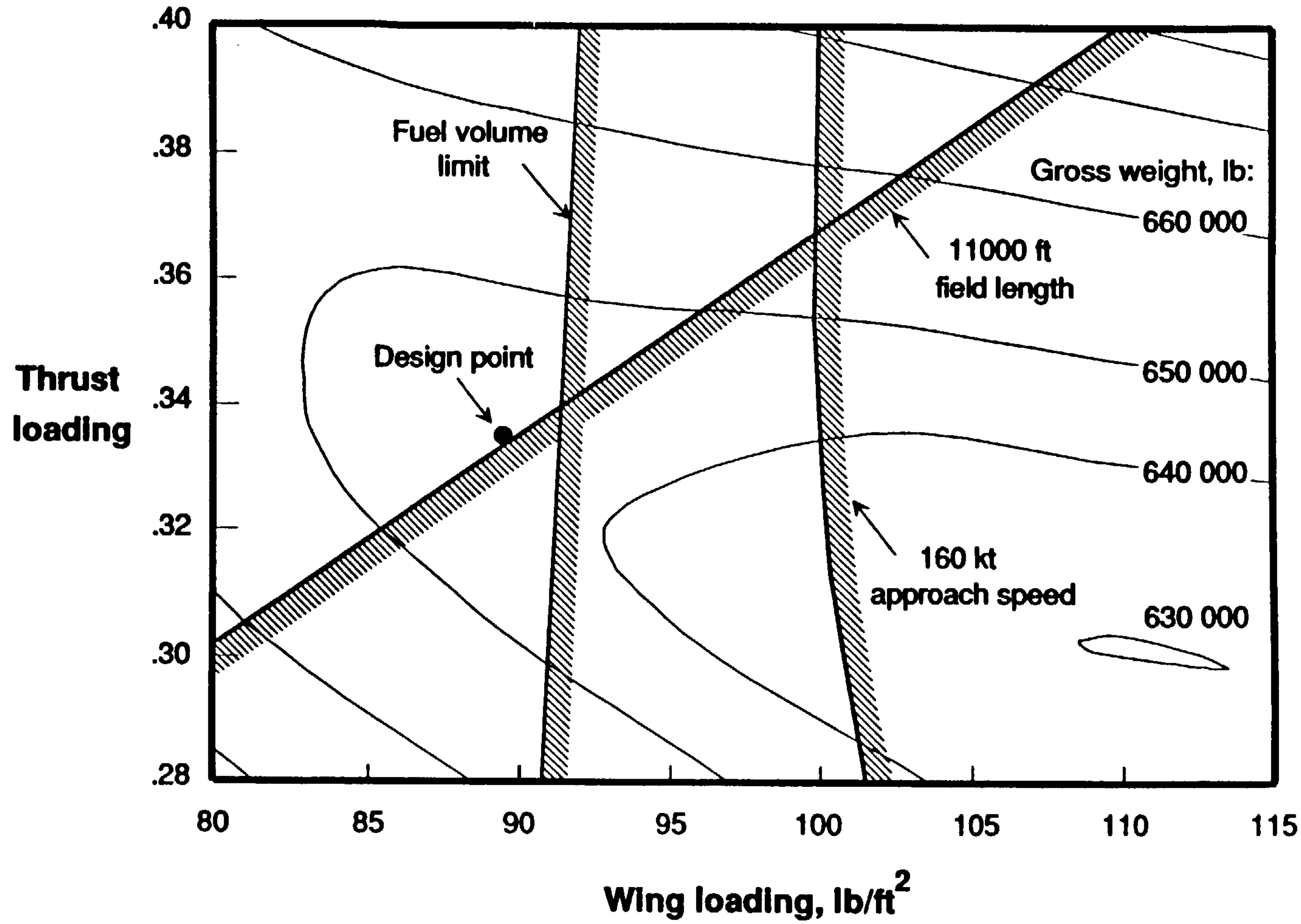
Design Point Aircraft Sizing - No Noise Constraint

Thumbprints of aircraft takeoff gross weight (TOGW) as a function of wing loading and thrust loading were generated. A low wing loading implies a larger wing and high thrust loading implies a larger engine. TOGW contours are shown on this thumbprint. Also shown are three of the constraints: the wing must be large enough to allow a 160 KT approach speed upper limit, the wing volume must be large enough to contain the mission fuel, and the wing must be large enough and the thrust high enough to takeoff in a field length less than 11,000 feet. The latter constraint is the only one that is active in constraining the gross weight on this figure.

Design Point Aircraft Sizing - No Noise Constraint

Mach 2.4 Cruise; 5000 n mi Range

Mixed Flow Turbofan



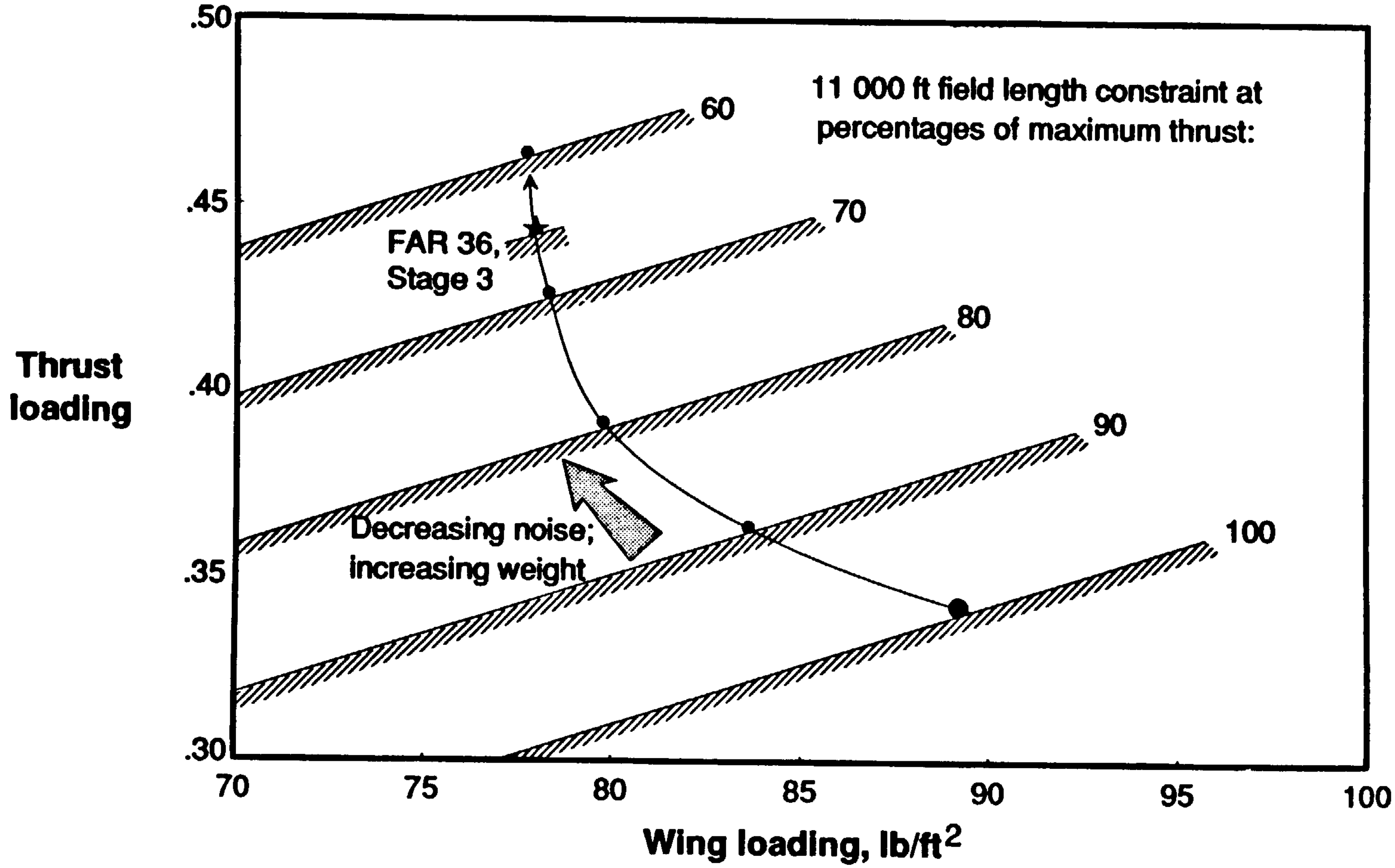
Impact of Noise Constraint

On the previous figure, all takeoffs were at 100% power. The field length constraint at this power is repeated here. The engines can be oversized (higher thrust loading) and then throttled back during takeoff to reduce the jet velocity, and hence, the noise. Larger degrees of oversizing results in lower noise but higher TOGW. Here it can be seen that at a 65% power takeoff, the FAR36 Stage 3 noise limit can be achieved.

Impact of Noise Constraint

Engine Oversizing With Part-Power Takeoff and Programmed Throttle

Mixed Flow Turbofan



Noise Impact on Aircraft Size

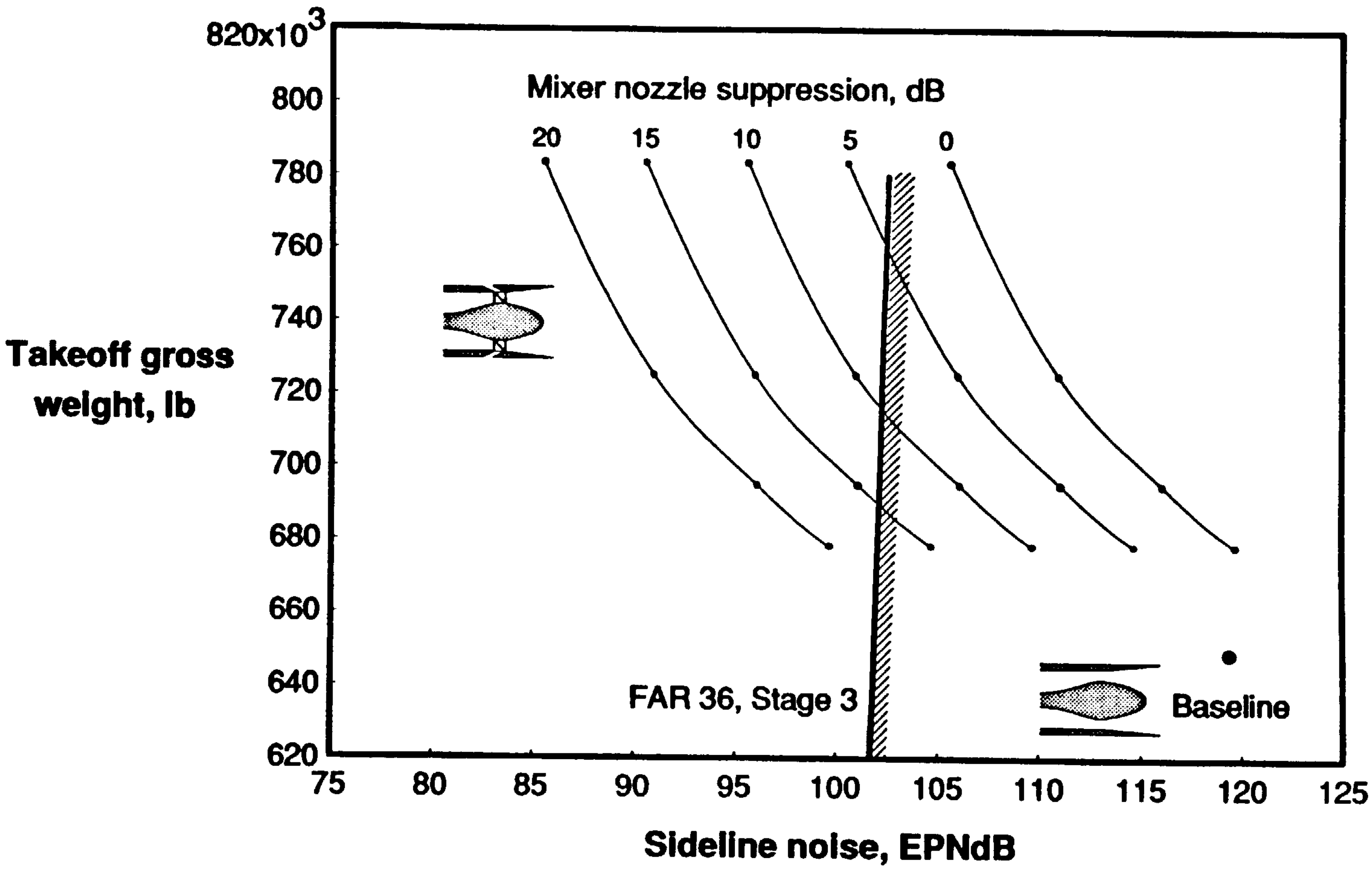
GE, P&W and Boeing are all investigating at mixer-ejector (M-E) nozzles for quieting the HSCT engines. If one calculates the fully-mixed jet velocity and corresponding jet noise for these nozzles using the Clark-Stone noise code, this resulting noise would be far below FAR36-Stage 3. Non-uniform mixing and mixing noise, however, has shown noise levels far above the ideal level in initial acoustic tests of these nozzles. Until a better database is available for developing noise models for the M-E nozzles, we are treating their performance parametrically.

The baseline point shown is the TOGW without a noise constraint. If the additional weight and thrust loss of a M-E nozzle is considered, the TOGW rises and the noise rises slightly. If it is assumed that no noise suppression is provided by the nozzle, then the TOGW increases as the noise level is reduced by oversizing the engine and taking off at part power as shown on the previous figure. This "0 dB" line is then translated to the left for 5, 10, 15, and 20 dB levels of assumed M-E nozzle noise suppression. Thus, if the suppression level is about 17 dB or more, no oversize is necessary. Anything less than this will require some amount of engine oversizing to meet the noise requirement.

Noise Impact on Aircraft Size

Clark-Stone Jet Noise Model

Mach 2.4 Turbine Bypass Engine



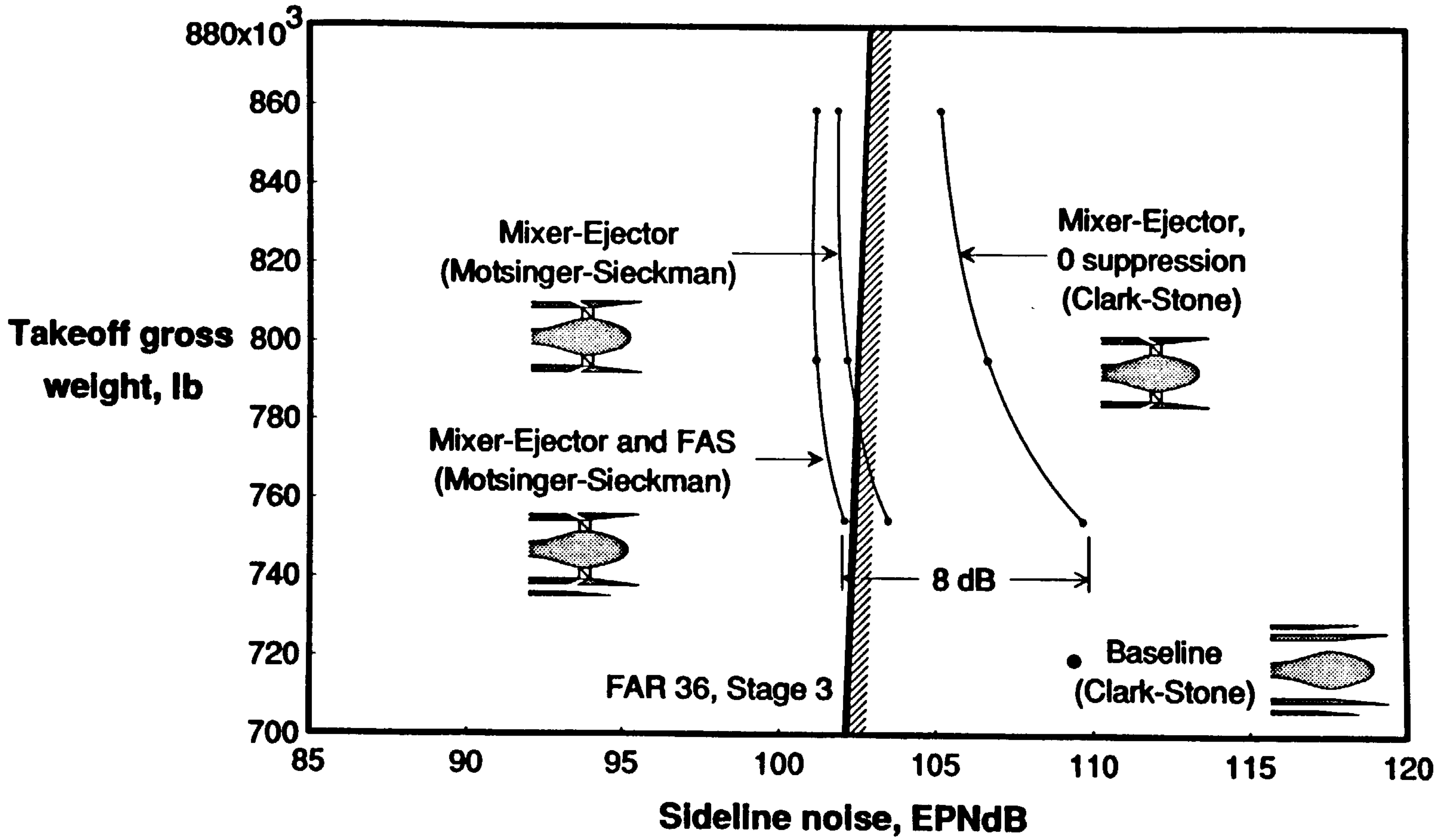
Noise Impact on Aircraft Size - Flade

For the Flade engine, an extensive noise database exists covering the range of exhaust conditions of the M-E nozzle. This database and the Motsinger-Sieckman (M-S) noise prediction code were a result of the previous SCR studies.

Again, a "0 dB" suppression curve is shown as well as the noise predicted by the M-S code. Only a small amount of engine oversize is necessary to meet Stage 3. If the Flade flow is collected into a fluid acoustic shield, the additional suppression (~1.5 dB) may enable the aircraft to meet Stage 3 with no engine oversizing based on this preliminary analysis.

Noise Impact on Aircraft Size

Mach 2.4 Flade Engine



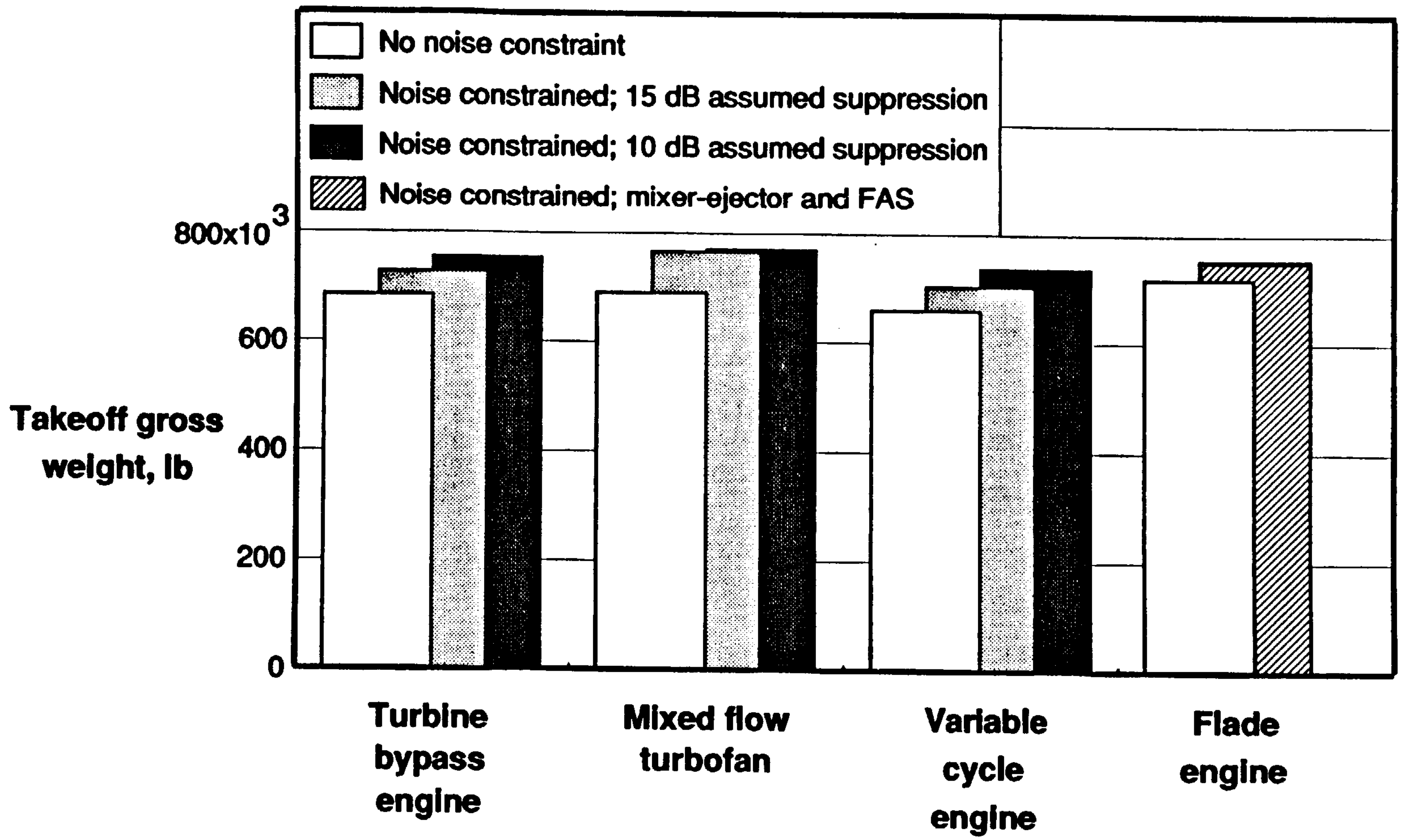
Takeoff Gross Weight Assessment

The takeoff gross weights (TOGW) for the four engine types are shown. The open bars represent the weights when there is no imposed noise constraint. The difference in weights is less than 5% between all the engines and is considered to be insignificant at this time. They are all, however, about 50,000 pounds higher than the previous comparison shown at the Aero Propulsion Conference held at NASA Lewis in March. The new ground rules agreed to by P&W and GE in terms of T3 and T4 limits, cooling requirements, AN^2, etc. have been incorporated into our in-house studies. This has resulted in about a 20% increase in base engine weight which is reflected in this TOGW growth.

For the TBE, MFTF and VCE, the method previously shown for calculating TOGW with various amounts of assumed mixer performance has been used. The MFTF only needs about 10 dB so there is essentially no difference in TOGW at 15 dB suppression. The TBE and VCE both require oversizing at both 10 and 15 dB. The Flade TOGW was calculated using the M-S code and the fluid acoustic shield noise reduction procedure. Again, noise constrained TOGW varies less than 5% between the candidate cycles. As previously mentioned, we have not yet reached the point in the analysis of the TBE with an inlet flow valve to include its performance in this status report.

Takeoff Gross Weight Assessment

All Supersonic 5000 n mi Mission

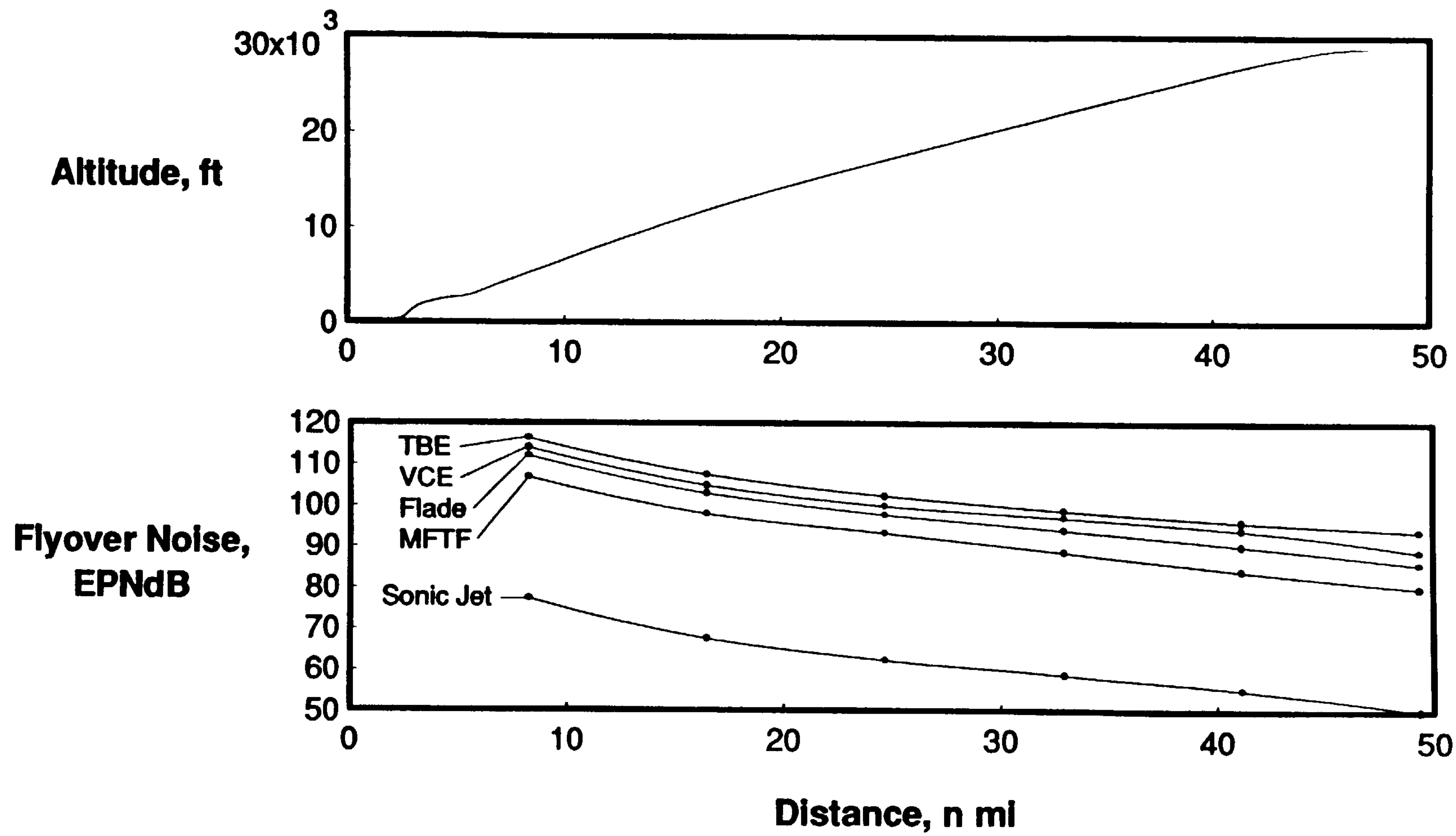


Impact of HSCT Flyover Noise

A possible problem with the HSCT is that high-altitude flyover noise along the flight path is significantly higher than that of subsonic aircraft.

In the airport vicinity, the HSCT engine operates with the mixer-suppressor nozzle deployed, a throttle cutback, and possibly a programmed throttle lapse rate. As the vehicle climbs to cruise, the suppressors are stowed and the engine power raised. Shown here is a band of flyover noise for all of the study engines as a function of distance from the airport and the corresponding altitude of the aircraft. Noise levels of 100 dB are reached at an altitude of 20,000 feet compared to 60 dB for a sonic jet representing subsonic aircraft. It therefore may be necessary to employ part power climbs to very high altitudes and/or noise suppression during the climbout based on this very preliminary assessment. In addition, it should be pointed out that the model used for calculating noise propagation may be deficient. More refined models of atmospheric attenuation and high aircraft velocity may significantly change the absolute level of these results.

Impact of HSCT High-Altitude Flyover Noise



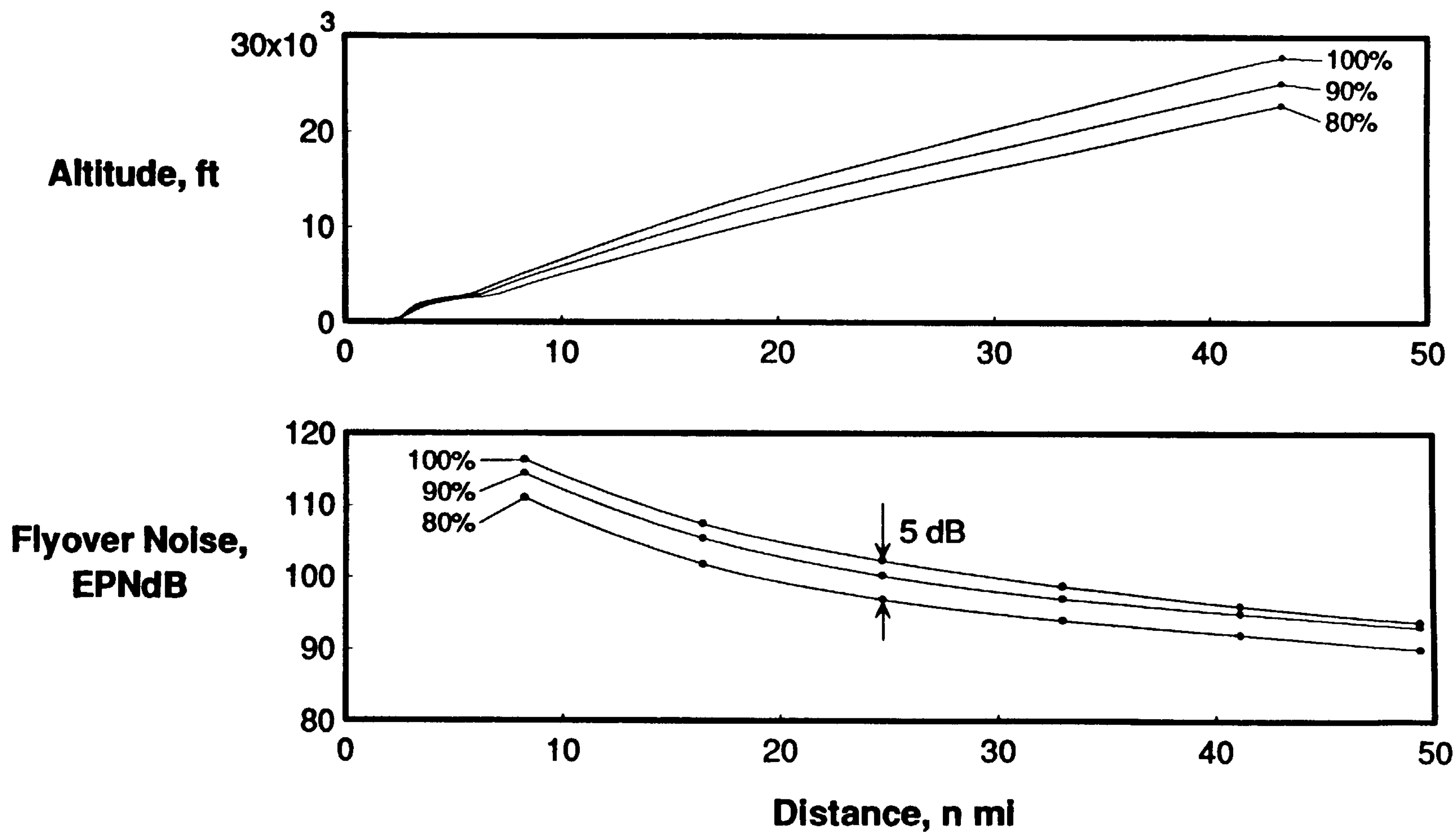
Impact of HSCT Flyover Noise - Throttled Climb

A throttled climb can potentially reduce the flyover noise along the climbout flight path by approximately 5 dB as shown. Further reductions may be possible, but this needs to be studied.

Impact of HSCT High-Altitude Flyover Noise

Throttled Climb - Turbine Bypass Engine

Throttle Settings: 100, 90, 80 Percent



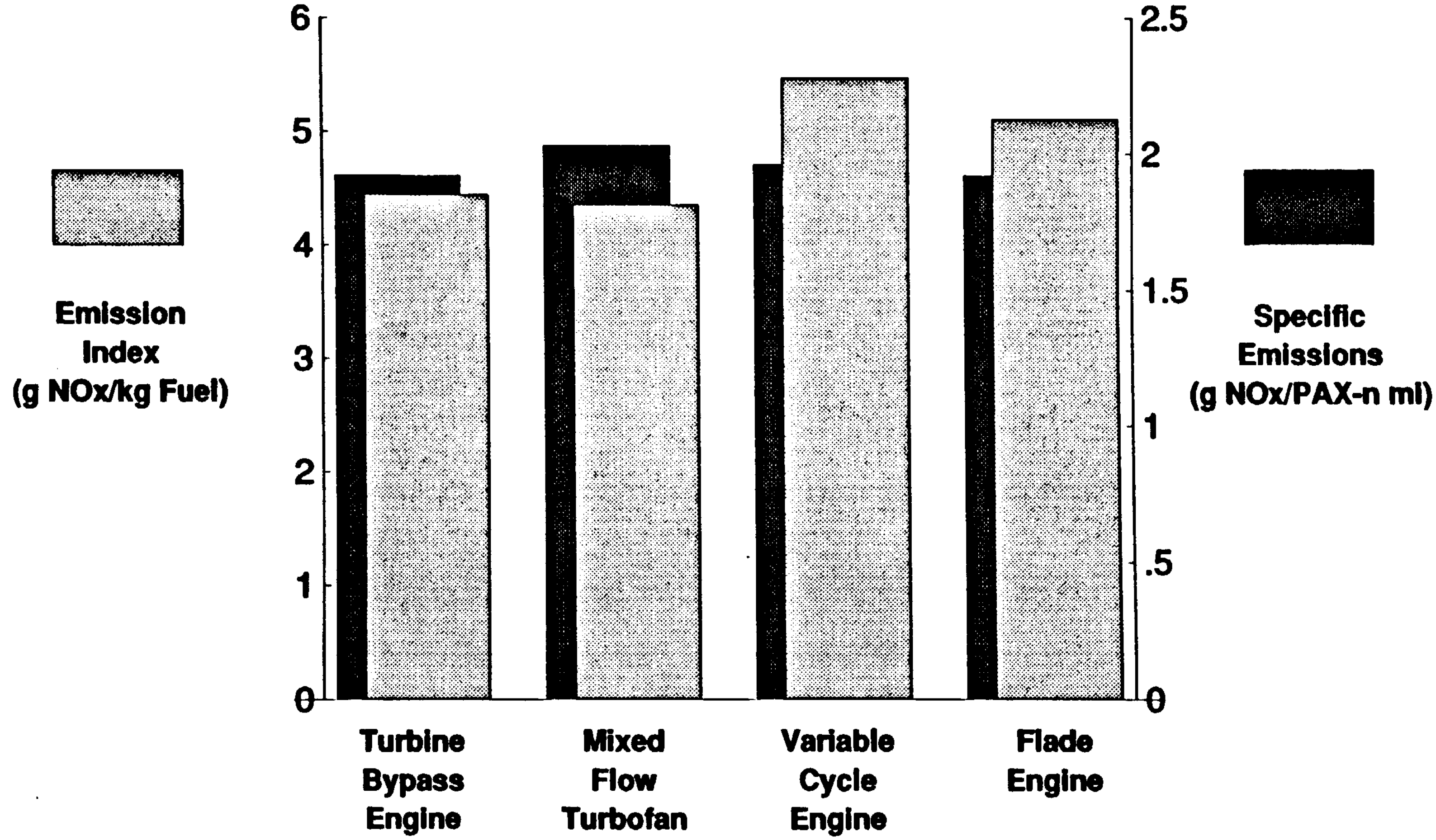
HSR NO_x Reduction Status

The emission index for the four engines are all approximately at the goal value of 5. This is a result of the engines meeting the P&W/GE agreed upon T_3 and T_4 limits. There has not yet been a correlation developed for the LPP and RQL combustor emissions because of the very limited flametube database. The correlation used to predict EI is based on clean combustor data from the 1970s adjusted to pass through the EI goal value of 5 at typical HSCT conditions.

Specific emission is also shown which is based on both the emissions index and fuel burned during cruise in terms of grams of NO_x per passenger nautical mile. This parameter would reflect any changes in engine fuel efficiency. None of the engines thus far show any significant advantage.

HSR NO_X Reduction Status

Based on HSR Goal for Emission Index Dependency



Current Assessment of HSCT Ozone Depletion

Ozone damage due to NO_x is a function of both the amount of NO_x produced and the altitude at which the NO_x is released.

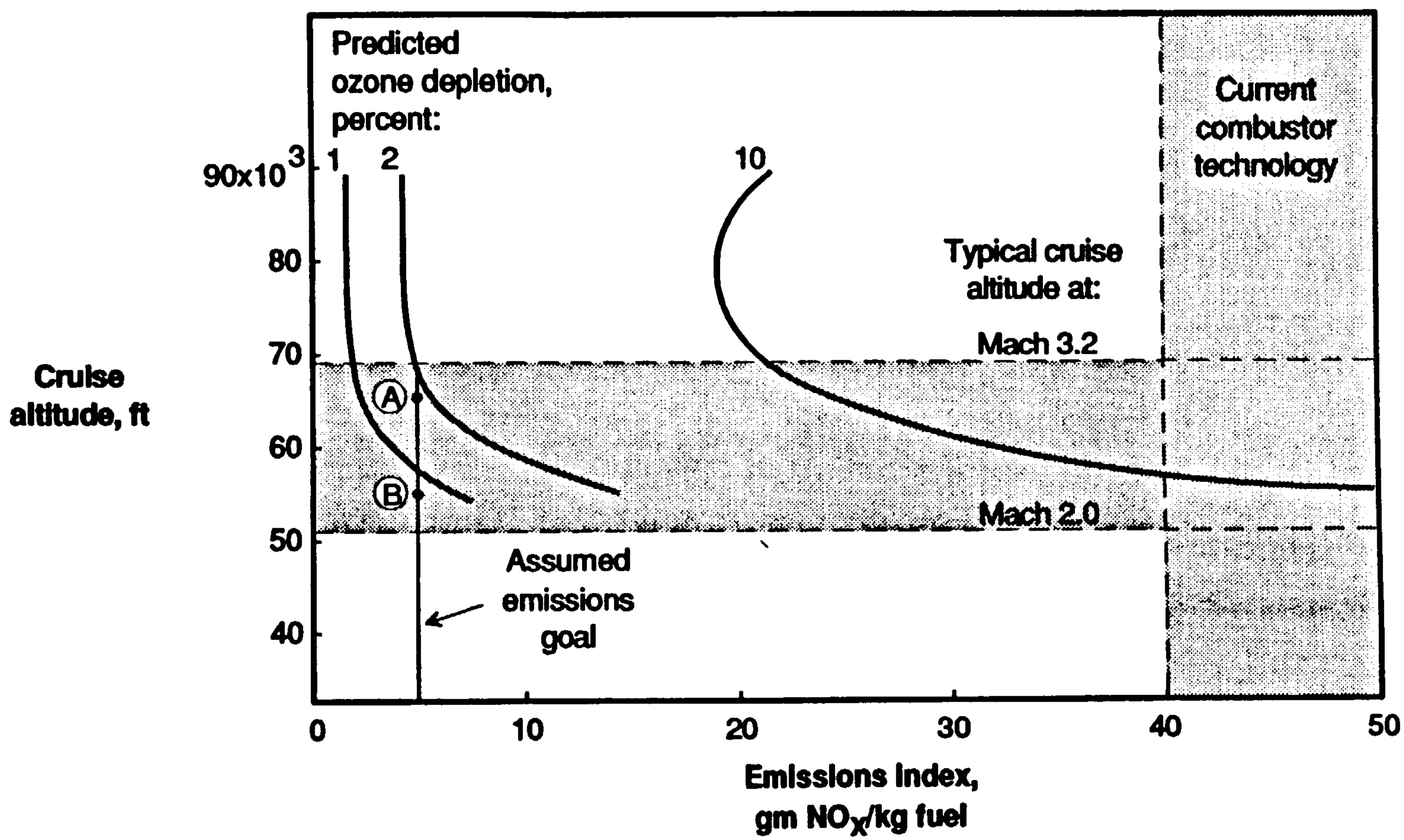
Shown here is a plot of emission index (EI) vs. cruise altitude and the levels of steady-state ozone depletion for a fleet of 600 HSCTs.

A typical cruise altitude for an HSCT would be about 50,000 feet at M2.0 and 70,000 feet at Mach 3.2. Current technology clean combustors have an EI of 40+.

At the assumed goal of the low NO_x combustor program of an EI of 5, the steady state depletion of the ozone layer is about 2 percent at 65,000 feet (point A). This damage can be reduced approximately in half by flying at 55,000 feet. It is not NASA's position to advocate a lower, non-optimal, cruise altitude to combat ozone depletion. It is much more preferable to design low NO_x combustors. Reduction of cruise altitude is a rather simplistic method of reducing ozone depletion. This lower cruise altitude could be used by either reducing the cruise design Mach number or by flying at a non-optimum altitude and suffering a range penalty.

Current Assessment of High Speed Civil Transport Ozone Depletion

NO_x Effect Alone

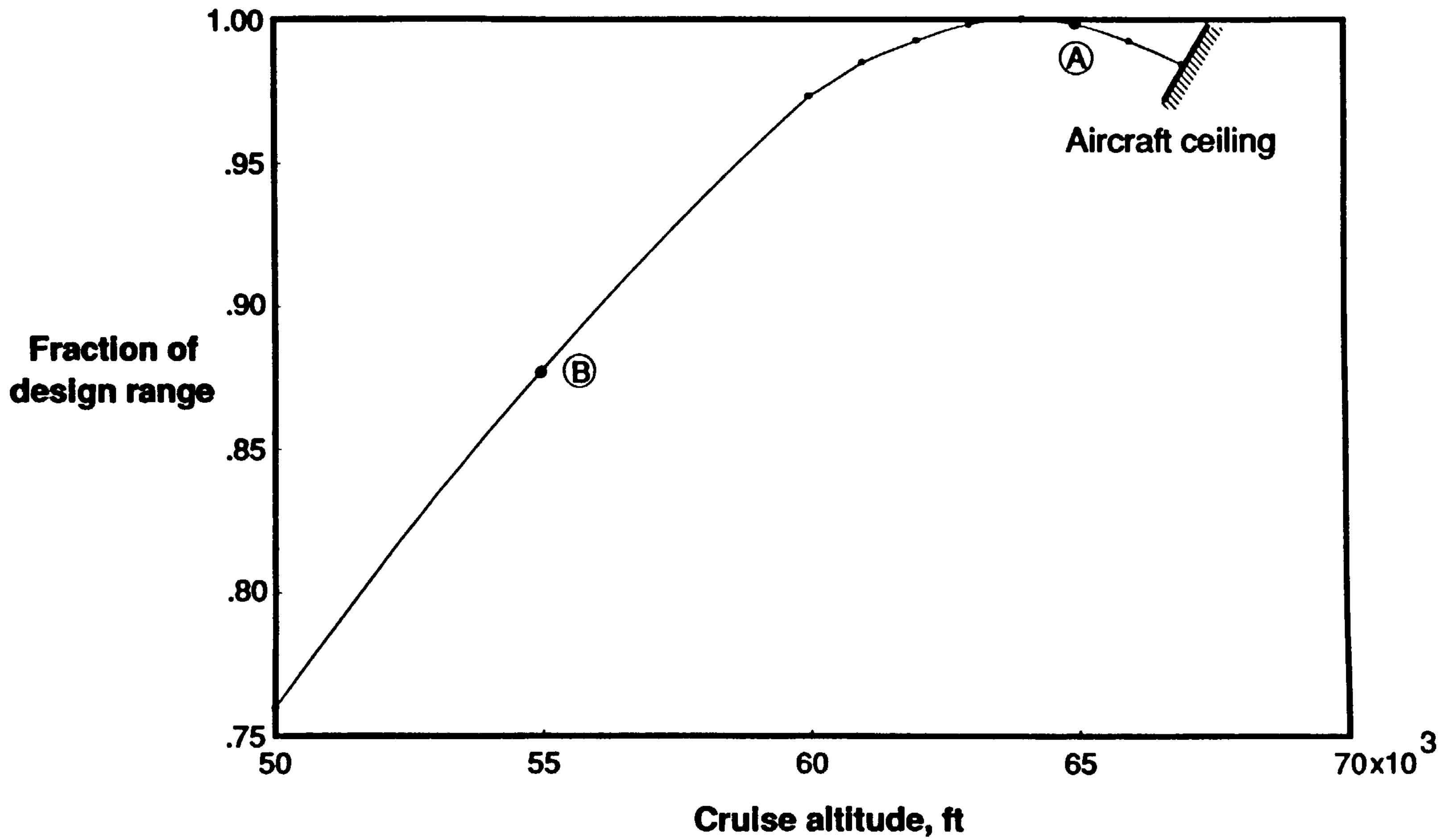


Influence of Non-Optimum Cruise Altitude on Range

The range penalty for flying an aircraft designed for M2.4 cruise at 65,000 feet at the non-optimum cruise altitude of 55,000 feet is shown here to be about 12%. This is a worse case scenario where the wing size and engine size have been fixed based on the higher altitude. If it were known in advance that the cruise altitude would be 10,000 feet lower, the aircraft and engine parameters would have taken on different optimum values and the range penalty would have been less than 12%.

Influence of Non-Optimum Cruise Altitude on Range

Mach 2.4 Turbine Bypass Engine Designed at 65 000 ft

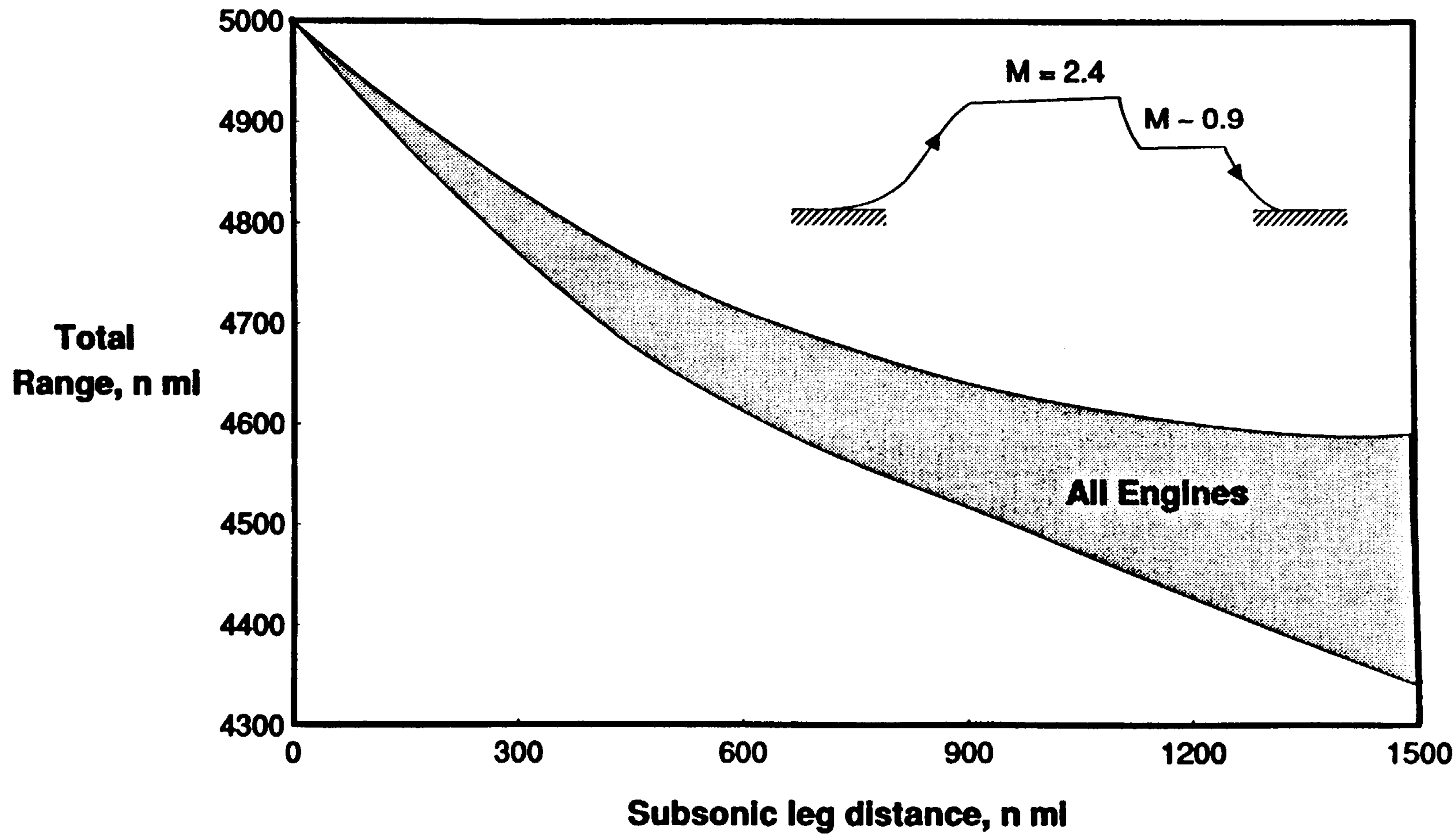


Influence of Subsonic Leg on Range

Here too, a worse case scenario has been assumed. For all four engine candidates, the penalty of flying 1/3 of the mission subsonically is about 500 nmi or 10% of the initial design range. The difference between the engine types is less than 5%. If a large subsonic range is to be included in the design mission, a different value of wing loading, engine size, and engine cycle parameters would be chosen.

Influence of Subsonic Leg on Range

Design Range: 5000 n mi



Study Conclusions

At the present time, there appears to be less than 5% difference in TOGW between the candidate engine cycles. TOGW may not be the sole determiner as to best engine. Cost, reliability, maintainability, complexity and other considerations will also enter into the selection process.

The aero/acoustic performance of mixer-ejector nozzles will be critical in the selection process. The two relatively low exhaust velocity engines, the MFTF and Flade, require the least nozzle noise suppression.

This study has been done only at M2.4. Emissions and the impact on the protective ozone shield could possibly force the lowering of cruise altitudes and Mach number.

Study Conclusions

- All four candidate propulsion systems are viable contenders.
- Mixer-ejector nozzle aeroacoustic performance is critical in meeting FAR 36, Stage 3, noise requirements and may influence propulsion cycle selection.
- Allowable emissions may dictate cruise altitude and Mach number.

Areas Requiring More In-Depth Analysis

Before a more definitive answer as to the best engine type can be ascertained, the analytical models used in conducting the mission analysis need improvement.

The mixer-ejector nozzle noise/performance requirements will vary with the engine type. Aircraft redesign/sizing models must be improved to account for the various effects of engine oversizing that reflects the accompanying changes in aircraft Cg, structure, flutter, landing gear etc. Better models for the propulsion/airframe integration must be developed to accurately reflect the different nacelle shapes and lengths between the engine types. Detailed flowpath calculations and experimental data must be generated to accurately predict engine weight and performance. Also, the accuracy of present noise prediction methods for flyover noise propagation must be verified or improved.

Areas Requiring More In-Depth Analysis

- Mixer-ejector nozzle noise/performance
- Aircraft redesign/sizing
- Propulsion/airframe integration
- Propulsion system weight/performance
- Takeoff noise modeling/techniques
- Other Mach numbers
- Other cycles
- High-altitude flyover noise propagation

Key Contracted Efforts

The major contracted studies in place to help improve the database were previously shown in the overview for this session. They address some of the key concerns, namely, the best type of inlet, the mixer ejector nozzle performance, 2D vs. Axi configurations for both, and the differences between military and commercial life requirements and duty cycle for supersonic engines.

Key Contracted Efforts

- Boeing inlet study
  - 2-D vs. axisymmetric
  - Amounts of internal/external compression
- Douglas inlet study for Flade engine
- Lockheed nozzle study
  - 2-D vs. axisymmetric
  - Amount of ejector augmentation
- General Electric and Pratt & Whitney nozzle study
- Pratt & Whitney engine life study

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