HSR PROPULSION SYSTEM STUDIES: A STATUS REPORT ON THE DOWN-SELECT PROCESS

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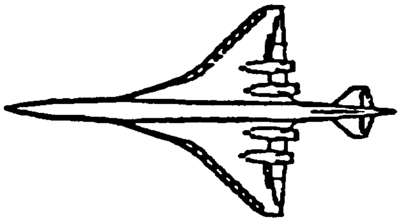
S31-71

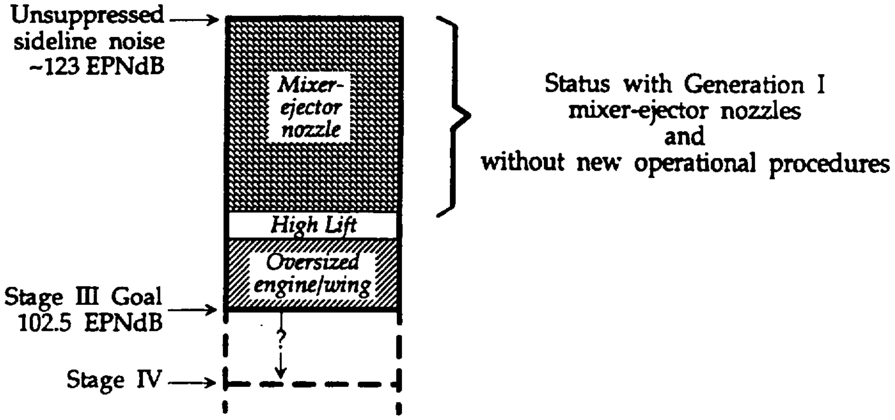
HSR Airport Noise Challenge

First Wish:

- *Simple turbojet engines ($V_{jet} \sim 3200$ ft/s)*
- *Acceptable 20^{+}dB mixer-ejector nozzles*



1992 Status:



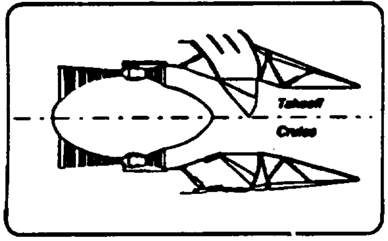
When the HSR program began there was widespread belief that a simple and familiar turbojet-like engine coupled to an advanced technology mixer-ejector nozzle was the propulsion system of choice for achieving FAR 36-Stage 3 noise requirements. Our ability to quickly demonstrate a practical 20^{+}dB suppression nozzle was confidently presumed by many. Our rate of progress towards that objective, however, has been somewhat humbling. At the moment we are reasonably confident of achieving about 15dB suppression with a mixer-ejector nozzle designed for a high specific thrust turbojet-like cycle. Therefore, if we make no further suppression progress and conservatively assume no new operational procedures such as programmed lapse rate (PLR), then meeting the Stage III goal requires a large amount of engine and/or wing oversizing which is economically prohibitive. The scenario is further aggravated by the possibility of eventually needing to comply with even more stringent regulations (Stage IV).

While this status may be somewhat disappointing to some, it must be remembered that the HSR program plan involves two generations of mixer-ejector nozzles beyond the current generation I nozzle designs. It is premature to conclude that we cannot design a practical 20^{+}dB mixer-ejector nozzle. On the other hand, it is prudent to consider alternative solutions to the noise problem. Thus, we are investigating four other propulsion system concepts.

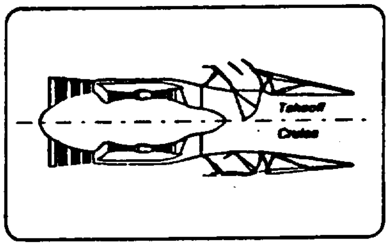
HSCT Noise Suppression Concepts

Rear End ***Hybrid*** ***Front End***

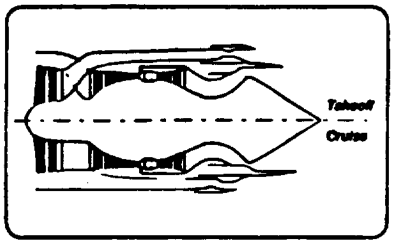
Turbine Bypass Engine



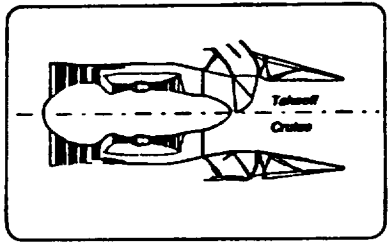
Mixed Flow Turbofan



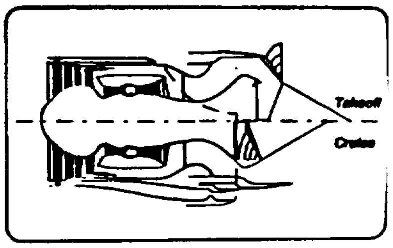
TBE / IFV



Variable Cycle Engine



Flade

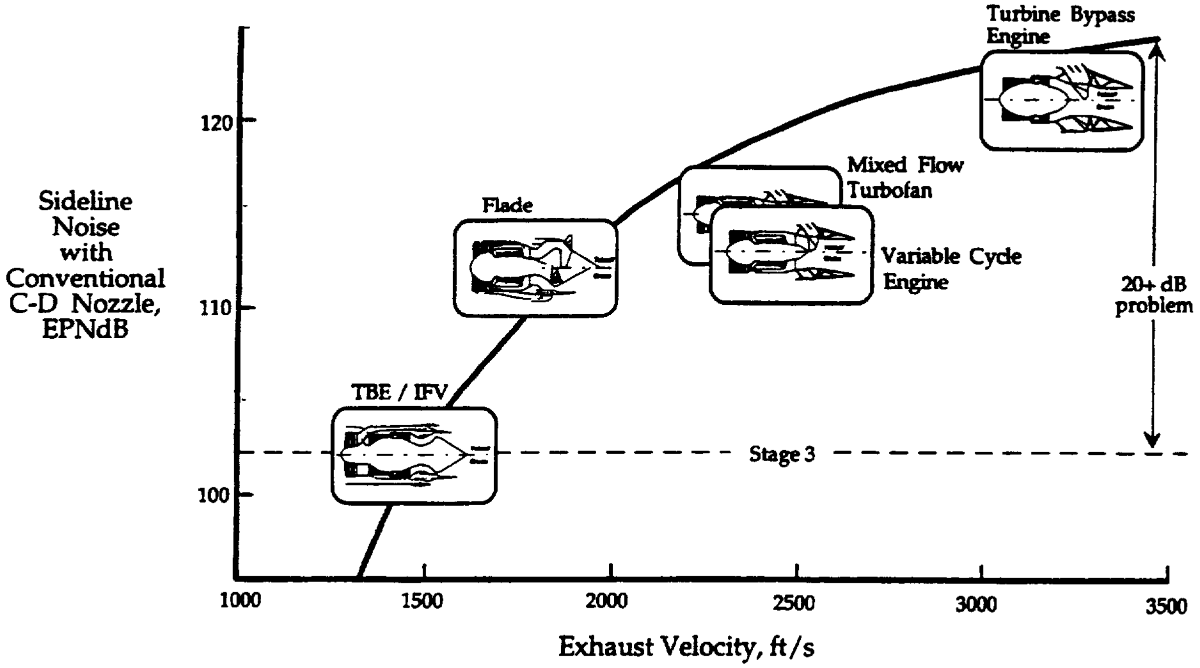


The highest specific thrust concept is the 1-spool turbine bypass engine (a slightly modified turbojet) combined with a very large mixer-ejector nozzle requiring approximately 120 percent airflow augmentation during takeoff. The mixed flow turbofan (MFTF) and variable cycle engine (VCE) concepts have intermediate jet velocities because a low-spool driven fan absorbs much of the core energy. Consequently, much less secondary air is required in the mixer-ejector nozzle to achieve low noise than the turbine bypass engine (TBE). The Flade engine is either a VCE or a MFTF with a third flowpath surrounding the fan and scrolled to the lower half of the engine. The fan driving this flowpath is modulated to absorb power during the takeoff and this provides a fluid acoustic shield underneath the mixer nozzle (no ejector). The TBE with an inlet flow valve (IFV) represents one member of the tandem fan class of concepts wherein a compression system reconfiguration can occur. During takeoff, auxiliary air is brought onboard and routed to the rear compressor while the normal inlet airflow is processed only by the front compressor before exhausting. In the cruise configuration, the auxiliary inlets are closed and the engine becomes a turbojet with an extra pressure loss due to the IFV.

All of these candidate concepts achieve about 1500 ft/s exhaust velocity during takeoff by raising the total airflow to about 1100 lb/sec. They differ in where the airflow is introduced into the cycle and which technologies need to be developed to achieve success.

Effect of Exhaust Velocity on Sideline Noise

Mach 0.322, 689 ft., 650 lb/s



Each of these five concepts can be characterized by its exhaust velocity and, therefore, its suppression requirements compared to a conventional unsuppressed nozzle. While a TBE presents a 20^{+}dB suppression problem to attain Stage III, the TBE/IFV can be designed to achieve Stage III without an elaborate suppression system, and the hybrid concepts fall somewhere in-between these extremes. There are, of course, other discriminating attributes to be considered such as weight, reliability, life, efficiency, thrust lapse, technology risk, tolerance to more severe noise constraints, installation drag, and climb noise. What is needed is an unbiased procedure to evaluate each of these concepts on a system basis that accounts for all of these criteria simultaneously.

Overall HSCT Noise Issues

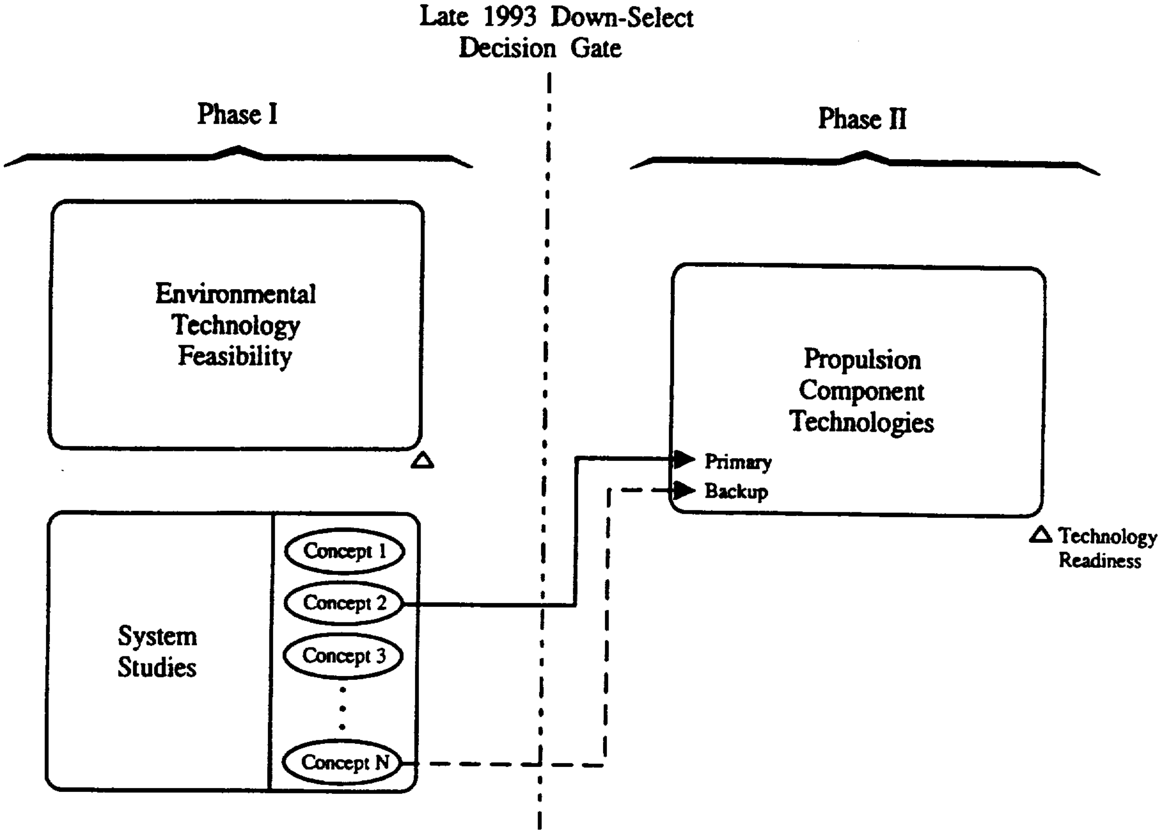
1. *Which propulsion concept best achieves a balanced compromise of performance, weight, size, noise, complexity, and life ?*

2. *What price do we pay to achieve noise levels below Stage III ?*

Issue 1 is important to resolve because the HSR program is resource-constrained to pursue technologies specific to only two concepts at most. This is also a difficult challenge to resolve with a high degree of confidence due to the large number of independent variables, the complex interactions between propulsion and airframe, multiplicity of merit criteria, and key technology and external uncertainties.

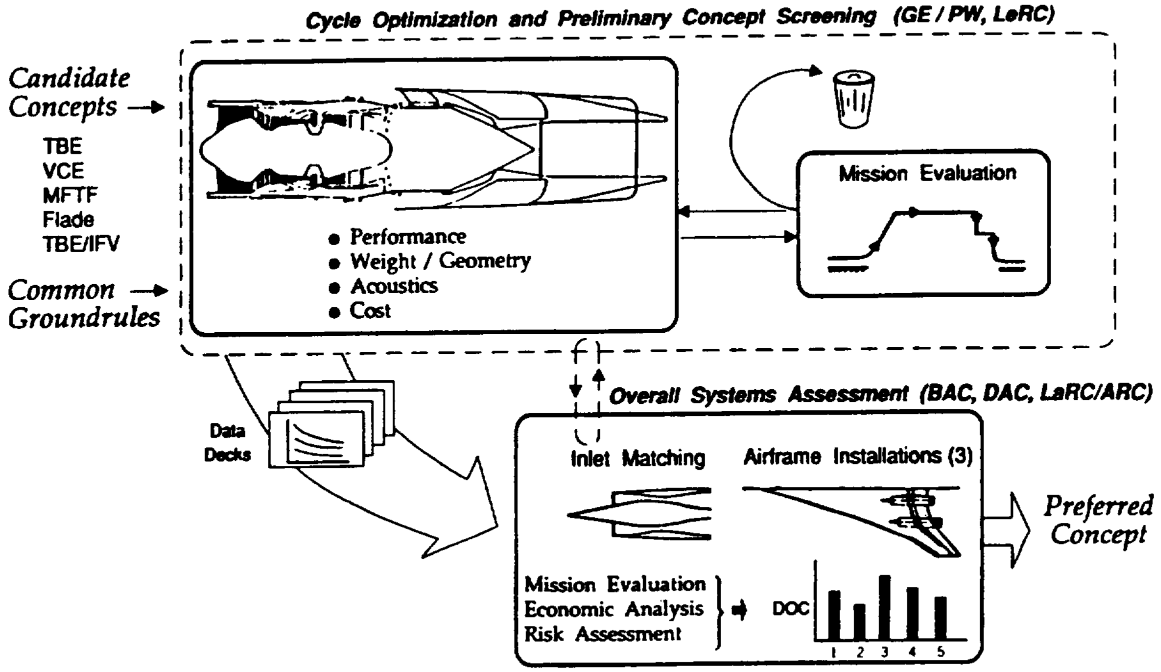
Since it is likely that noise regulations will be tightened sometime in the future it is important to determine the economic penalty associated with such an eventuality. Also, some propulsion concepts are able to accommodate severe noise constraints better than other concepts. Thus, this information could be a key discriminator during the concept selection process. It would be best if we generate a curve of penalty (e.g., ΔDOC) versus ΔdB below Stage III rather than presume a definition of Stage IV. Then, there could be more rational future rule-making.

A Propulsion System Down-Select is Needed to Focus the Phase II Technology Program



In addition to the mainline environmental technology feasibility effort in HSR Phase I, a systems studies effort is also underway to address the issues listed on the previous chart. The schedule calls for a down-select to both a primary and backup concept by late 1993. This will focus the technology effort in HSR Phase II. Note that this down-select pertains to the NASA sponsored technology thrust only--i.e., it is not a production engine down-select. The intent of the '93 down-select is to insure that the correct concept-specific technology is pursued in the earlier portion of Phase II to enable a low-risk final down-select in late '95.

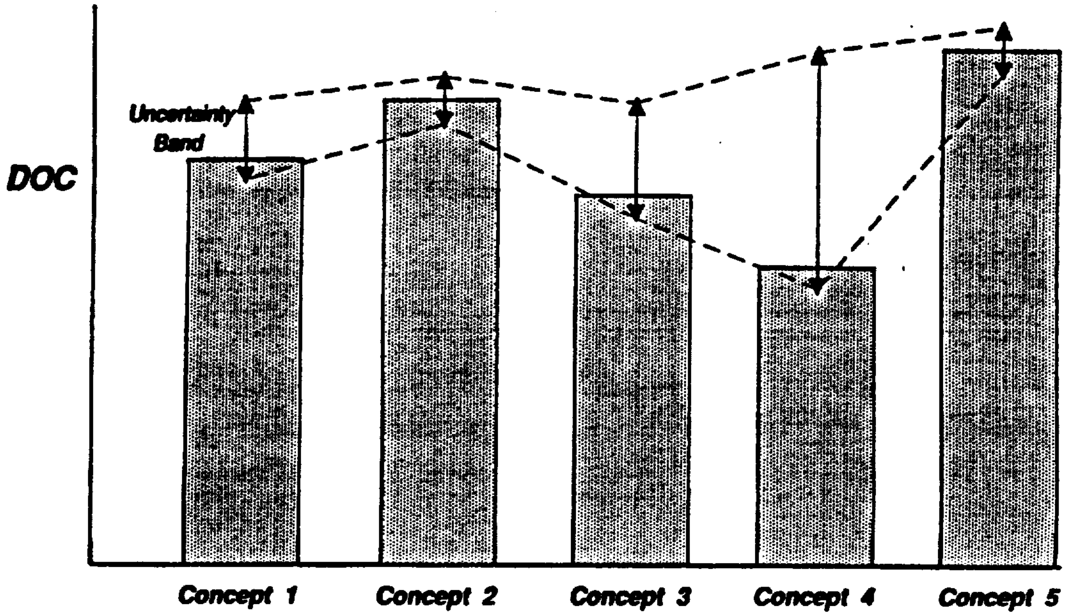
HSR Propulsion System Selection Process



The process by which the down-select information is acquired begins with the establishment of a common set of groundrules for all participants to minimize the risk of disparate results. GE/PW are to perform a preliminary concept screening using takeoff gross weight as the prime evaluation criterion. This means that for each candidate concept the cycle will be optimized and representative airplane and mission models adopted. Propulsion-airframe installation (PAI) differences such as interference drag will not be captured, however. The output of this first level screening is passed to Boeing and Douglas for detailed comparative evaluations that include PAI effects. Boeing and Douglas have adopted somewhat different airframes and mission definitions (e.g., programmed lapse rate assumption) which means that somewhat different results may ensue. The merit criteria will be direct operating cost (DOC) and technical risk.

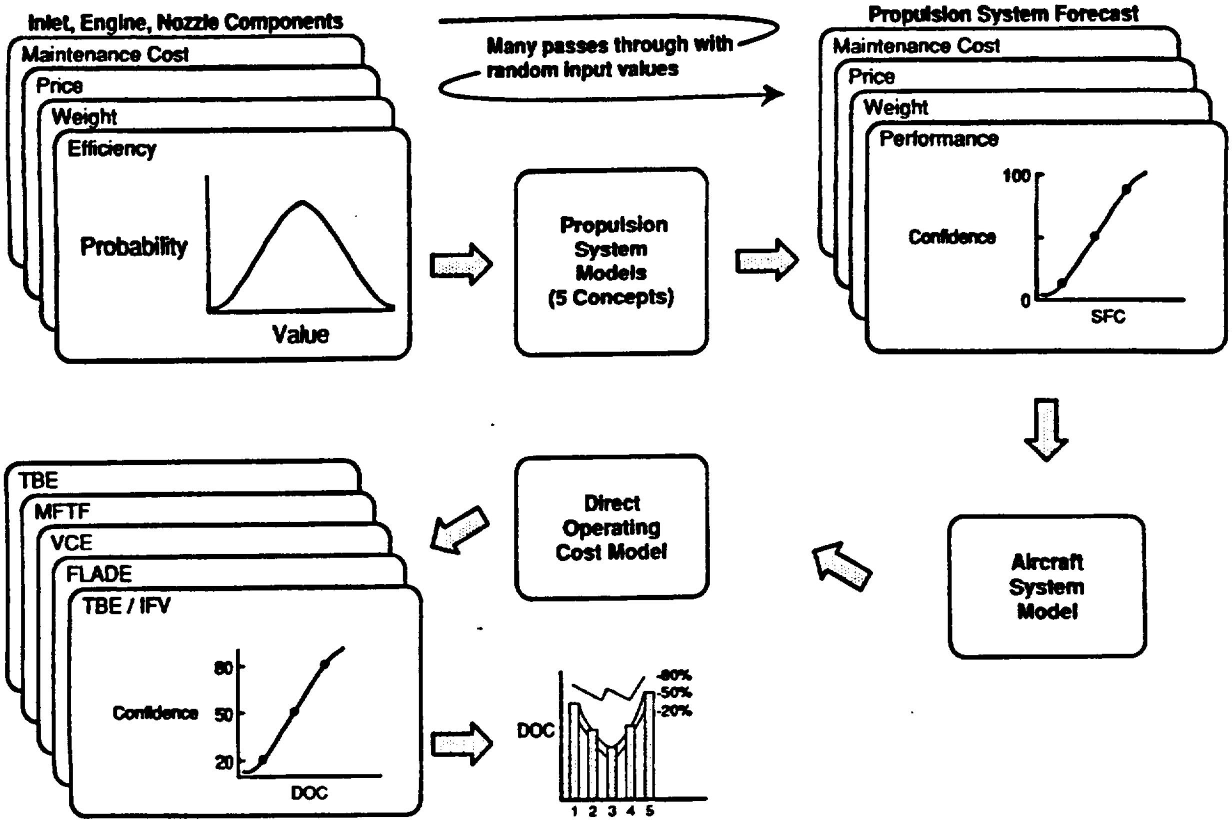
HSR Propulsion System Concept Selection Criterion

- *Prime discriminators: Direct operating cost (DOC)*
  Technical risk (uncertainty band)
- *Risk to be incorporated into DOC when feasible*



To avoid an unwieldy number of risks associated with the various technologies, risks will be incorporated into DOC wherever possible. For example, if an unconventional component such as a mixer-ejector nozzle requires an expensive R&D program to reach acceptable risk, then the cost of this element is incorporated into the DOC. The end result is an uncertainty band on DOC that reflects the agglomerated risks associated with each concept. Conceivably, the down-select process will produce results as depicted wherein the nominally lowest DOC concept (arbitrarily drawn as concept 4) also has the highest risk. In this case, the decision-maker will need to make a judgement concerning the balance between DOC benefit and increased risk. In the example shown, concept 3 might be preferred over concept 4 due to its lower technical risk.

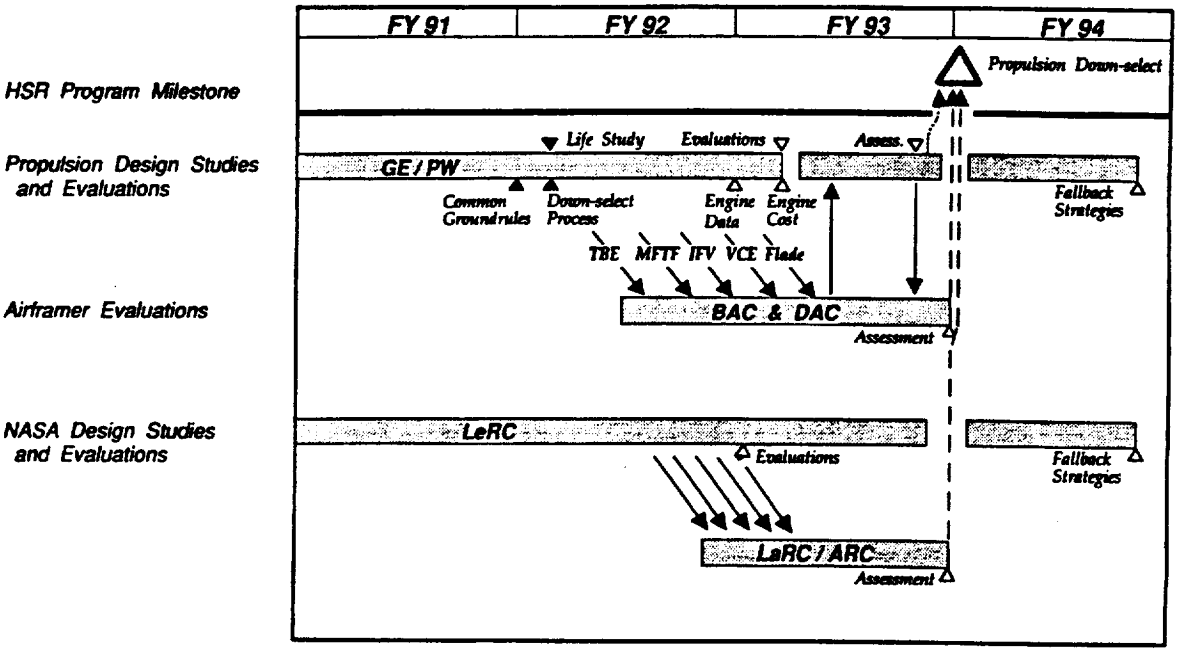
Monte Carlo Simulation Risk Analysis



In order to determine the DOC uncertainties for each concept, GE/PW and Douglas are invoking a Monte Carlo simulation risk analysis. Component experts will estimate the probability of attaining several values of the key component criteria such as efficiency weight, acquisition cost, and maintenance cost. This will define sets of probability curves for each propulsion component such as the mixer-ejector nozzle, IFV, Flade fan, and mixed compression inlets. Random sampling of these component probabilities done many times, together with a propulsion systems model, will yield another (smaller) set of curves for each concept. These are confidence curves for the complete propulsion system. Combining this information with aircraft, mission, and economic models will lead to DOC confidence curves for each of the five propulsion concepts. Finally, these DOC confidence curves can be interrogated at three levels to yield the desired DOC uncertainty bands (e.g., 20 percent, 50 percent, and 80 percent).

Boeing prefers to do a more traditional risk analysis instead of a Monte Carlo analysis. They will interrogate a group of experienced technology experts to estimate risks associated with each candidate concept. This traditional approach will provide a check on the Monte Carlo simulation.

Level 2 HSR Program Schedule - Propulsion System Studies

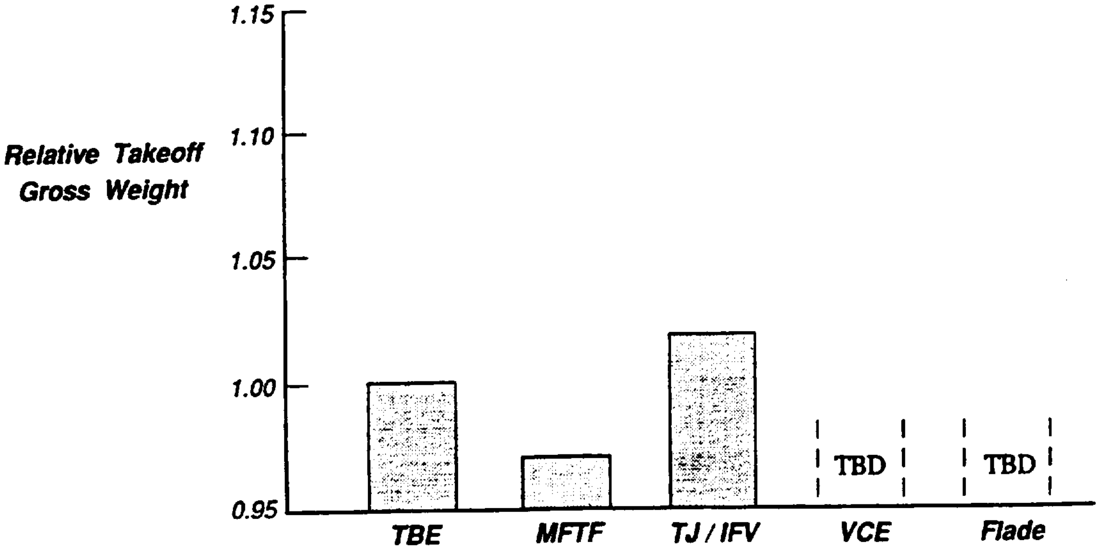


Having established common groundrules amongst GE/PW, Boeing, Douglas, and NASA, the propulsion system design studies are well underway within the propulsion community. Mach 2.4 data have been generated and delivered to the airframers for the TBE, MFTF (bypass ratios of 0.4, .63, 1.13), and the TBE/IFV. The VCE and Flade data are nearly complete. These data include performance, weights, cost, and acoustic information. In the spring of 1993, Boeing and Douglas will have completed a first pass comparison of all of the engine candidates. At this point, all first-order technical issues and concept-specific concerns will be identified. From then on, detailed analyses will be conducted to insure that each concept is fairly judged. This entails exploring ways to mitigate the weaknesses associated with each propulsion concept. The plan calls for sufficient information to be acquired by the beginning of FY94 to enable a credible down-select decision. NASA is also performing design studies and comparative evaluations to strengthen the overall effort. Because the technical challenges are complex and five organizations are involved in designing and evaluating numerous engine and nozzle concepts, there is also an enormous information management challenge to ensure effective use of available resources.

Status of NASA In-House Comparative Propulsion Studies

Mach 2.4, 100% supersonic 5000 n.mi. range, 292 passengers

Stage III sideline constraint
Assumes material goals and mixer-ejector nozzle goals are achieved
LeRC results as of September, 1992



Currently, there is not much comparative data to examine and what data does exist is quite tentative and laced with caveats. Nevertheless, this chart displays NASA's current state of understanding of three of the five concepts. Relative takeoff gross weight is shown assuming the EPM materials goals and the HSR mixer-ejector nozzle goals are achieved (e.g., the TBE nozzle delivers 18^+dB suppression in an acceptable size), and that no significant PAI penalties exist. Even with these assumptions the MFTF is superior to the TBE because its cruise efficiency is significantly better. If the PAI differences do not hurt the MFTF, this candidate appears to be very competitive. Because the VCE is essentially a MFTF derivative, it too is expected to compete well--especially on missions with large subsonic legs. The Flade is also anticipated to be quite competitive for similar reasons.

Key Propulsion System Uncertainties

Technical

1. *Adequate mixer - ejector nozzle aero / acoustic performance*
2. *Materials progress*

External

3. *More severe airport noise regulations*
4. *Operational procedure regulations (e.g., programmed lapse rate)*
5. *Climb noise*
6. *Mach number selection*

By itself, the previous chart depicts an oversimplified situation. In reality, there are a number of first-order uncertainties that need to be considered in the selection process. The sensitivity of the comparison with respect to these uncertainties needs to be determined to select wisely.

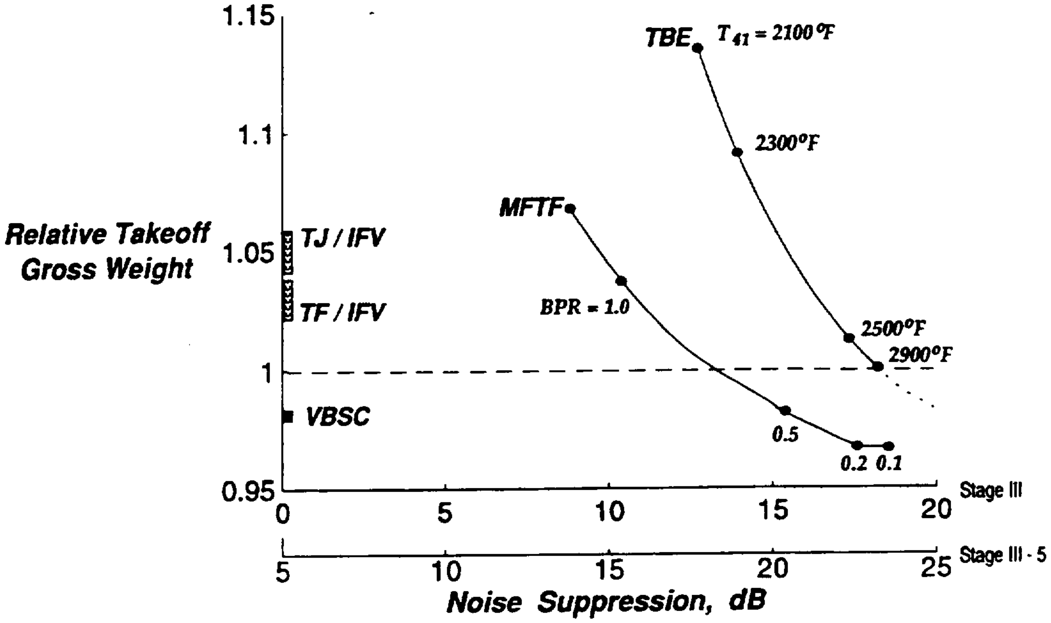
Impact of Noise Suppression Technology and Noise Constraint

Mach 2.4, all supersonic 5000 n.mi. range, 292 passengers

Cycle, nozzle, wing loading, thrust loading vary along each curve

Ignores aircraft installation differences and possible climb noise constraint

NASA Lewis results as of November 1992



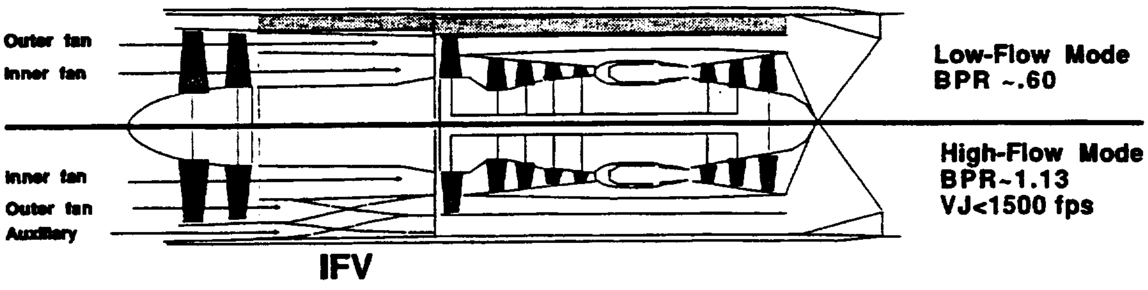
An example of the impact of the first three key uncertainties is displayed here in terms of takeoff gross weight relative to a TBE powered airplane with a 2900°F T_{41}. (The TBE would yield lower TOGW if it were not constrained by turbine blade material limits and unavailability of a suitable high-suppression nozzle.) Note that the TBE is quite sensitive to the degree of success in achieving a quiet nozzle. If only 13dB of suppression is achieved, then the TBE's TOGW penalty is about 14 percent. The TBE curve represents various amounts of wing and engine oversizing to meet Stage III sideline noise. The MFTF (and the other concepts as well) offer more degrees of freedom in the form of cycle changes (BPR) to mitigate the adverse impact of a mixer-ejector nozzle technology shortfall. Hence the MFTF curve is less steeply sloped, and it could accommodate even a 10dB suppressor nozzle without a show-stopping penalty.

The NASA results shown here also indicate that a 400°F material temperature shortfall would not be disastrous although 600°F would be. On the other hand, industry generated data show at least twice the sensitivity displayed here. These differences will be resolved soon.

The impact of a Stage III-5dB noise constraint may be determined by comparing results using the lower abscissa scale with results using the upper scale. For example, the ΔTOGW for a MFTF is about 7 percent for a 15dB suppressor nozzle.

Finally, it should be understood that this figure is just the beginning. Undoubtedly it will change as more realism is added. Firm conclusions based on this alone are premature.

Variable Bypass Supercharged Core (VBSC)



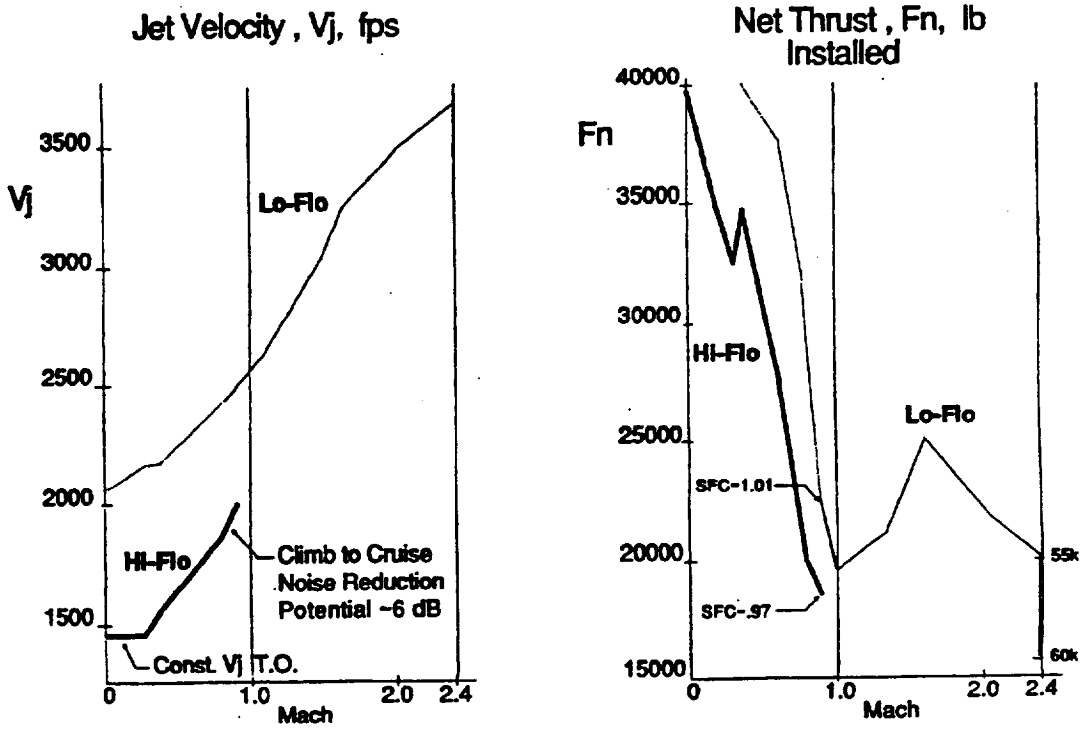
Advantages

- *Core remains supercharged in high-flow mode*
- *Less pressure drop, better cruise TSFC*
- *Less auxiliary inlet air required*
- *Lower engine weight*

The previous chart contained several points for TBE/IFV and TJ/IFV engines. At the moment there is some controversy concerning whether the plotted points are too optimistic or not. Regardless of how that controversy is resolved, it is clear that, while such high flow concepts are appealing because they obviate the need for a high-risk mixer-ejector nozzle, they also suffer serious deficiencies. Namely, a non-supercharged core and consequently low thrust in the takeoff mode, large and heavy engines, and pressure drop through the IFV during cruise. These deficiencies may be partially alleviated by the new concept illustrated here. It is a turbofan/IFV with a flow splitter that keeps the core supercharged by the inner fan flow at all times. It also features a core-driven aft fan stage that prevents bypass ratio from rising at higher flight speeds (opposite of mission requirement).

VBSC

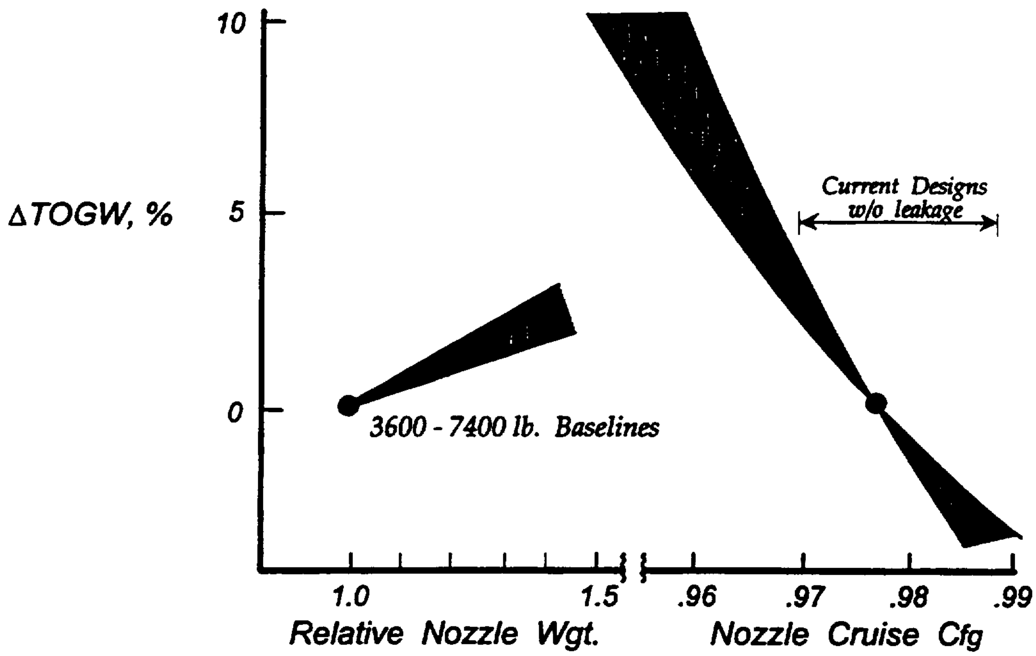
Takeoff and Climb to Cruise



Another advantage of the variable bypass supercharged core (VBSC) concept is its ability to efficiently stay in the high-flow mode throughout climb. This may prove to be important to reduce climb noise. Shown here is the exhaust velocity V_j and net thrust F_n during a typical climb path. Note the modest V_j throughout--rising from 1450 ft/s at Mach 0.3 to 2000 ft/s at Mach 0.9 at which point the mode switch occurs. NASA has conceptualized this engine very recently and has solicited industry feedback (pending) before adopting its inclusion into the down-select process.

TOGW Sensitivity to Nozzle Performance and Weight

Mach 2.4 HSCT



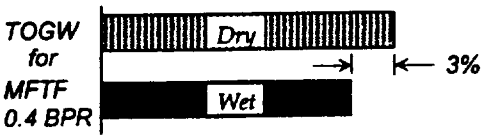
Achieving high nozzle cruise efficiency is absolutely essential. A 1 percent C_{fg} shortfall can increase TOGW by over 4 percent. Clearly, we need confidence in our predictive codes to substitute for lack of experimental data for many of the unconventional nozzle concepts.

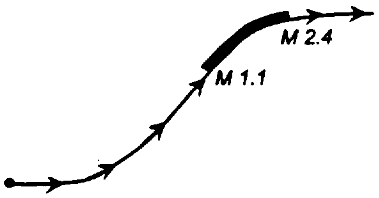
Nozzle weight is also a sensitive parameter. As the studies progress, the initially large spread in weight estimates has significantly diminished.

Avoided on this figure is any mention of the takeoff nozzle performance which is often cited as important also. (E.g., it is one of the two merit criteria in the oft-used mixer-ejector nozzle technology goal charts.) This omission was deliberate because some of the high-specific thrust engines are top-of-climb sized and therefore do not suffer large penalties for takeoff C_{fg}'s as low as 0.85 or so. There is also some evidence that even takeoff sized engines could tolerate relatively poor takeoff C_{fg}'s if wing size is free to vary to compensate.

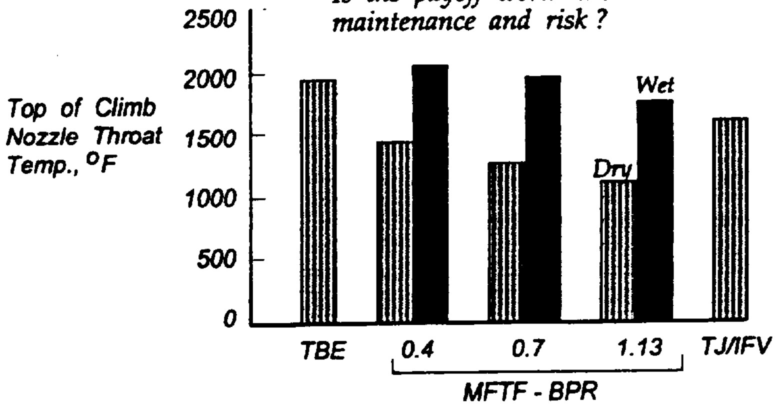
Thrust Augmentation Issue

Some cycles benefit from a mini-augmentor during climb



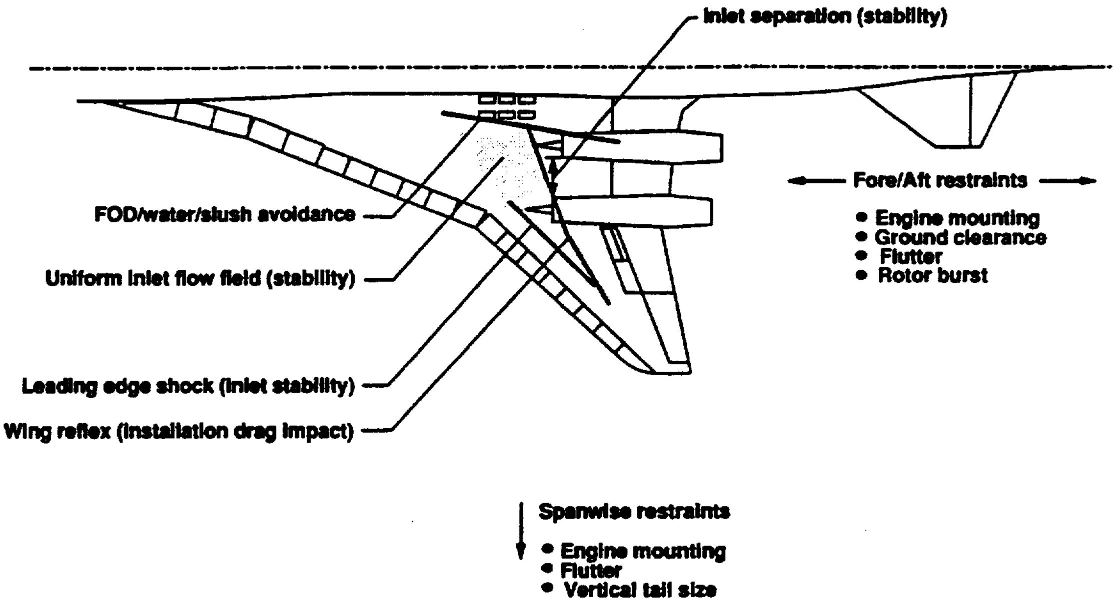


But


Is the payoff worth the increased maintenance and risk ?

One of the more recently discovered issues is whether to use a mini-thrust augmentor or not in the high specific flow engines. For example, Boeing prefers to use a mini-augmentor during the upper climb path to offset marginal thrust levels that cause inefficient transonic system performance. A 3 percent TOGW reduction is possible using a mini-augmentor rather than a dry engine for a MFTF with 0.4 bypass ratio. However, the use of augmentation also boosts the nozzle temperature levels about 600°F from the 1200-1400°F level to the 1700-2000°F level. The question is whether the TOGW payoff is worth the increased risk and maintenance associated with the higher temperature experienced during the upper climb. This issue is being investigated further.

Nacelle Placement Restraints



Another powerful influence on the down-select decision is propulsion-airframe integration (PAI). For example, the nacelle shape, which is driven by the propulsion geometry and changes significantly from one concept to another, and placement can dramatically alter the interference wave drag. Hence, to compare the alternative propulsion concepts we need to assure ourselves that PAI effects are properly determined even if this requires more than the usual analysis depth to understand. From early calculations it appears that some of the concepts do not integrate easily with the airframe and some re-design effort is warranted to avoid premature judgements.

Summary

1. *Late 1993 propulsion system down-select requires reliable M-E nozzle database*
   - *Adequate progress but not established yet*
2. *Considerable concern exists about M-E nozzle risk*
   - *Aero / acoustic performance* -- *Weight / size* -- *Life*
3. *Interest shifting toward low specific thrust cycle solutions to noise challenge*
4. *Stage III-5 dB incurs approximately a 7% airplane takeoff weight penalty for mixed-flow turbofans with M-E nozzles*

At the moment, the propulsion system down-select process is hindered by our lack of an adequate experimental mixer-ejector nozzle database to enable high-confidence aero/acoustic/weight modeling. Progress in establishing the needed data base is progressing adequately but fitfully. Certainly there exists considerable concern about M-E nozzles--enough to spawn a new wave of interest in the high-specific flow alternatives. In the end, it is likely to come down to a matter of which technology challenges do we prefer to pursue. The decision may depend upon risks as much as on potential benefits.