JOURNAL OF AIRCRAFT
Vol. 33, No. 1, January–February 1996

Matching Engine and Aircraft Lapse Rates for High Speed Civil Aircraft

C. R. Salay* and D. W. Elliott†
General Electric Aircraft Engines, Cincinnati, Ohio 45215

An economically viable and environmentally acceptable High Speed Civil Transport (HSCT) will not be possible without the latest technology and most rigorous matching of airframe and engine. The goal is to match the airframe drag lapse with the engine thrust lapse. When these lapses match, the two primary sizing constraints [acoustic takeoff and top-of-climb performance] are coincidentally met and the takeoff gross weight will be a minimum. In designing these cycles for the HSCT, it must be remembered that the appropriate emphasis on fuel flow for subsonic vehicles is replaced by specific thrust as the predominant parameter for supersonic vehicles. The engine types studied for the HSCT are high specific thrust cycles and high flow cycles. The high specific thrust cycles are relatively small engines, but require complex exhaust nozzles for noise suppression. The high flow engines provide a way to simplify the nozzle design by reducing the jet velocity required for a given thrust, however, these engines have larger cross sections that increase drag. For either engine type, the fan pressure ratio, throttle ratio, and overall pressure ratio must be selected to match the engine's thrust lapse to the aircraft lapse. Both airframe and engine sensitivities are addressed.

Introduction

THE need to optimize the sizing of the propulsion system and airframe to provide the "perfect" match has always been paramount for conceptual designers. Current designers' efforts on the High Speed Civil Transport (HSCT) share this goal, as did the designers of the previous generation of supersonic transports. The system goals and requirements, however, have become more stringent in the environmentally conscious 1990s. The additional requirements include constraints on takeoff and landing noise levels, enroute noise levels, sonic boom overpressures, and nitrogen oxides (NOx) emissions. All of these requirements involve the propulsion system, both engine and nozzle. Even the sonic boom requirement must be addressed by the engine, since the current solution is to fly subsonically over land. This demands that the subsonic cruise specific fuel consumption (SFC) be as economically viable as the Mach 2.4 SFC.

The current system requirements are summarized in Table 1. Of these constraints, achievement of the desired noise levels will require the most effort. Conventional solutions to meeting the noise levels and other environmental constraints run contrary to the usual performance-oriented requirements, and impose weight and efficiency penalties that detract from HSCT revenue generating capability. These problems may be attacked from four distinct areas: 1) aerodynamic characteristics of the airframe, 2) operational procedures, 3) relaxation of the goals/requirements, and 4) cycle and nozzle characteristics of the propulsion package.

The primary airframe parameters that can effect these goals are the cruise lift to drag ratio (L/D), takeoff L/D, and the thrust to aircraft weight ratio (T/W). Improvements in any of these would bring the system closer to meeting performance and environmental requirements. Several types of takeoff operational procedures have been investigated and are listed in order of their increasing effectiveness: 1) fixed throttle from brake release, 2) fixed high-lift positions with variable throttle during the takeoff and initial climb, and 3) variable throttle and variable leading, and trailing-edge positions throughout takeoff. Selective relaxation of some of the less critical goals could also be used to improve the program's economic viability. Although we can influence the matching of the system with either the engine or the airframe, as well as the requirements and operational procedures, this article will emphasize the capability within the engine cycle and engine types to achieve the goals and requirements of the HSCT.

SFC and Engine Size Trades for Supersonic Systems

For long range subsonic missions, the trade between engine size and SFC historically has emphasized SFC; in the HSCT, this is not the case. For supersonic vehicles, the aircraft size penalty due to the lower specific thrust of lower fan pressure ratio (FPR) engines is unacceptable, despite the SFC benefit. Table 2 illustrates the impact on takeoff gross weight (TOGW) of changes in cycle FPRs for subsonic and supersonic speed regimes.

For supersonic flight, exhaust velocities more than twice as high as comparable subsonic cycles are required. These are made possible by the much higher fan pressure ratios of the

Table 1 System requirements

Entry into service in 2010
12% return on investment conditions
Performance
Cruise Mach number, 2.4
Takeoff over 35-ft obstacle, 11,000 ft
Range + FAR reserves, 5,000 n mile
Passengers, 300
Acoustics
FAR 36, stage III levels at sideline, community and approach
Emissions
NOx emissions index levels <5.0
Sonic boom (over land)
Delta P < 1.0 psf

Presented as Paper 93-1808 at the AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit, Monterey, CA, June 28–30, 1993; received May 25, 1994; revision received May 2, 1995; accepted for publication July 10, 1995.

*Lead Engineer, Performance Engineering.

†Staff Engineer, Advanced Systems Design and Analysis. Member AIAA.

Table 2 Subsonic to supersonic comparison

	Cycle characteristics			
	Subsonic		Supersonic	
Change in FPR	+0.2		+1.1	
Cycle parameters				
Specific fuel consumption	0.54	+5.5%	1.2	+4.2%
Specific propulsion weight	5.7	+16%	14.6	+15%
Specific thrust	18.6	+31%	56.6	+31%
Impact on TOGW (%)				
Specific fuel consumption	+1.3		+8.8	
Specific weight	+2.4		+3.9	
Specific thrust	−3.1		−31.0	
System impact (%)				
Delta TOGW	+0.6		−18.0	

supersonic engines. As shown under the cycle parameters heading (Table 2), these supersonic cycles generate two and a half times as much thrust as the subsonic cycles. However, the Mach 2.4 aircraft has a cruise L/D that is less than half of the equivalent-sized subsonic system, readily absorbing the additional thrust. Since the SFC and engine specific weight are doubled in the supersonic regime, 5.5 times the subsonic fuel is required to generate an appropriate supersonic thrust level.

The impact of these cycles changes on TOGW is also shown in Table 2. The penalties for the increased SFC and propulsion weight are 7 times and 1.6 times greater, respectively, for the supersonic system. However, the benefit for the improved specific thrust is 10 times greater. The net effect is that for the same increase in specific thrust, the subsonic vehicle's takeoff gross weight increases by 0.6%, while the Mach 2.4 system has an 18% reduction in TOGW. This illustrates that the supersonic vehicle demands the benefit of high specific thrust, even at the expense of poorer SFC.

Interaction of Airframe and Engine Lapse

Figure 1 shows a characteristic distribution of TOGWs for HSCTs powered by a selection of mixed flow turbofans (MFTFs) over a wide range of FPRs. The chart is annotated to show the sizing criteria, either top of climb (TOC) or acoustic takeoff (TO) set by stage III rules. All MFTFs were equipped with miniburners that were operated solely during the supersonic climb. The miniburner eliminated any possibility of having a transonic pinch-point crop up as a sizing criteria, as well as reducing the TOGW compared to dry-powered HSCTs. Note the line transposed over the figure that divides the aircraft with respect to sizing criteria. This line represents the condition where TOC and stage III takeoff requirements are simultaneously met; this is the minimum weight HSCT.

Figure 2 is presented to clarify the impact of sizing criteria. These plots show the aircraft lapse (i.e., thrust required by the airframe at takeoff and top of climb) and the engine lapse (i.e., thrust available at TOC and TO). The left-hand figure shows the engine thrust equal to the airframe drag, with the excess representing the required TOC margin. At a sea level takeoff, this particular engine and airframe combination shows excess thrust available. The engine is being sized by the TOC, since more than adequate thrust is available at takeoff. The opposite condition exists in the right-hand figure. This combination is takeoff sized, with the potential for a much greater margin available at TOC. If the aircraft and engine lapses were identical, the sizing criteria would be met simultaneously and the overlaid line in Fig. 1 would result.

Engine Cycle Effects on Specific Thrust and Lapse

For HSCT aircraft, engines with high specific thrust and thrust lapse matching the aircraft requirements are needed. Both engine type and cycle design parameters are selected to match the engine to the aircraft. The primary reason to investigate various cycle types is the stringent FAR 36, stage III acoustic takeoff requirements. Two general classes of cycle types are considered: high specific thrust engines and high flow engines. The high specific thrust engines currently under investigation are mixed flow turbofans, turbine bypass engines (TBEs) and variable cycle engines (VCEs). The nozzles for the high specific thrust engines demand both elaborate mechanical suppressors and the ability to entrain large amounts of ambient airflow. The high flow cycles, represented by General Electric's Flade and Pratt and Whitney's Inlet Flow Valve/TBE engine, are capable of taking onboard a secondary flow to reduce the nozzle jet velocity (V_{jet}). The noise suppression required decreases with lower nozzle exit velocity, and so the lower V_{jet} of the high flow cycles allows a simpler nozzle than the high specific thrust engines.

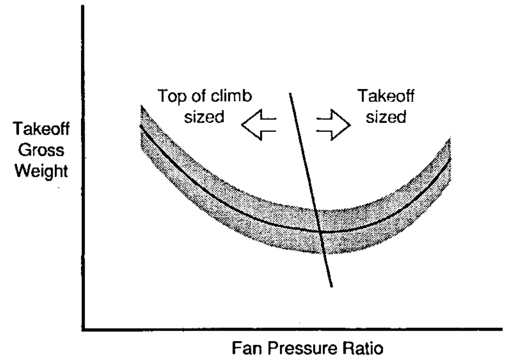

Fig. 1 Cycle impact on HSCT TOGW; simultaneous sized HSCTs, lightest TOGW.

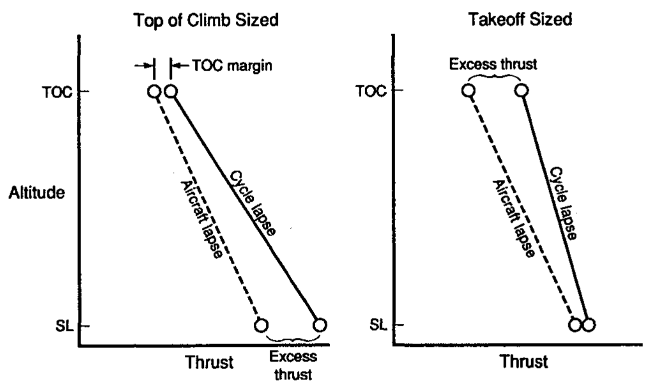

Fig. 2 Engine/airframe matching sizing criteria; relative lapse determines critical sizing criteria.

High Specific Thrust Engine Cycles

Two types of high specific thrust engines are currently being studied under the HSCT program at GE: 1) mixed flow turbofans and 2) variable cycle engines. The turbofans are high fan pressure ratio, mixed flow engines, with variable area mixers and variable area exhaust nozzles. The VCEs have variable area mixers and exhaust nozzles, but a portion of the fan work is moved to an extended first compressor stage, called a core-driven fan. A VCE can operate in single bypass, with the front fan and core-driven stage in series, or in double bypass, with some fan flow bypassing the core-driven fan stage. The ability to operate in single or in double bypass mode extends the airflow holding capability of the variable cycle engine, allowing more efficient part power/full airflow operation for cruise. In addition, splitting the fan work between the low- and high-pressure spools allows lighter turbine designs for high fan pressure ratio cycles.

In the design of a high specific thrust engine, there are three primary independent variables. Each of these influences

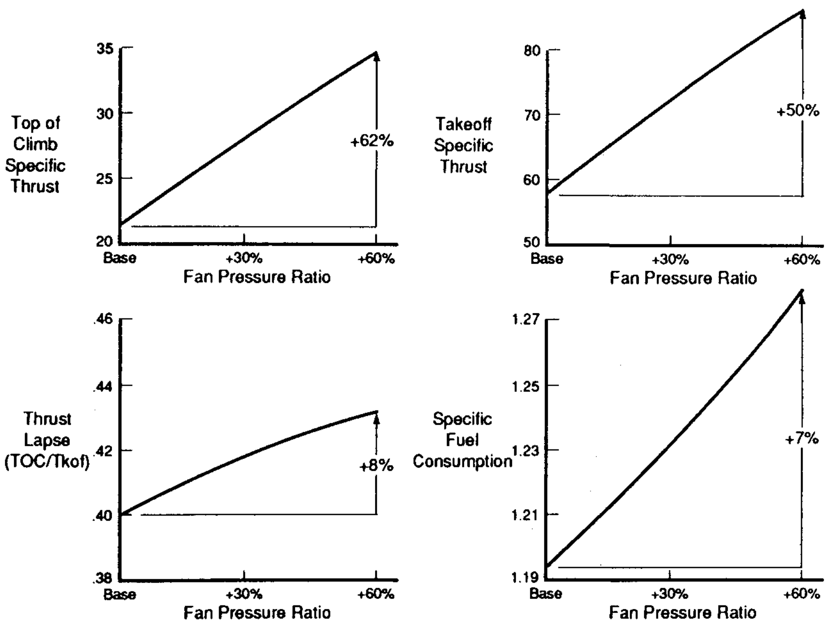

Fig. 3 Fan pressure ratio trends; higher FPR increases thrust lapse and thrust level at the expense of SFC.

the thrust lapse and SFC. They are fan pressure ratio, overall pressure ratio, and throttle ratio. The engine designer's choice of these variables is restricted by a variety of constraints. The engine cycle constraints include material-driven limits on compressor exit and turbine inlet temperatures, minimum bypass ratio for nozzle cooling flow, and maximum total pressure mismatch at the mixing plane (to allow effective mixing). The takeoff thrust can also become limited by the noise suppression capability of the exhaust nozzle. High levels of specific thrust require substatial noise suppression, which implies higher nozzle weight and complexity.

The trends of top of climb specific thrust, takeoff specific thrust, thrust lapse, and SFC with fan pressure ratio are shown in Fig. 3. The specific thrust values used here are calculated based on design airflow at sea level. The top of the climb reference point is at 55,000 ft, Mach 2.4, and the takeoff reference point is at the sideline acoustic measuring point of 689 ft, 0.322 Mach. Because of the small thrust difference between end of climb and beginning of cruise for the HSCT, SFC values are quoted at the top of climb reference point.

Fan pressure ratio is the strongest driver on specific thrust and specific fuel consumption. Increasing the fan pressure ratio increases both takeoff and top-of-climb specific thrust substantially. Since top-of-climb thrust increases faster than takeoff-specific thrust, the thrust lapse rises as fan pressure ratio increases. However, there is a significant SFC penalty for raising the fan pressure ratio. Because of the more favorable thrust lapse and higher specific thrust (smaller engine size), higher fan pressure ratios are preferred for HSCT engines, despite the SFC penalty. The maximum fan pressure ratio that can be used for a mixed flow turbofan or VCE is limited by the minimum bypass ratio constraint.

Throttle ratio is defined as the ratio of maximum (top-of-climb) turbine inlet temperature to sea level static design point turbine inlet temperature. Increasing the throttle ratio for a given fan pressure ratio results in a decrease in bypass ratio, as shown in Fig. 4. Figure 5 shows that an increase in throttle ratio increases top-of-climb specific thrust. Since takeoff thrust is not limited by temperature, the impact of throttle ratio on takeoff specific thrust is very small. Because throttle ratio is a strong driver on top of climb specific thrust, but a weak driver on takeoff specific thrust, a higher throttle ratio results in a higher thrust lapse.

At the higher fan pressure ratios currently favored in HSCT studies, the throttle ratio range available is restricted by the

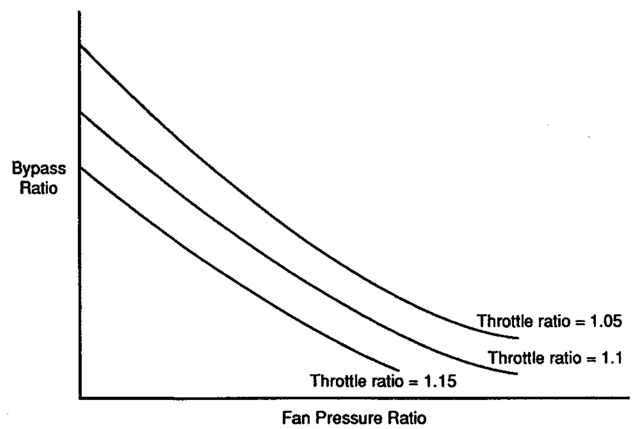

Fig. 4 Variation of bypass ratio with fan pressure ratio and throttle ratio; higher throttle ratio results in lower BPR at constant FPR.

minimum bypass ratio constraint. Within this constraint, a high throttle ratio (low bypass ratio) tends to provide the thrust lapse closest to the aircraft requirements, although at a SFC penalty. Raising throttle ratio has the additional benefit of reducing the mixing plane total pressure mismatch at top of climb, allowing more effective mixing.

The final key engine design variable is overall pressure ratio (OPR). As shown in Fig. 6, an increase in OPR produces a decrease in specific thrust at top-of-climb, which is higher than that at takeoff. This increased OPR results in a reduction in the thrust lapse of the engine, which is detrimental to the current HSCT system. The SFC benefit for increasing overall ratio has so far outweighed the specific thrust penalties for the current HSCT aircraft. Within the limits of compressor discharge temperature, OPR should be maximized for HSCT engines.

To meet the requirements of FAR 36 stage III, or possibly even more stringent goals, significant noise suppression capability is required. The noise predicted for a high specific thrust engine with a conic nozzle as a function of takeoff specific thrust is shown in Fig. 7. For the best engine/aircraft match, the high fan pressure ratio engines require exhaust nozzles that are able to suppress as much as 15 dB. Exhaust nozzles tend to increase in weight and complexity and lose performance due to poorer nozzle thrust coefficients and leak-

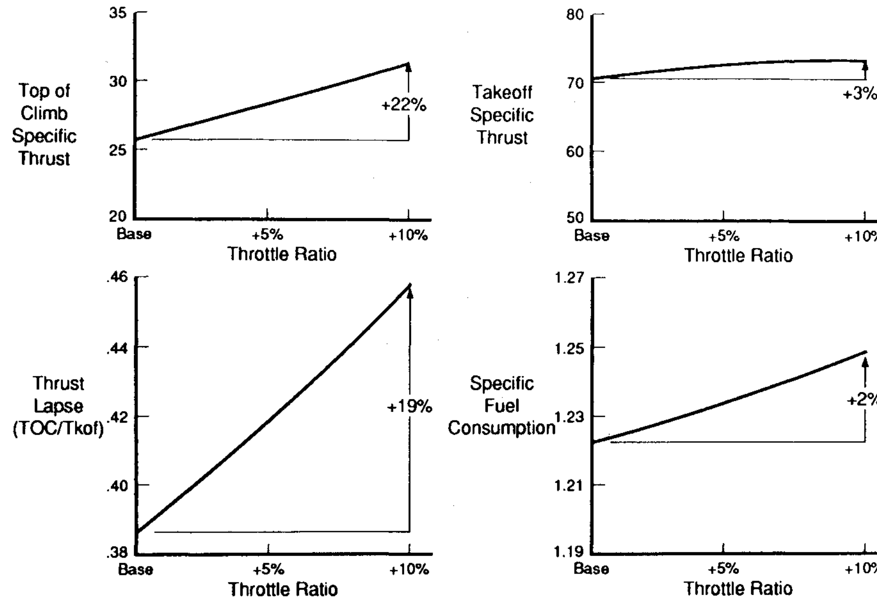

Fig. 5 Throttle ratio trends; higher throttle ratio increases thrust lapse at the expense of SFC; weaker driver on thrust level.

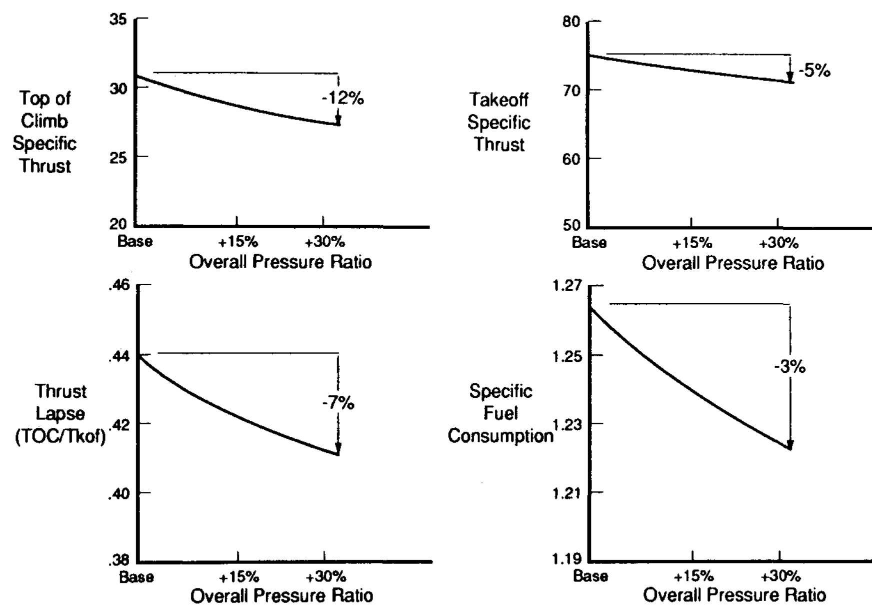

Fig. 6 Overall pressure ratio trends; increasing OPR reduces specific thrust and thrust lapses and improves SFC.

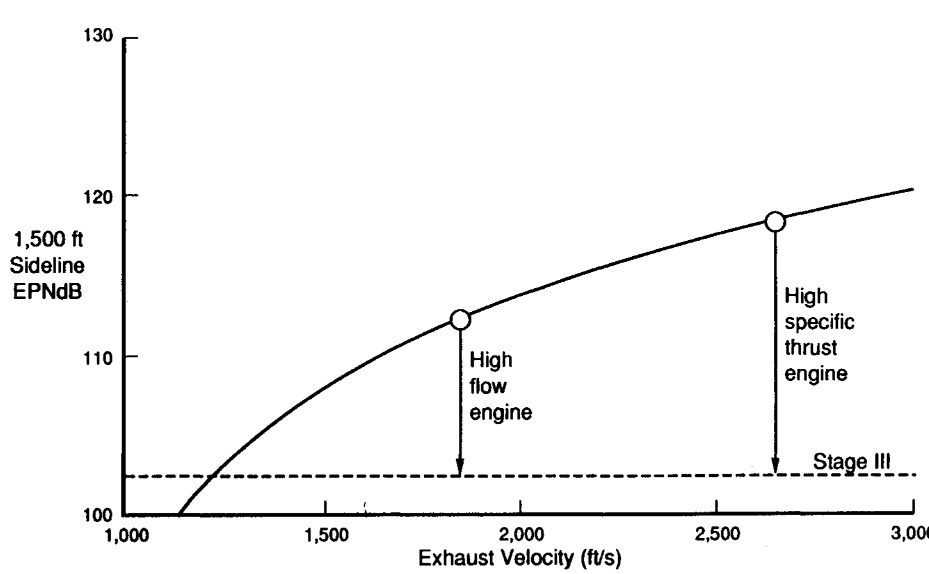

Fig. 7 Acoustic supression requirements; high flow engines require less noise suppression.

age as the noise suppression increases. There is a significant level of risk involved in the design of systems requiring high levels of acoustic suppression. If an acceptable nozzle of the required suppression level cannot be designed, the engine must be oversized so that the required takeoff thrust can be produced at a reduced jet velocity, resulting in a TOGW penalty.

High Flow Engine Cycles

An alternate approach to noise reduction is provided by the high flow engines. The high flow concept currently being studied by GE is the Flade engine. A Flade engine consists of a VCE or mixed flow turbofan with a single-stage extension of the fan tip, providing a separate, low-pressure ratio flow stream. These two engine concepts are contrasted in Figs. 8 and 9. The nozzle shown on the mixed flow turbofan (Fig. 8) entrains ambient air to mix with the core and fan flows to reduce the noise signature. In Fig. 9 the tertiary flow compressed by the fan tip extension is not mixed with the core or fan flow, but is ejected in a separate 200-deg circumferential nozzle to provide a fluid shield surrounding the core flows. The additional airflow is used to provide takeoff thrust at a lower average jet velocity, as shown in Fig. 10. Additional noise reduction is provided by the fluid shield effect of the low-velocity Flade stream. As a result, the amount of mechanical suppression required in the exhaust nozzle is reduced. For subsonic cruise, the Flade stage continues to provide thrust with higher airflow and lower exhaust velocity, resulting in better SFC. At supersonic flight conditions, inlet guide vanes are used to close off the Flade stream as much

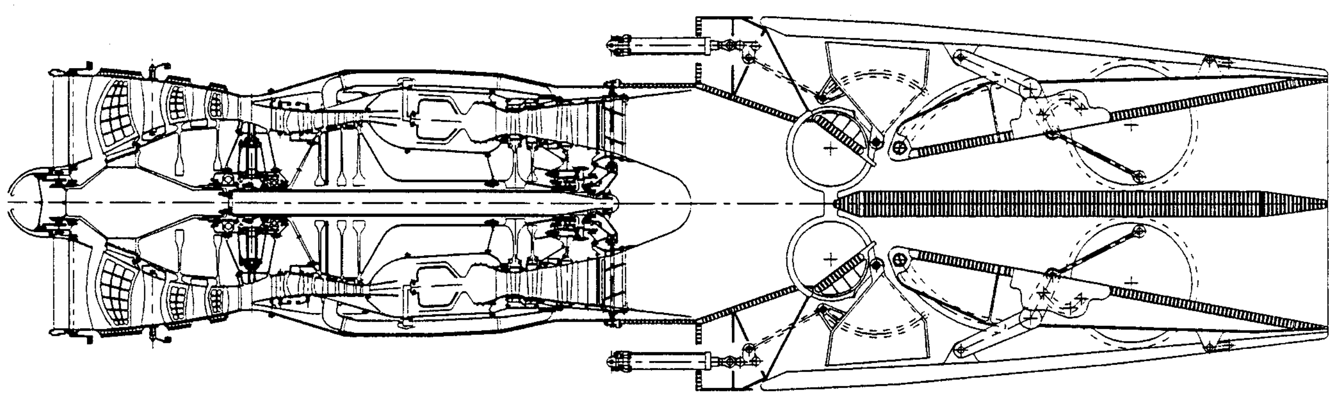

Fig. 8 Flow path diagram, mixed flow turbofan; turbofan shown with mixer ejector nozzle for noise suppression.

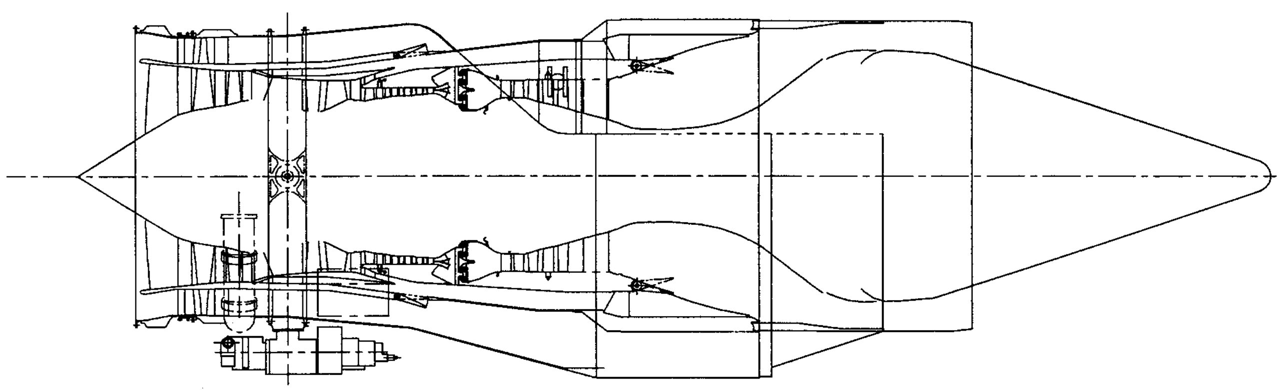

Fig. 9 Flow path diagram, Flade; Flade shown with fluid shield nozzle surrounding lower 200 deg of engine.

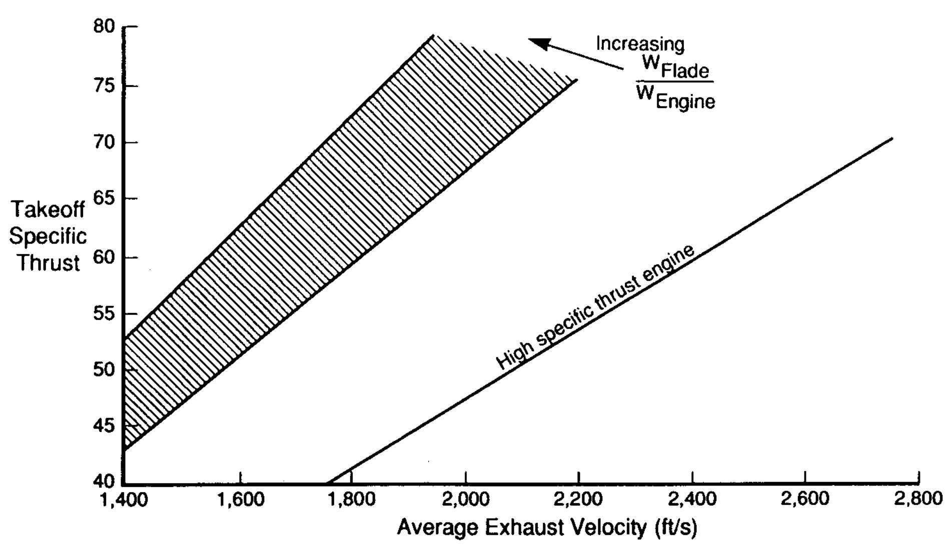

Fig. 10 Takeoff specific thrust trends for Flade engines; increasing Flade size increases specific thrust at same exhaust velocity.

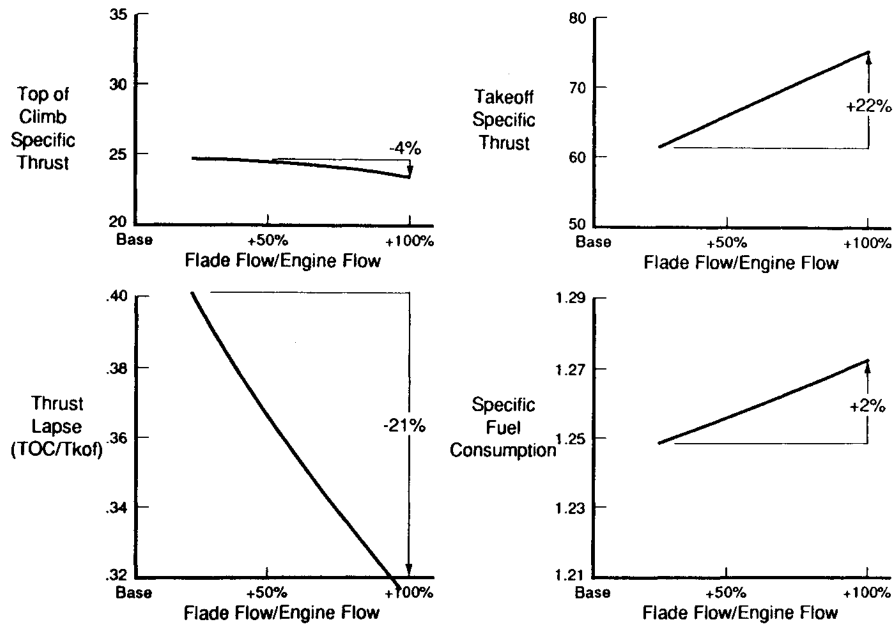

Fig. 11 Flade size trends; larger Flade increases takeoff thrust at V_{jet}; reduces thrust lapse and increases SFC.

as possible, so that the Flade engine operates much like its high specific thrust parent. Optimizing the HSCT with a Flade or mixed flow turbofan yields engines of similar core airflow, since they are both sized at top-of-climb. The Flade has a 10% higher sea level static thrust to weight, but a 19% higher volume, primarily in diameter since it is 12% shorter than a comparable mixed flow turbofan.

The trends of specific thrust, lapse, and SFC associated with Flade streams of varying size are shown in Fig. 11. Note that the specific thrust values are based on the flow of the core VCE engine only. The top of climb specific thrust declines slightly with Flade size, because the Flade stream generates more drag than thrust at Mach 2.4. The SFC deteriorates with increasing Flade size for the same reason. At takeoff, the Flade engine is operated at a reduced power setting to lower the jet velocity, because of its low suppression nozzle. At a given jet velocity, the takeoff thrust increases directly with the total engine airflow. The result is a decreasing thrust lapse with Flade flow. For the current HSCT requirements, a minimum size Flade comes closest to matching the required thrust lapse both subsonically and supersonically, and also minimizes the Mach 2.4 SVD penalty.

Engine/Aircraft System Sensitivities

Minimizing the TOGW for the HSCT will require optimizing both the propulsion package and the airframe together.[1] Figure 12 shows the relative magnitude of the effects of key independent parameters on TOGW. The strongest airframe driver on TOGW is the M2.4 *L/D*. For the propulsion system, cruise nozzle thrust coefficient, top of climb thrust, and cruise SFC are the strongest drivers. A change of 1 dB, either in acoustic requirements or in nozzle suppression capability, also has a strong impact on TOGW. The remaining variables, subsonic SFC and thrust, takeoff nozzle coefficient, and engine weight, have relatively small impacts on TOGW.

Figure 13 shows the impact of matching thrust lapse on TOGW. Engine cycles A–D are four HSCT cycles recently studied by GE. These cycles were all top-of-climb sized. This allows the takeoff to be performed using less than the maximum thrust available. As the cycle lapse approaches the airframe lapse, the engines become smaller and the mismatch between the thrust available and thrust required at takeoff is reduced. The apparent excess thrust in Fig. 13 at takeoff may not be available if the noise goals cannot be met at maximum dry power. All of the engines shown could provide a satis-

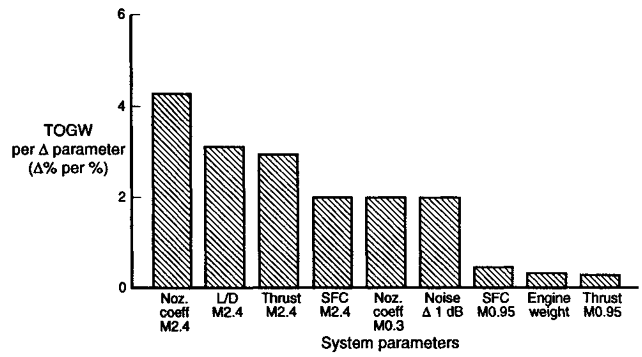

Fig. 12 Various system sensitivities; variables exist to control TOGW in airframe, propulsion, operations, and requirements.

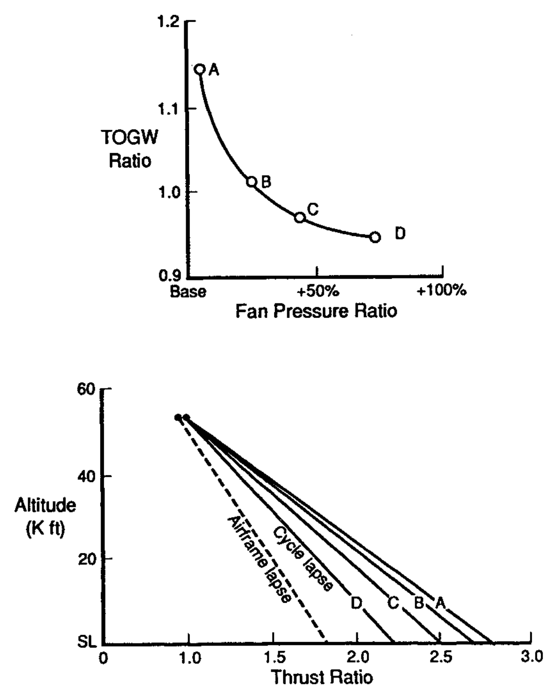

Fig. 13 Engine/airframe matching optimization; HSCT weight minimized as engine lapse approaches aircraft lapse.

factory takeoff at less than maximum power (i.e., lower V_{jet}), thus relieving the suppression level of the nozzle. The minimum TOGW system for this set of assumptions will be reached at the point where the engine and airframe thrust lapses are matched, a coincidentally sized system. The engine cycle providing the minimum system weight for supersonic transports will be the highest fan pressure ratio for which adequate noise suppression can be provided, not the engine with the best SFC.

A critical point to note is that the choice of engine cycle is highly dependent on the airframe characteristics. For instance, an improvement in M2.4 L/D would reduce the TOC thrust requirement, reducing the required thrust lapse and changing the optimum engine cycle. Similarly, poorer takeoff L/D would increase the thrust requirement at takeoff, also reducing the thrust lapse. To select an appropriate engine cycle, the aircraft characteristics should be known with a high degree of confidence. This will require close cooperation in the conceptual design stages between the airframers and engine manufacturers. Also, it should be clear from the preceding discussion that two proposed aircraft with disparate aerodynamic characteristics cannot be optimized to the same engine selection. An airframe with better cruise and/or worse takeoff performance will require a lower lapse, lower FPR engine.

Conclusions

The HSCT has more challenging environmental and economic goals than any preceding commercial aircraft program. To meet these goals, all aspects of the program must be optimized as a system, including the propulsion system, airframe, operational procedure, and requirements. The choice of engine cycle type is driven primarily by nozzle philosophy. A high specific thrust engine will require a complex, high-risk exhaust nozzle. A high flow engine will have a simpler nozzle, but a larger and more complex engine. Within either engine type, the selection of fan pressure ratio, throttle ratio, and overall pressure ratio is driven by the airframe thrust lapse requirements. If the engine and airframe lapses are matched, the HSCT takeoff gross weight will be at a minimum. And finally, as the airframe thrust requirements evolve during the conceptual design process, changes in the engine cycle design will be required to keep the system optimized for a minimum TOGW and maximum economic return.

Reference

[1]Elliott, D. W., Hoskins, P. D., and Miller, R. F., "A Variable Geometry HSCT," AIAA Paper 91-3101, Sept. 1991.