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Conceptual Design of a Supersonic Business Jet Propulsion System

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Conceptual Design of a Supersonic Business Jet Propulsion System

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Abstract

NASA's Ultra-Efficient Engine Technology Program (UEETP) is developing a suite of technology to enhance the performance of future aircraft propulsion systems. Areas of focus for this suite of technology include: Highly Loaded Turbomachinery, Emissions Reduction, Materials and Structures, Controls, and Propulsion-Airframe Integration. The two major goals of the UEETP are emissions reduction of both landing and take-off nitrogen oxides (LTO-NO_X) and mission carbon dioxide (CO_2) through fuel burn reductions. The specific goals include a 70% reduction in the current LTO-NO_X rule and an 8% reduction in mission CO_2 emissions. In order to gain insight into the potential applications and benefits of these technologies on future aircraft, a set of representative flight vehicles was selected for systems level conceptual studies. The Supersonic Business Jet (SBJ) is one of these vehicles. The particular SBJ considered in this study has a capacity of 6 passengers, cruise Mach Number of 2.0, and a range of 4,000 nautical miles. Without the current existence of an SBJ the study of this vehicle requires a two-phased approach. Initially, a hypothetical baseline SBJ is designed which utilizes only current state of the art technology. Finally, an advanced SBJ propulsion system is designed and optimized which incorporates the advanced technologies under development within the UEETP. System benefits are then evaluated and compared to the program and design requirements. Although the program goals are only concerned with LTO-NO_X and CO_2 emissions it is acknowledged that additional concerns for an SBJ include take-off noise, overland supersonic flight, and cruise NO_X emissions at high altitudes. Propulsion system trade-offs in the conceptual design phase acknowledge these issues as well as the program goals. With the inclusion of UEETP technologies a propulsion system is designed which performs at 81% below the LTO-NO_X rule, and reduces fuel burn by 23% compared to the current technology.

Nomenclature

BPR	Bypass Ratio
F	figure of merit
Fn	Engine thrust
Fn_{lapse}	Engine thrust at TOC/Engine thrust at SLS
FPR	Fan Pressure Ratio
HPC	High Pressure Compressor
LTO	Landing and Take-Off
NO_x	Nitrogen oxides
P_3	compressor discharge pressure
SBJ	Supersonic Business Jet
SLS	Sea Level Static
T_3	compressor discharge temperature
T_4	combustor discharge temperature
TOC	Top Of Climb
TTR	Throttle Ratio
UEETP	Ultra-Efficient Engine Technology Program
Wc	Corrected weight flow
Wc_{lapse}	Wc at TOC/Wc at SLS
α_{1-5}	coefficients of the figure of merit surfaces
Φ	independent variable fan pressure ratio
τ	independent variable throttle ratio

Introduction

NASA's Ultra Efficient Engine Technology Program (UEETP) is developing a suite of technology to enhance the performance of future aircraft propulsion systems. Areas of focus for this suite of technology include: Highly Loaded Turbomachinery, Emissions Reduction, Materials and Structures, Controls, and Propulsion-Airframe Integration. The two major goals of the UEETP is emissions reduction of both landing and take-off nitrogen oxides (LTO-NO_X) and mission carbon dioxide (CO_2) through fuel burn reductions. The specific goals include a 70% reduction in the current LTO-NO_X rule and an 8% reduction in mission CO_2 emissions.

The commercial jet aircraft fleet is quite uniform in its appearance and function and has been this way for several decades. The common features include a cylindrical fuselage mounted on top of a slender, swept wing with under-hung engines at the leading edge flying at high subsonic speeds. However, the SBJ vehicle chosen for this study follows the more current trend of smaller jet aircraft. In addition to its smaller size, the SBJ also incorporates the desire for speed beyond the high subsonic Mach Numbers of the modern commercial fleet.

The high end of commercial travel is eroding from the large commercial carriers [1] and being deposited into the business jet market, which has seen dramatic growth in recent years. As such, the acquisition cost of today's high-end business jets is no longer that much different from the projected cost of a SBJ. This commercial argument for the analysis of the SBJ seems powerful enough to include this aircraft in the program. However, this does not consider other potential applications of a small supersonic aircraft such as military use and the delivery of time-critical payloads. The selection of a small yet fast aircraft to represent the supersonic technologies of UEETP is based upon the historical success of first developing aircraft speed followed by the ensuing growth in size.

Without the existence of a current SBJ in today's aircraft market, this study required a two-phased approach. The initial phase required the design of a current technology SBJ engine and vehicle that is representative of what might be possible given the current state-of-the-art. The second phase of the study included the addition of the UEETP technologies to the baseline mixed-flow turbofan engine and a parametric study that examined the effects of throttle ratio and fan pressure ratio on the final vehicle design. A final engine design was then selected from this parametric study. Preliminary component designs were carried out on the final engine to add confidence to the conceptual design philosophy and weight estimates. An economic analysis was also conducted on the final engine.

SBJ Design Requirements

The mission requirements of the SBJ are rather standard for a civilian aircraft with the exception of the supersonic cruise Mach number. The SBJ, which is considered in this study, has a capacity for 6 passengers, range of 4,000 nautical miles, and cruise Mach number of 2.0. A complete listing of the mission requirements is presented in Table 1. The SBJ conceptual design is also constrained emissions, noise and affordability. The first of these, emissions, include the LTO-NO_X and mission CO_2 goals of the UEETP as well as the mission NO_X due to the higher cruising altitude of the SBJ. The noise constraint is primarily a take-off issue and is evaluated by using exhaust jet velocity as a surrogate for jet noise and applying appropriate acoustic attenuation methods. This constraint also manifests itself in the overland supercruise scenario. In order to make the SBJ more economically viable, overland supersonic flight is desirable. Although the UEETP does not address sonic boom issues, the assumption for this study is that in the timeframe required to bring the UEETP engine technologies to maturity, complementary airframe programs will develop technologies, which will make overland supersonic flight possible. The constraint of affordability in the conceptual design phase is only evaluated on the final, selected engine.

Current Technology Engine Design

The only propulsion system type, which is considered in both the baseline design as well as the advanced technology design, is the low bypass ratio mixed-flow turbofan engine.

A summary of the main engine cycle parameters that were used in the current technology design is contained in Table 2. Figure 1 shows a cross section of the baseline engine. This engine is not meant to represent any particular engine available today. Rather, it is representative of the type of engine that could be built for the SBJ with the current state of the art.

UEETP Technology Suite

The technology developed by the UEETP falls into the following categories: Highly Loaded Turbomachinery, Emissions Reduction, Materials and Structures, Controls, and Propulsion-Airframe Integration. The specific technologies, which are applied to the SBJ, are detailed in Table 3. Some of the key engine cycle parameters were chosen as follows. The overall pressure ratio was selected such that the maximum compressor discharge pressure, P_3, was achieved at the top of climb point, Mach Number 2.0 and 50,000 feet altitude. The bypass ratio was selected to yield an extraction ratio, the ratio of bypass to core stagnation pressure, of 1.05 at the cycle design point. Fan pressure ratio and throttle ratio, the ratio of maximum temperature at top of climb to the maximum temperature at sea level static, were varied in the parametric study of the design space. All of the engine cycles in the parametric study used a velocity coefficient of 0.975, a mixer-ejector nozzle to suppress take-off noise, 75 horsepower take-off from the high pressure spool, 0.5 pounds per second of customer bleed at the compressor discharge, 4.65% non-chargeable cooling flow for the high pressure turbine, 0.96% chargeable cooling flow to the high pressure turbine, and no cooling to the low pressure turbine.

Advanced Technology Design Space Study

A preliminary design space was investigated which ranged from 2.4 to 3.6 in fan pressure ratio and from 1.104 to 1.149 in throttle ratio. Five engines, designated e1 through e5, were included in the cycle, aeromechanical, mission, and aircraft sizing analysis. Mission block fuel, aircraft take-off gross weight, LTO- NO_X, mission NO_X, and ideal mixed jet velocity were used as figures of merit to evaluate the design space of this parametric study. Contour surfaces were modeled which examined the first order effects of both fan pressure ratio and throttle ratio, second order effects of fan pressure ratio, and the interaction of both parameters. As such the mathematical form of the figure of merit surfaces is detailed below.

$$F(\tau,\phi) = \alpha_1 + \alpha_2 \tau + \alpha_3 \phi + \alpha_4 \phi^2 + \alpha_5 \tau \phi$$

Here $F(\tau,\phi)$ represents one of the figures of merit, mission block fuel, take-off gross weight, LTO-NO_X, mission NO_X, or unsuppressed sea level static, SLS, jet velocity. The coefficients, α_{1-5}, are calculated deterministically from the results of the five e-series engines.

The initial design space contours indicated that the optimum engine selection would lie near the point of 3.0 fan pressure ratio and maximum achievable throttle ratio. However this point is difficult to determine precisely since at high throttle ratio the maximum T_4 may not be achieved in the engine cycle. In order to design the most compact and efficient engine possible given the UEET suite of technologies it is desirable to reach the maximum T_4. Therefore, the strategy used to determine the optimum engine design included designing a new series of 12 engines in the range of 2.8 to 3.2 fan pressure ratio and 1.108 to maximum achievable throttle ratio. These engines were designated f1 through f12. Contour plots of the five figures of merit are shown in figures 2–6. The contours in these figures are calculated based on the initial set of five engines, e1 through e5. The second series of engines, f1 through f12, are shown on the figures to illustrate the region of focus.

Figures 2 and 3 contain the contours of mission fuel weight and take-off gross weight. The trends in both figures indicate that for the minimum fuel burn and system weight it is desired to move the design toward higher throttle ratio and medium fan pressure ratio. This trend provides for the minimum fuel burn that in turn maximizes the CO_2 reduction. It also minimizes the overall weight, which has historically been a very accurate predictor of cost.

Figure 4 contains the contour of mission NO_X emissions. Here the trend for minimizing mission NO_X is to move toward higher fan pressure ratios at low throttle ratios, but is somewhat independent of fan pressure ratio at higher throttle ratio. Therefore, this figure of merit also indicates a desire to move toward both higher throttle ratio and fan pressure ratio.

Figure 5 contains the LTO-NO_X trends. Here the desire to minimize LTO-NO_X emissions would indicate a trend toward higher throttle ratios and lower fan pressure ratios. However, not highlighted on this figure is the fact that the entire design space investigated by this parametric study satisfies the UEETP goal of a 70% LTO-NO_X reduction from the current rule. Similar to the mission NO_X figure of merit, the trend for minimizing LTO-NO_X is to move toward as high of a throttle ratio as is possible while still achieving the maximum T_4 allowed under the UEETP technologies.

Finally, in figure 6 the ideal, unsuppressed jet velocity is shown as a surrogate for take-off noise. The trend that lower jet velocities yield quieter aircraft indicates that the SBJ engine should be designed at lower fan pressure ratios. However, all the engines shown in the design space would require some means of noise suppression based on the projected noise rule for this type of aircraft. The jet velocity also appears to be rather insensitive to the throttle ratio.

The selection of engine f6 was made as the best choice in balancing all of the desired figures of merit for this conceptual design. All of the figures of merit showed a trend toward higher throttle ratio with the exception of SLS jet velocity. The jet velocity trend showed very little sensitivity to throttle ratio and was primarily driven by fan pressure ratio. Engines f1, f5, and f12 were not selected because these engines did not reach the maximum allowable temperatures at top of climb, TOC, which is an indication that they were throttled back too much at the design point. The block fuel, take-off gross weight, and the jet velocity determined the fan pressure ratio selection of

3.0. While the f6 and f10 engines showed comparable fuel and gross weight, the decision for the selection of the lower fan pressure ratio was driven by the reduced SLS jet velocity. A summary of the f6 engine characteristic as well as a conceptual flowpath design is contained in Table 4 and Figure 7 respectively.

Upon selection of the optimum SBJ engine from the design space of the f series engines a preliminary component design exercise was perform which substantiated many of the assumptions of the flowpath design and weight estimations of the conceptual phase. An economic analysis was performed which indicated that the Supersonic Business Jet, which incorporates the UEETP technologies, would reduce the cost of the aircraft by nearly 14%.

Summary

A propulsion system has been designed for a supersonic business jet, which incorporates the advanced technologies of NASA's Ultra Efficient Engine Technology Program. A parametric study was performed over a range of fan pressure ratio and throttle ratio to determine the optimum engine configuration for these conditions. Based on the UEETP goals of reduced CO_2 and LTO-NO_x emissions as well as ancillary considerations of minimum take-off gross weight, mission NO_x emissions, and projected take-off noise, the final engine was designed to have a fan pressure ratio of 3.0 and throttle ratio of 1.143. The resultant system satisfied all program goals by reducing fuel burn by over 23% compared to the current technology system and produced LTO-NO_x at 81% below the current rule.

References

[1]Aboulafia, Richard, "The Business Case for Higher Speed," Aerospace America, AIAA, July, 2001.

SBJ design requirements and constraints	
Mission	
Payload	6 passengers
Range	4000 nautical miles
Cruise Speed	2.0 Mach Number
Cruise Altitude	(50,000 – 60,000) feet
Emissions	
LTO-NO_x	–70% compared to current rule
Mission CO_2	–8% compared to current technology
Cruise NO_x	minimize high altitude impact
Noise	
Takeoff	Suppressed to current rules
Cruise	Overland supersonic flight
Economics	
Affordability	Evaluated for baseline and final design

Table 1. SBJ design requirements and constraints

SBJ Baseline Propulsion System	
FPR, Φ	2.80
HPC PR	9.60
BPR Des	1.21
T_4 Max (deg. R)	3385
T_4 Des (deg. R)	3160
SLS Jet Velocity (fps)	1808
TTR, τ	1.071
Wc lapse	0.825
Fn lapse	0.30
Fn SLS (lbf)	22112
SFC SLS [(lbm/hr)/lbf]	0.594
Fn TOC (lbf)	6385
SFC TOC [(lbm/hr)/lbf]	1.170
TOGW (lbm)	119294
Block Fuel (lbm)	52488
LTO NO_x (g NOx/kN)	60.96
Mission NO_x (lbm)	1427

Table 2. Current Technology Engine Design Cycle Parameters

SBJ-Baseline Propulsion System

Thrust SLS (LBF) = 22,112

Engine Pod Weight (LBF)= 11,599

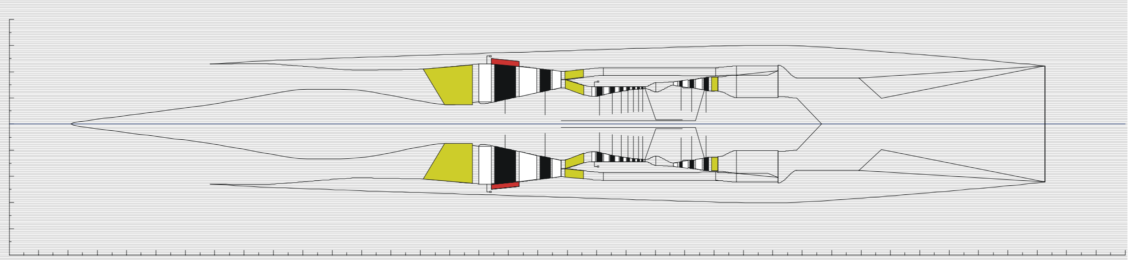


Figure 1. SBJ Baseline Propulsion System

Technology Name	Maximum Technology Impact
Emission Reduction for Regional Engines	–70% Emission Index; Reduce combustor liner cooling to 10%
High-Loaded Multistage Compressor	Increase fan/HPC loading by 50%; Increase fan/HPC polytropic efficiency by 1%
High-Loaded HP/LP Turbine Systems	Increase HPT/LPT loading by 25%; increase LPT adiabatic efficiency by 1%
2700 °F CMC Components	Increase allowable turbine vane temperature to 2700 °F
Turbomachinery Disk Alloy	Increase allowable T_3 temperature to 1350 °F
Low Conductivity Ceramic TBC for Turbine Airfoils	Increase allowable turbine blade temperature to 2250 °F
Lightweight Nozzle Materials	Reduce mixer-ejector weight (if used) by 10%
Active Shape Control Technologies for Variable Radius Inlet Lip	Remove inlet blow-in door weight
High Reynolds No. Design Tools for Advanced Configurations	Reduce total A/C drag by 1%
Combustor Controls	Reduce T_4 margin requirement (improved pattern factor) by 60 °F
Adaptive Engine Controls	Reduce engine SFC by 0.5%

Table 3. Technology Suite of the UEETP

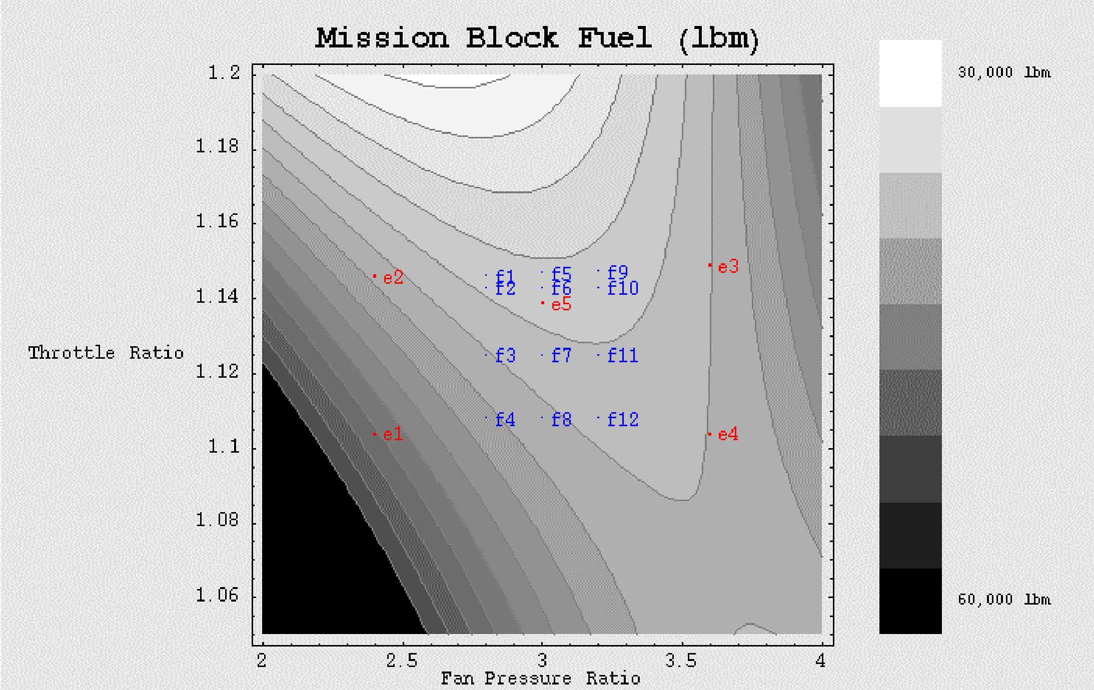


Figure 2. Contours of Mission Block Fuel

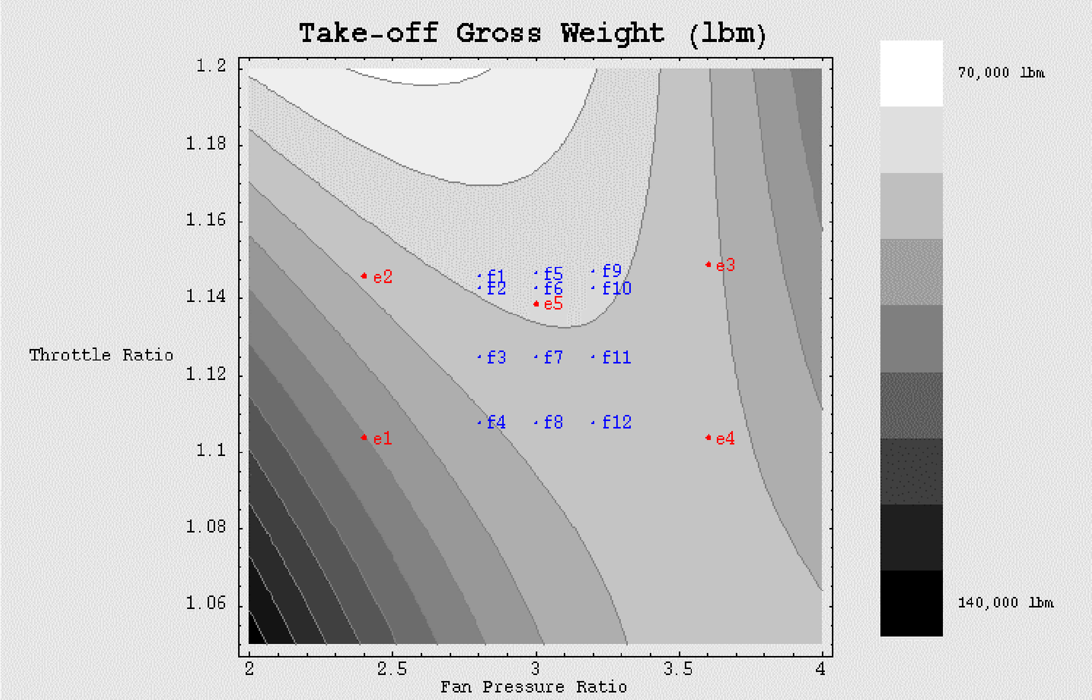


Figure 3. Contours of Take-off Gross Weight

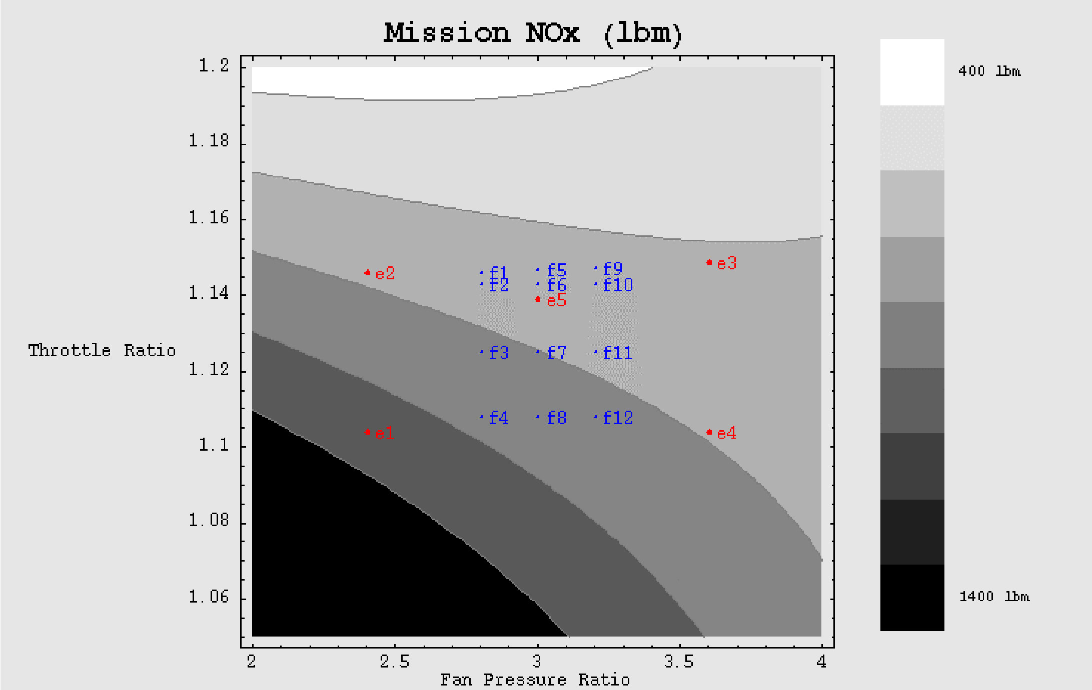


Figure 4. Contours of Mission NOx Emissions

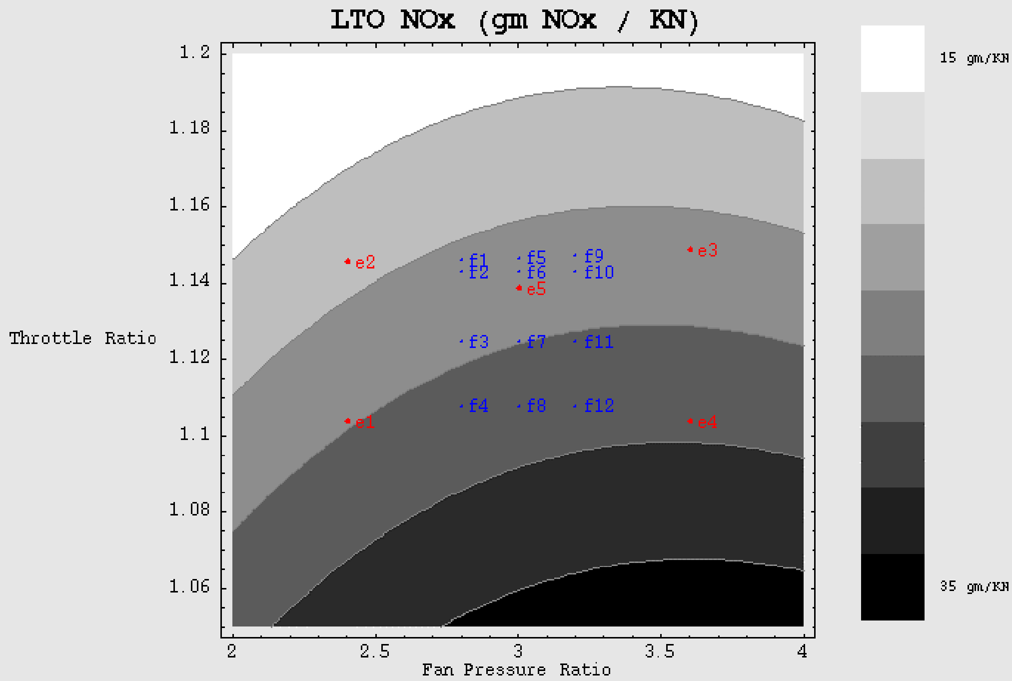


Figure 5. Contours of LTO-NOx Emissions

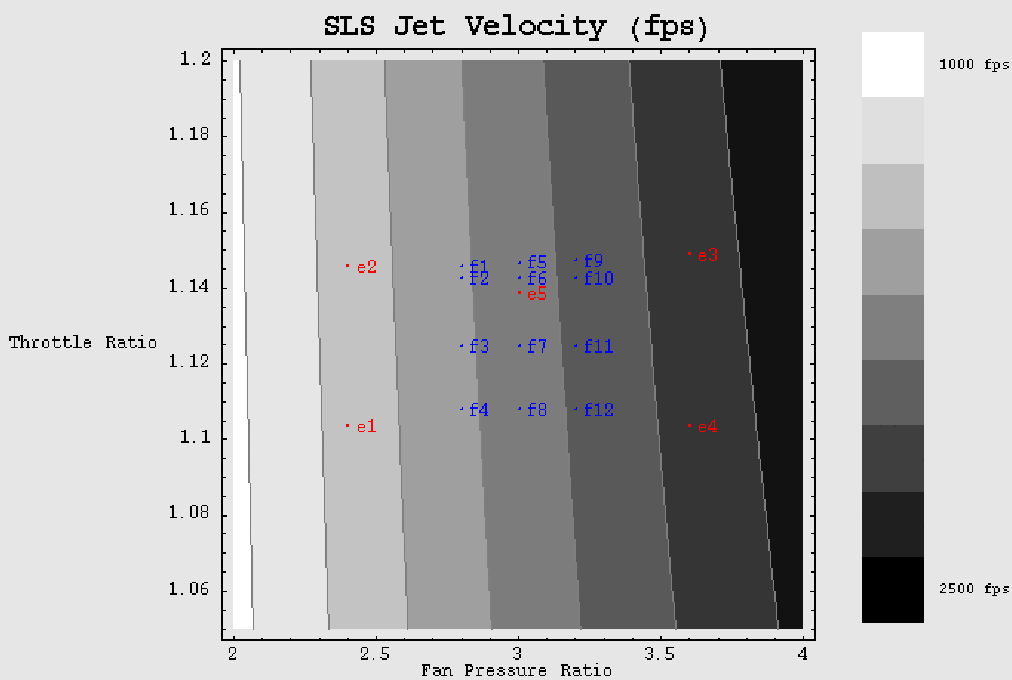


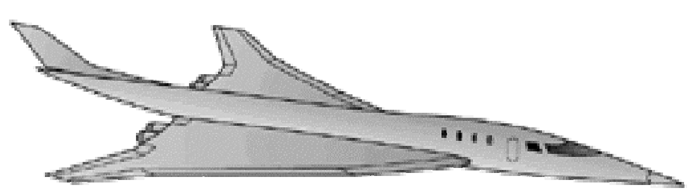
Figure 6. Contours of SLS Jet Velocity

SBJ Baseline Propulsion System	
FPR, Φ	3.00
HPC PR	11.20
BPR Des	1.88
T_4 Max (deg. R)	3600
T_4 Des (deg. R)	3150
SLS Jet Velocity (fps)	1833
TTR, τ	1.143
Wc lapse	0.825
Fn lapse	0.33
Fn SLS (lbf)	22398
SFC SLS [(lbm/hr)/lbf]	0.547
Fn TOC (lbf)	7442
SFC TOC [(lbm/hr)/lbf]	1.102
TOGW (lbm)	93368
Block Fuel (lbm)	40166
LTO NO_x (g NOx/kN)	22.33
Mission NO_x (lbm)	897

Table 4. Current Technology Engine Design Cycle Parameters

Comparison of the Baseline and UEETP Propulsion System		
	Baseline	UEETP
FPR, Φ	2.80	3.00
HPC PR	9.60	11.20
BPR Des	1.21	1.88
T_4 Max (deg. R)	3385	3600
T_4 Des (deg. R)	3160	3150
SLS Jet Velocity (fps)	1808	1833
TTR, τ	1.071	1.143
Wc lapse	0.825	0.825
Fn lapse	0.30	0.33
Fn SLS (lbf)	22112	22398
SFC SLS [(lbm/hr)/lbf]	0.594	0.547
Fn TOC (lbf)	6385	7442
SFC TOC [(lbm/hr)/lbf]	1.170	1.102
TOGW (lbm)	119294	93368
Block Fuel (lbm)	52488	40166
LTO NO_x (g NOx/kN)	60.96	22.33
Mission NO_x (lbm)	1427	897
% Below NO_x Rule	39.7	81.0
% Fuel Burn Reduction (from baseline)	-	23.48
Cost ($M)	87.90	75.70
Cost Reduction (%)		13.88
LTO-NOx rule (g NOx/KN)		117.31
LTO-NOx reduction from baseline system (%)		63.37

Table 5. Comparison of the Baseline and UEETP SBJ Propulsion System.



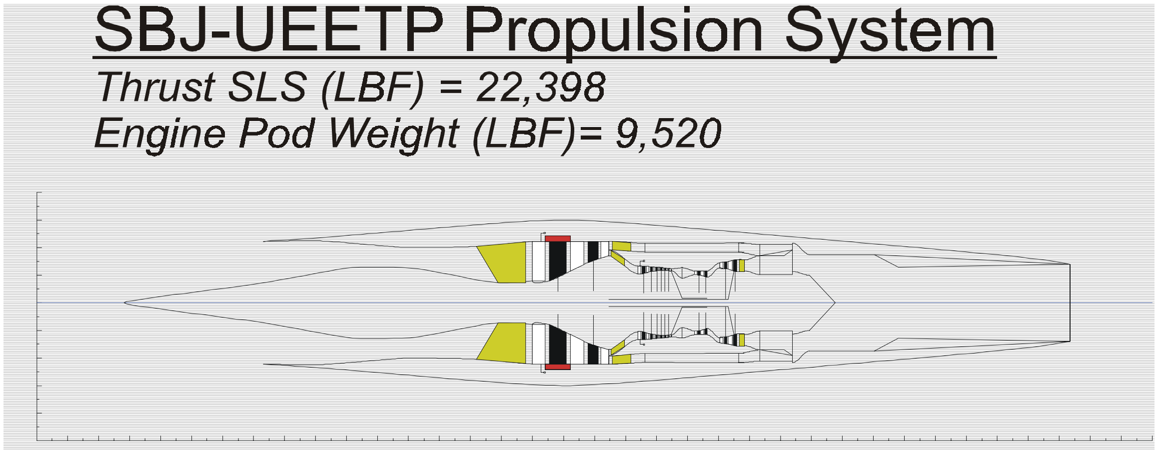


Figure 7. SBJ UEETP Propulsion System

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13. ABSTRACT ***(Maximum 200 words)***

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