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August 2004

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Document History

This research was originally published internally as HSR049 in February 1997.

Available from

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Abstract

A parametric study is conducted to evaluate a mixed-flow turbofan equipped with a supersonic through-flow rotor and a supersonic counter-rotating diffuser (SSTR/SSCRD) for a Mach 2.4 civil transport. Engine cycle, weight, and mission analyses are performed to obtain a minimum takeoff gross weight aircraft. With the presence of SSTR/SSCRD, the inlet can be shortened to provide better pressure recovery. For the same engine airflow, the inlet, nacelle, and pylon weights are estimated to be 73 percent lighter than those of a conventional inlet. The fan weight is 31 percent heavier, but overall the installed engine pod weight is 11 percent lighter than the current high-speed civil transport baseline conventional mixed-flow turbofan. The installed specific fuel consumption of the supersonic fan engine is 2 percent higher than that of the baseline turbofan at supersonic cruise. Finally, the optimum SSTR/SSCRD airplane meets the FAR36 Stage 3 noise limit and is within 7 percent of the baseline turbofan airplane takeoff gross weight over a 5000-n mi mission.

Nomenclature

$A_{O_{eng}}/A_c$	ratio of engine airflow to inlet capture area
Arotor	rotor entrance area, ft^2
BPR	bypass ratio
CET	combustor exit total temperature, °R
C_v	nozzle velocity coefficient
C_M	mixer momentum coefficient
dcm	supersonic counter-rotating diffuser choke margin
dcp	parameter indicating margin of maximum fan pressure ratio limit
E	mixer effectiveness
F_n/W_a	specific thrust, lb/lbm/s
FPR	fan overall pressure ratio
k	ratio of mixer secondary to primary total pressure
LHV	lower heating value, Btu/lbm
MFTF	mixed-flow turbofan
$m_1\sqrt{\theta}/(\delta\ Arotor)$	rotor specific flow, $lbm/s/ft^2$
$N_1/\sqrt{\theta}$	rotor corrected speed
OEW	operating empty weight, lb
$\Delta P/P$	frictional relative total pressure drop
PTR1	supersonic rotor pressure ratio
PTR2	supersonic rotating diffuser pressure ratio
SLS	sea level static
SSCRD	supersonic counter-rotating diffuser
SSTR	supersonic through-flow rotor
scm	stator choke margin
TOGW	takeoff gross weight, lb
TSFC	thrust specific fuel consumption, lbm/hr/lb
TT3	compressor exit total temperature, °R
TT41	high-pressure turbine rotor inlet total temperature, °R

$T8_{max}$	maximum nozzle exit total temperature, °R
TTR	ratio of maximum CET over sea level static CET
V_j	jet velocity, ft/s
W_{corr}	corrected airflow, lbm/s
w_l / w_t	fraction of air not heated in the burner but allowed to mix at exit, reducing the exit temperature
δ	ratio of total pressure at supersonic rotor face to SLS total pressure
θ	ratio of total temperature at super sonic rotor face to SLS total temperature
η	efficiency

Subscripts:

ad	adiabatic
b	burner
c	cowl
eng	engine
p	polytropic
0	ambient

Introduction

In the mid 1970's, NASA Glenn Research Center sponsored studies through Pratt and Whitney and General Electric to identify propulsion systems that would be suitable for long-range supersonic cruise aircraft.[1-7] These propulsion systems comprised conventional and variable-cycle concepts. Towards the end of the decade, an alternative concept arose, the supersonic through-flow fan variable-bypass (STFF) engine. This propulsion system was studied by Advanced Technology Laboratory[8] and NASA Glenn.[9-11] The engine (fig. 1)[12] incorporates a single-stage supersonic through-flow fan that has supersonic axial Mach numbers at the fan face and stator exit. The flow exiting the STFF splits into two streams: the bypass stream exits the engine through a variable-area fan exhaust nozzle, and the core stream passes through an inlet and diffuses to subsonic conditions prior to entering the high-pressure compressor.

In 1989, NASA sponsored the High Speed Research (HSR) Program with the objective of providing a future high-speed civil transport (HSCT). Both airframe and engine manufacturers were involved in the program to develop an environmentally compatible, economically viable, Mach 2.4 HSCT with a market-entering year of 2005. Environmental compatibility is defined as complying with the FAR36 Stage 3 noise rules at takeoff and meeting the acceptable level of ozone-depleting NO_x emissions. Economic viability is defined as achieving a balance between the aircraft cost and the commercial value.[13]

Method of Analysis

The engine cycle performance was calculated using the NASA Engine Performance Program (NEPP),[14] which performs a one-dimensional, steady-state thermodynamic analysis. Compressor and turbine maps were used to represent the thermodynamic and aerodynamic performance of the rotating components. Each studied engine had to adhere to the high-speed research engine cycle ground rules shown in table 1.[15]

The inlet performance data were obtained using the Inlet Performance Analysis Code (IPAC),[16] which applies the oblique shock and Prandtl-Meyer expansion theories to predict inlet performance. Additive, bleed, bypass, and spillage drag coefficients are being calculated for all flight Mach numbers. Boattail drags were estimated using the integral mean slope (IMS) boattail drag method on a two-dimensional fixed-chute nozzle (FCN).

The geometry and weights of SSTR/SSCRD components were estimated using the engine weight code WATE-2.[17] WATE-2 requires thermodynamic cycle outputs from NEPP and user-supplied material and structural inputs. The engine material and structural assumptions for the supersonic fan were obtained from reference 12. For cycle screening purposes, all engines were sized for the same engine sea level static (SLS)

corrected airflow of 680 lbm/sec, had the same capture area of 23.6 ft^2, the same rotor area of 14.3 ft^2, and a combined inlet, nacelle, and pylon weight of 1310 lb. Based on the nozzle weight evaluations of mixer-ejector nozzles done in support of HSR system studies, the fixed-chute nozzle (FCN, fig. 2)[18] with an estimated weight of 4400 lb was selected. It was assumed that this nozzle weight would be the same for all cycles evaluated in this study and that the nozzle had sufficient noise suppression capability to ensure that the loudest of the SSTR/SSCRD engines would meet stage III noise requirements. Noise estimations were not performed; however, ideal jet velocities are presented for acoustic comparison.

The mission was evaluated using the Flight Optimization Program (FLOPS Version 5.7).[19] Using methods that are applicable to high-speed transport aircraft, the wing and engine sizes were parametrically varied while the aircraft weights and aerodynamics were systematically altered. The aspect ratio of the wing remains constant as the wing changes. An aircraft-sizing "thumbprint" (fig. 3) is included to show the effect of various constraints with SLS thrust and wing area. The following constraints were used in the analysis: a FAR 25 takeoff field length of 10 800 ft, an approach velocity of 155 knots, an excess fuel weight of 20 000 lb, and a climbing time of 60 min. A typical "aircraft design point" that met all the constraints was selected on the thumbprint. The airplane used in the study (fig. 4)[20] is a NASA derivative of the Technology Concept Airplane (TCA) that carries 301 passengers and cruises at Mach 2.4 at 60 000 ft. The aircraft design, a joint effort of Boeing and McDonnell Douglas, is based on projected 2005 technology. The HSCT design mission is shown in figure 5.[20] The fuel weight is a cumulative total based on all the segments shown in figure 5 plus reserves. Fuel reserves are based on a 200-mile mission to an alternate airport plus a 30-min hold and contingency fuel.

Engine Description

A fairly new concept is the supersonic through-flow rotor with a supersonic counter-rotating diffuser (SSTR/SSCRD) engine for a Mach 2.4 transport (fig. 6).[12] Because this engine provides a lower propulsion weight and a better engine performance, we can expect a lower takeoff gross weight airplane than that having the STFF engine. This paper presents the results of a parametric study conducted on an SSTR/SSCRD turbofan engine to determine the lowest takeoff gross weight airplane. The results are compared with a baseline conventional mixed-flow turbofan (MFTF) engine for a range of 5000 n mi. Then, the SSTR/SSCRD turbofan engines were evaluated on an HSCT aircraft. An advantage of the SSTR/SSCRD engine is its short, low-weight supersonic inlet, which results in a lower engine pod weight than that of a conventional turbofan with the same engine airflow.

The supersonic through-flow rotor with a supersonic counter-rotating diffuser was modeled at NASA Glenn by using a Fortran subroutine to represent the fan overall performance (Daniel Tweedt, NASA Lewis Research Center, 1996, private communication). The SSTR/SSCRD turbofan configuration is similar to a conventional mixed-flow turbofan with the exception of an all-supersonic axisymmetric inlet and a counter-rotating rotor and diffuser. The supersonic through-flow rotor hub-tip ratio is 0.625 and the blade aspect ratio is 0.92. Blade solidity, the ratio of the chord to spacing, is 3.06. The supersonic counter-rotating diffuser has a hub-tip ratio of 0.68, a blade aspect ratio of 0.40, and a blade solidity of 1.71. The stator has a blade aspect ratio of 0.967 and a blade solidity of 1.80.

To illustrate the characteristics of the supersonic fan, a meanline Mach number vector diagram of the flow through the SSTR/SSCRD at cruise is shown in figure 7. There are three blades rows: a supersonic through-flow rotor, a super-sonic rotating diffuser, and a stator. Note that the diffuser rotates in the opposite direction of the supersonic rotor. The supersonic rotor (SSTR) can operate with subsonic or supersonic inflow. For subsonic inflow, the flow is accelerated to super-sonic conditions at the SSTR exit. At high rotational speeds, the SSTR fixed the engine corrected airflow to a nearly constant value. For supersonic inflow, the engine corrected airflow can vary but the rotor face Mach number must be maintained at 1.35 or above to avoid fan unstart. The rotor exit outflow usually is supersonic except at very low part power operation. The supersonic rotating diffuser (SSCRD) is "started" with supersonic inflow and diffuses the flow to subsonic absolute Mach numbers. The exit guide vanes then remove the swirl from the subsonic flow before it enters the high-pressure compressor and the bypass duct.

Figures 8 and 9 represent the supersonic rotor performance maps. In figure 8, the rotor pressure ratio is plotted against specific flow for a range of speed lines for subsonic inflow. For a constant speed line, specific flow can be increased by reducing the rotor back pressure until the rotor chokes. Further reduction in back pressure will cause the pressure ratio of the rotor to decrease. Figure 9 shows the rotor map for supersonic inflow. A boundary line shown in the figure separates subsonic and supersonic inflows.

The block diagram of figure 10 presents the cycle components in the NEPP analysis. About 23 percent of the airflow is bled off the high-pressure compressor for turbine cooling. Of that flow, 70 percent is used to cool the high-pressure turbine and the remaining 30 percent, to cool the low-pressure turbine. The inner spool drives the high-pressure compressor and the outer spool drives the rotor and rotating diffuser. A gear box is required to reduce the speed from the rotating diffuser to the rotor. The SSTR/SSCRD fan must meet three aerodynamic performance limits: the maximum fan overall pressure ratio (dcp), the stator choke margin (scm), and the SSCRD choke margin (dcm). When the stator choke margin limit is reached, the secondary mixer area must be varied to fix a specific corrected airflow at the stator exit. During part power operation, bleeding air off the SSCRD is required to prevent the mixer secondary Mach number from reaching sonic. An interesting characteristic of the SSTR/SSCRD turbofan is that the engine maintains a constant corrected airflow at moderate to high fan speeds because the SSTR is always choked.

Results and Discussion

The inlet performance of the SSTR/SSCRD and the baseline MFTF was compared in this study. The SSTR/SSCRD turbofan has a fixed-throat axisymmetric inlet design whereas the MFTF is equipped with a translating center body, variable-throat axisymmetric inlet. Figure 11 shows the pressure recovery changes with flight Mach number for each inlet. From sea level static to Mach 0.4, the pressure recovery was significantly lower for the SSTR/SSCRD inlet as a result of a large lip loss. The pressure recovery improved from Mach 0.4 to low supersonic Mach numbers because of a shorter inlet design and a smaller diffuser loss but fell off between

Mach 1.4 to 1.75 because unstarted external shock losses began to rise. The SSTR/SSCRD inlet has a starting Mach number of 1.75. At Mach 1.9, the rotor starts and the shock wave moves into the fan and disappears. From Mach 1.75 to 2.4, the recovery was higher because of a single reflected internal oblique shock wave as opposed to the multiple shocks on the MFTF inlet (fig. 12). Bypass doors were opened between Mach 0.9 to 2.1 to lower the drag and to assist in matching the supplied airflow to the engine demand.

In figure 13, it can be seen that the drag coefficient for the SSTR/SSCR inlet is four times greater than that for the conventional axisymmetric inlet in the transonic region. This is attributed to a fixed-geometry inlet design, which requires that a larger amount of air be spilled by the inlet. This effect is also seen in figure 14 where, for the same capture area, the SSTR/SSCRD engine receives less airflow than that of the MFTF. Between Mach 2.1 and 2.4, the drag coefficient is minimal because little air is being spilled or bypassed. A benefit of the SSTR/SSCRD inlet is that it requires no inlet bleed air for stability anywhere in the flight regime. For subsonic inflow, the Mach number at the rotor face is constant at 0.8, which results in constant engine corrected airflow from takeoff until the fan starts (fig. 15). Once the fan starts, supersonic inflow occurs and all the air captured by the inlet goes through the fan.

For the parametric study, three sea level static cycle design parameters were investigated for the SSTR/SSCRD turbofan (table 2). A range of each variable is examined to find the best engine that would result in the airplane with the lowest takeoff gross weight. The overall pressure ratio is tied directly to the TTR to ensure that the cycle operate at the maximum allowable TT3 at the top of the climb. A maximum TT3 is necessary to obtain the optimum cycle thermal efficiency. The ratio of the mixer secondary to primary total pressure, k, is set to 1 at sea level static to ensure adequate mixing of the two streams.

Tables 3 and 4 list important SSTR/SSCRD cycle parameters of the engine matrix at SLS and at cruise. The bypass ratio (BPR) was varied to maintain equal total pressures at the mixer entrance at SLS. The SSTR/SSCRD engine overall pressure ratio (OPR) was varied to obtain the maximum high-pressure compressor exit total temperature of 1660 °R at the top of the climb. From these tables, one can see that thermal

efficiency, TSFC, and nozzle exhaust jet velocity are the lowest for higher BPR engines (SSTR/SSCRD1, SSTR/SSCRD4, and SSTR/SSCRD7). Figures 16 and 17 show the effect of the fan overall pressure ratio (FPR) and the TTR on engine performance. In figure 16, for a constant TTR of 1.183, the cruise TSFC is the lowest at the smallest FPR of 3.05 because as FPR decreases, BPR increases. This will decrease specific thrust but will improve TSFC. Figure 17 shows the effect of decreasing TTR for a constant FPR of 3.05. Of nine engines studied, SSTR/SSCRD7 had the lowest cruise TSFC. Figure 18 presents a number of sea level static engine design points and reveals the trends seen in figures 16 and 17. That is, FPR decreases with an increasing BPR at a constant combustor exit temperature and BPR increases with CET along a constant line of FPR.

Figure 19 presents the installed propulsion system weights of three selected SSTR/SSCRD engines sized at a corrected airflow of 680 lbm/sec SLS. As mentioned earlier, the inlet, nacelle, and pylon weights are 1310 lb and the mixer-ejector nozzle weight is 4400 lb for all SSTR/SSCRD cycles. Therefore, the difference between the three SSTR/SSCRD propulsion systems is the bare engine weight, which is about 9 percent between the lightest (SSTR/SSCRD7) and the heaviest (SSTR/SSCRD1) engines. When compared with the conventional mixed-flow turbofan, the SSTR/SSCRD inlet, nacelle and pylon weights are 73 percent lighter and bare engine and nozzle weights are 15 percent heavier than those of the baseline turbofan. Still, the SSTR/SSCRD engine pod weight is 11 percent lower than the baseline turbofan.

The results of the SSTR/SSCRD airplane mission sizing are presented in figure 20 where the combustor exit temperatures are plotted to show the effect of BPR on airplane takeoff gross weight. All the airplanes are sized for takeoff field length. Out of the range of SSTR/SSCRD SLS cycle parameters in table 2, only three curves of temperatures are shown here because the SSTR/SSCRD fan operation constraints restrict the engine cycle to perform over a limited range of TTR. For curves of maximum CET above 3000 °R, the aircraft failed to meet the required mission constraints. The low BPR engine (SSTR/SSCRD1) has a higher supersonic cruise TSFC that results in extra fuel weight. Similar reasoning is applied for lower BPR engines along a constant line of CET. The higher BPR engine

(SSTR/SSCRD7) has a lower cruise TSFC but may require a larger engine size for takeoff, which results in an additional weight penalty. However, the SSTR/SSCRD7 turbofan has the right combination of engine pod weight and total fuel weight to provide the optimum airplane with the lowest TOGW of 814 000 lb at a SLS BPR of 0.56 and an FPR of 3.05. The SSTR/SSCRD7 turbofan also has the highest overall efficiency of the nine engines studied (table 4) and this has an effect on the aircraft TOGW. The cruise installed thrust specific fuel consumption of the SSTR/SSCRD7 airplane is 2 percent higher than that of the baseline turbofan. Once again, a further reduction in FPR cannot be accomplished because of the SSTR/SSCRD fan operation limits. The baseline conventional MFTF has a TOGW of 758 000 lb at an SLS BPR of 0.80.

Figure 21 further breaks down the takeoff gross weight of the optimum airplane (SSTR/SSCRD7) versus the MFTF airplane. The TOGW mainly consists of the operating empty weight (OEW) and total fuel weights. More details of OEW and the total fuel weight are included with the percentage of change in weight being computed for each segment. The effect of bleeding air off the supersonic rotating diffuser during part power operation causes subsonic and supersonic descent fuel weights to be slightly higher than those of the conventional turbofan. The mission-sized SSTR/SSCRD7 propulsion weight is 33 percent lower, resulting in an overall 3-percent lower operating empty weight than that of the baseline turbofan. The SSTR/SSCRD7 airplane also has 12-percent better climb fuel because the aircraft has more power to climb at a faster rate. However, subsonic and supersonic cruise fuel consumption are 15 percent and 18 percent higher, respectively. The percentage change in fuel reserves is significant at 52 percent. The final result is a 19-percent increase in total fuel weight. Finally, the offset between the OEW and the total fuel weight is 7 percent higher in aircraft TOGW for the SSTR/SSCRD7 turbofan compared with that of the baseline mixed-flow turbofan.

Clearly, one can conclude that the SSTR/SSCRD7 turbofan offers an advantage of lower propulsion system weight, thus giving a lower OEW than the baseline turbofan. However, improvement in the fuel flow is needed, especially at supersonic cruise and for reserves. Supersonic cruise and reserve fuel weights make up a substantial 36 percent of the SSTR/SSCRD7

aircraft TOGW. Overall, the SSTR/ SSCRD7 engine performance shows promising results compared with the conventional mixed-flow turbofan in terms of a comparable aircraft takeoff gross weight while still satisfying the FAR36 Stage 3 noise requirement. Noise level basically is a function of primary jet velocity and augmentation air jet velocity, primary jet total temperature, suppressor area ratio, nozzle aspect ratio, and nozzle L/D. NOx formation can be reduced by decreasing the burner temperature, which can be accomplished by lowering the temperature of the gas coming into the burner and by operating at a leaner fuel-to-air ratio.

A takeoff door on the supersonic inlet of the SSTR/SSCRD7 turbofan was used to increase the take- off thrust by providing better pressure recoveries from sea level static to Mach 0.4 with the same $A_{O_{eng}}/A_c$. The result was a smaller inlet capture area and a lower SLS engine corrected airflow of 621 lbm/sec accompanied by an increase in net thrust and a decrease in TSFC at takeoff. The installed fuel flow at supersonic cruise was 6 percent lower, which resulted in a reduction of 4 percent in aircraft TOGW. Therefore, the takeoff door augmented takeoff thrust, improved the supersonic cruise fuel consumption, and more important, lowered the aircraft TOGW.

Summary

A parametric study was conducted to evaluate the potential benefits of nine supersonic through-flow rotors with supersonic counter-rotating diffuser turbofan engines for a commercial supersonic cruise aircraft. Engine cycle, weight, and mission analyses were performed for the SSTR/SSCRD turbofan and the high-speed civil transport baseline conventional mixed-flow turbofan. The supersonic fan engines were evaluated in terms of a takeoff gross weight comparison with the baseline turbofan over a 5000-n mi range at a Mach 2.4 cruise mission. The aircraft used for the mission was jointly designed by Boeing and McDonnel Douglas. An advantage of the SSTR/SSCRD engine is the short, low-weight supersonic inlet that provides better pressure recovery and a lower engine pod weight than that of the conventional turbofan for the same engine airflow. The installed engine pod weight is 11 percent lighter, and the aircraft operating empty weight is 3 percent lower than that of the baseline turbofan. The cruise installed thrust specific fuel consumption of the supersonic fan engine is 2 percent higher than that of the baseline turbofan. The supersonic cruise and reserve fuel weights are 18 and 52 percent higher, respectively, resulting in an increase of 19 percent in total fuel weight over that of the baseline turbofan. The final result is that the optimum SSTR/SSCRD airplane is within 7 percent of the baseline turbofan airplane takeoff gross weight and still meets the FAR36 Stage 3 noise requirement at takeoff.

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20. High Speed Civil Transport (HSCT) Technology Concept Airplane Configuration Description

TABLE 1.—ABRIDGED HSR CYCLE DESIGN GROUND RULES (THERMODYNAMIC)

Component	Specifications
Inlet	W_{corr} = 680 lbm/s at SLS, recoveries given in figure 11
Fan/LPC	η_p = 0.895 at SLS
HPC	η_p = 0.920 at SLS $T_{3\ max}$ = 1200 ºF (1660 ºR)
Combustor	η_b = 0.999 LHV = 18 500 BTU/lb $\Delta P/P$ = 0.060 w_l/w_t = 0.14
HPT	η_{ad} = 0.920 (peak) $T_{41\ max}$ = 2800 ºF (3260 ºR)
LPT	η_{ad} = 0.925 (peak)
Mixer	E = 0.80 (forced mixers) C_M = 0.95
Ducts	$\Delta P/P$ = 0.010 (duct, splitter, or VABI) $\Delta P/P$ = 0.005 (turbine exit frame)
Nozzles	$T_{8\ max}$ = 1700 ºF (2160 ºR) $C_v = C_v$ (NPR)
Parasitics	200 hp high spool power extraction 1.0 lb/s customer bleed (ref.: 650 lb/s airflow)

TABLE 2.—RANGE OF SSTR/SSCRD SLS
CYCLE PARAMETERS INVESTIGATED

FPR	3.0 → 4.5
OPR	15 → 20
TTR	1.06 → 1.30
k	1.0

TABLE 3.—CANDIDATE SSTR/SSCRD CYCLES WITH SLS PARAMETERS

	SSTR/ SSCRD1	SSTR/ SSCRD2	SSTR/ SSCRD3	SSTR/ SSCRD4	SSTR/ SSCRD5	SSTR/ SSCRD6	SSTR/ SSCRD7	SSTR/ SSCRD8	SSTR/ SSCRD9
Installed F_N/W_a	65.2	68.8	72.3	64.5	68.0	71.4	63	67.4	70.7
PTR1	2.16	2.24	2.33	2.16	2.25	2.33	2.16	2.24	2.33
PTR2	1.41	1.43	1.45	1.41	1.43	1.45	1.41	1.43	1.45
FPR	3.05	3.22	3.39	3.05	3.22	3.39	3.05	3.22	3.39
OPR	13.6	14.1	14.6	13.9	14.4	15.0	14.2	14.7	15.2
BPR	0.303	0.188	0.09	0.429	0.306	0.200	0.559	0.426	0.312
k	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TTR	1.2675	1.2675	1.2675	1.2237	1.2237	1.2237	1.183	1.183	1.183
V_{jet}, ft/s	2082	2193	2299	2064	2172	2276	2047	2154	2256
$\left(W\sqrt{\theta}/\delta\right)$ engine	680	680	680	680	680	680	680	680	680
Combustor exit temp., °R	2800	2800	2800	2900	2900	2900	3000	3000	3000
HPT rotor inlet temp., °R	2550	2552	2554	2637	2639	2641	2724	2726	2728
Installed F_N, lb	38470	40612	42687	38075	40161	42160	37706	39763	41721
Installed TSFC, lb/hr/lb	0.8548	0.8791	0.9035	0.8407	0.8641	0.8867	0.8276	0.8507	0.8729
F_N (2.4)/F_N (SLS)	0.5259	0.5226	0.5202	0.4859	0.4832	0.4811	0.449	0.4475	0.446
Thermal eff., %	30.14	30.80	31.34	30.43	31.09	31.69	30.71	31.36	31.96

TABLE 4.—CANDIDATE SSTR/SSCRD CYCLES WITH M = 2.40, 60 000 FT PARAMETERS

	SSTR/ SSCRD1	SSTR/ SSCRD2	SSTR/ SSCRD3	SSTR/ SSCRD4	SSTR/ SSCRD5	SSTR/ SSCRD6	SSTR/ SSCRD7	SSTR/ SSCRD8	SSTR/ SSCRD9
Installed F_N/W_a	50.4	52.9	55.3	46.0	48.3	50.5	42.1	44.3	46.3
PTR1	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
PTR2	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
FPR	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
OPR	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
BPR	0.394	0.320	0.253	0.538	0.459	0.388	0.688	0.602	0.526
k	1.16	1.12	1.08	1.25	1.21	1.16	1.3661	1.30	1.25
$\left(W\sqrt{\theta}/\delta\right)$ engine	512	512	512	512	512	512	512	512	512
HPC exit temp, °R	1660	1660	1660	1660	1660	1660	1660	1660	1660
HPT rotor inlet temp, °R	3260	3260	3260	3260	3260	3260	3260	3260	3260
V_{jet}, ft/s	3887	3961	4033	3758	3826	3891	3639	3704	3766
Installed FN, lb	20232	21224	22207	18500	19410	20283	16933	17794	18610
Installed TSFC, lb/hr/lb	1.301	1.3099	1.3193	1.2899	1.2963	1.3033	1.283	1.2874	1.2921
Thermal eff., %	58.97	59.22	59.41	58.33	58.65	58.9	57.56	57.95	58.3
Propulsion eff., %	74.81	73.93	73.09	76.4	75.55	74.76	77.92	77.08	76.3
Overall eff.,%	44.11	43.78	43.42	44.56	44.31	44.03	44.85	44.66	44.48
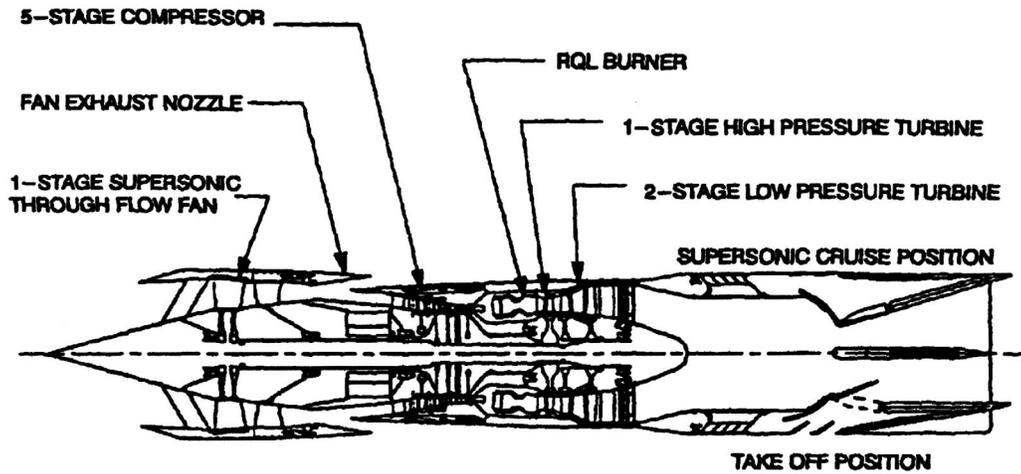
Figure 1.—Supersonic Through-Flow Fan engine (STFF).
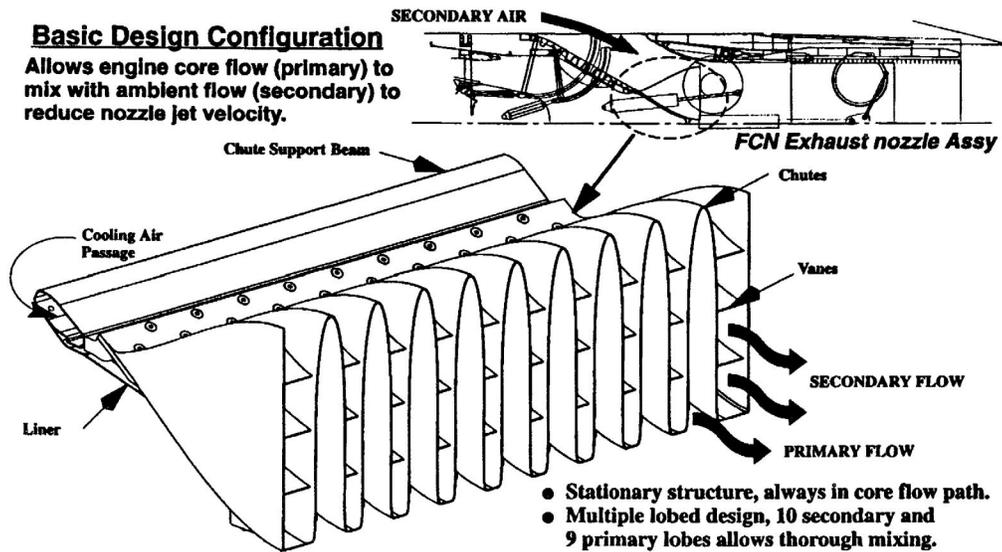
Figure 2.—Fixed chute nozzle layout.
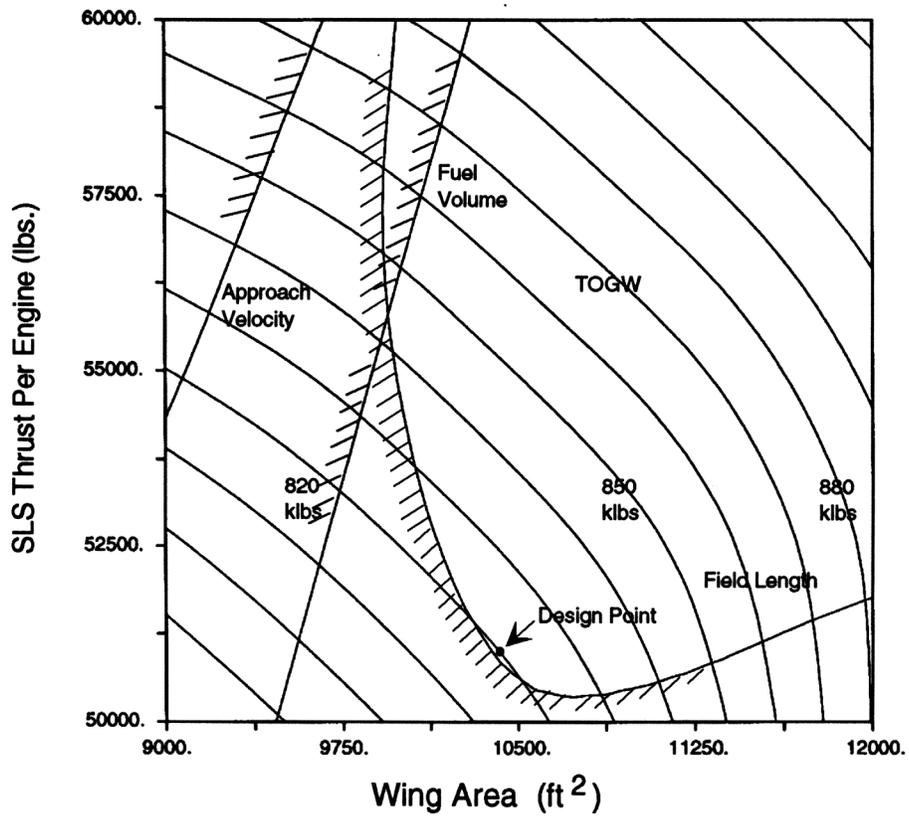
Figure 3.—Aircraft sizing "thumb print". SSTR/SSCRD engine on TCA HSCT aircraft.
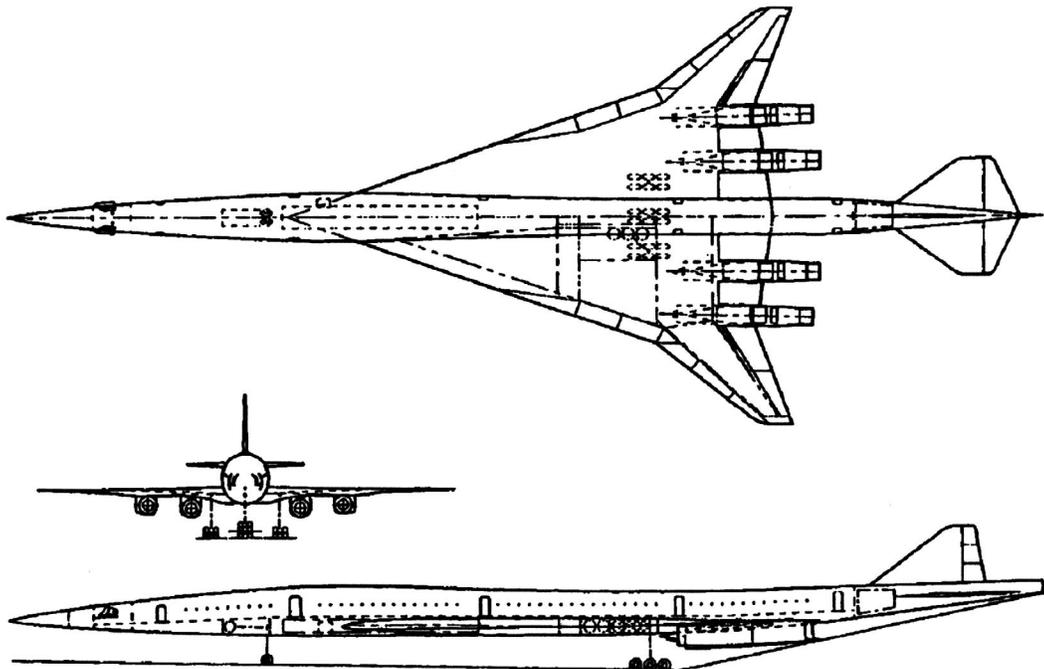
Figure 4.—Technology Concept Airplane TCA HSCT configuration.
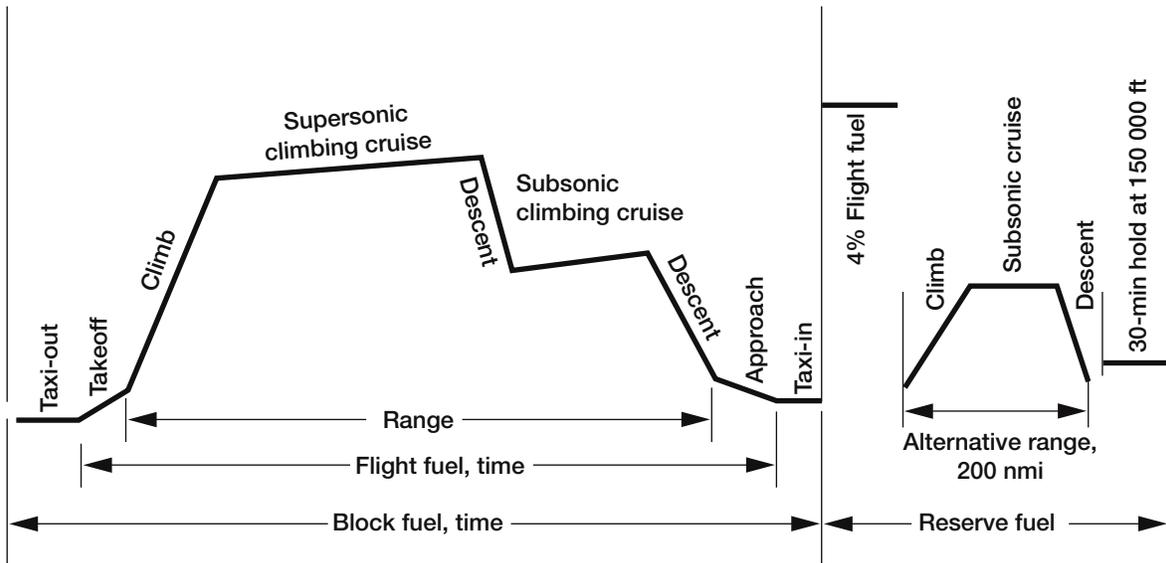
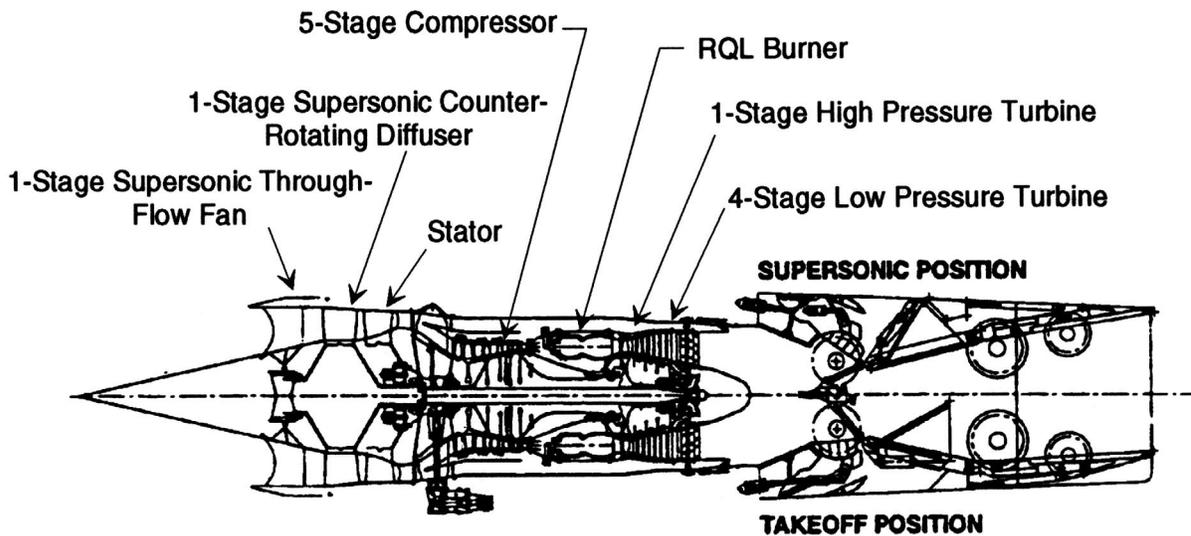Figure 5.—Design HSCT mission.

Figure 6.—Supersonic Through-Flow Rotor with Supersonic Counter-Rotating Diffuser engine (SSTR/SSCRD).
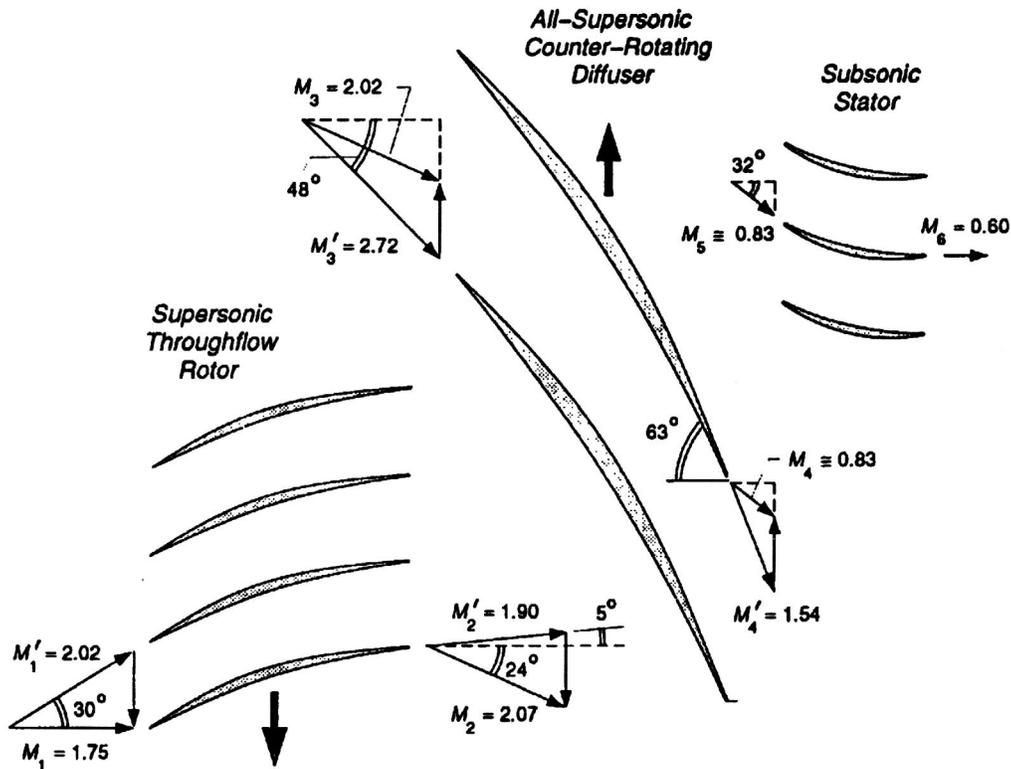
Figure 7.—Meanline Mach number vector diagrams at cruise.
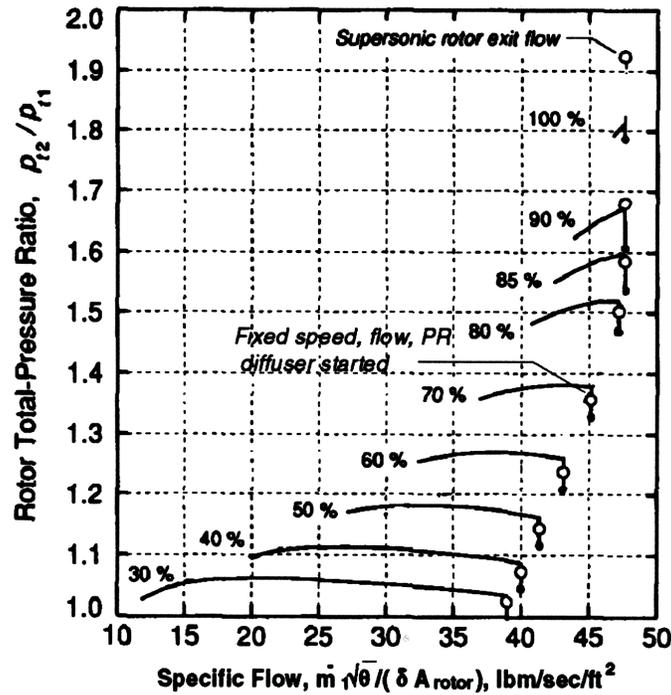
Supersonic Throughflow Rotor
Approximate Subsonic Performance Map

Figure 8.—Rotor total pressure ratio versus specific flow
for subsonic inflow.
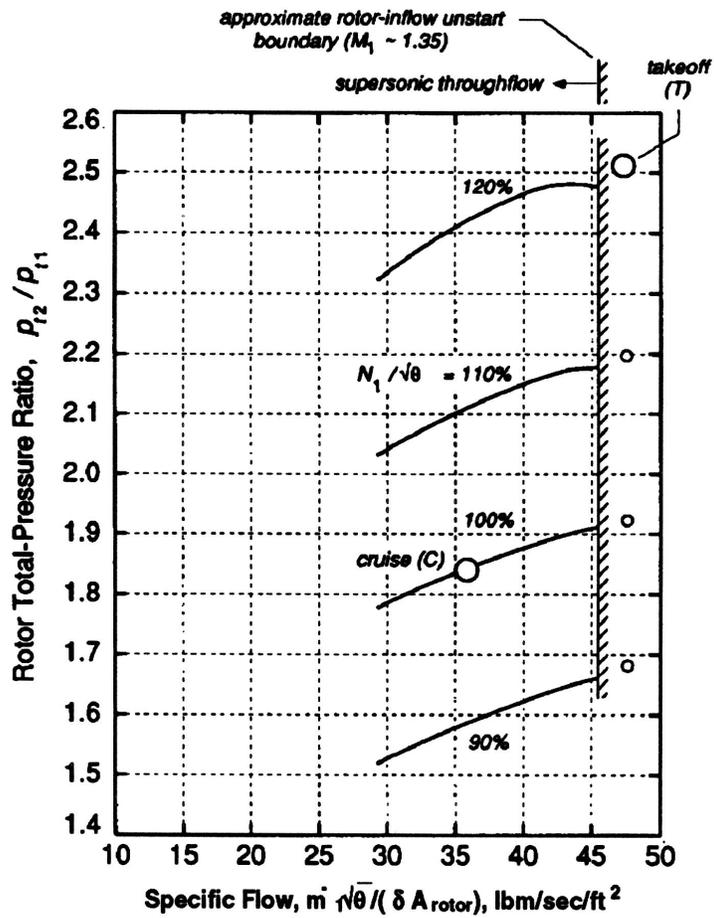
Figure 9.—Rotor total pressure ratio versus specific flow
for supersonic inflow.
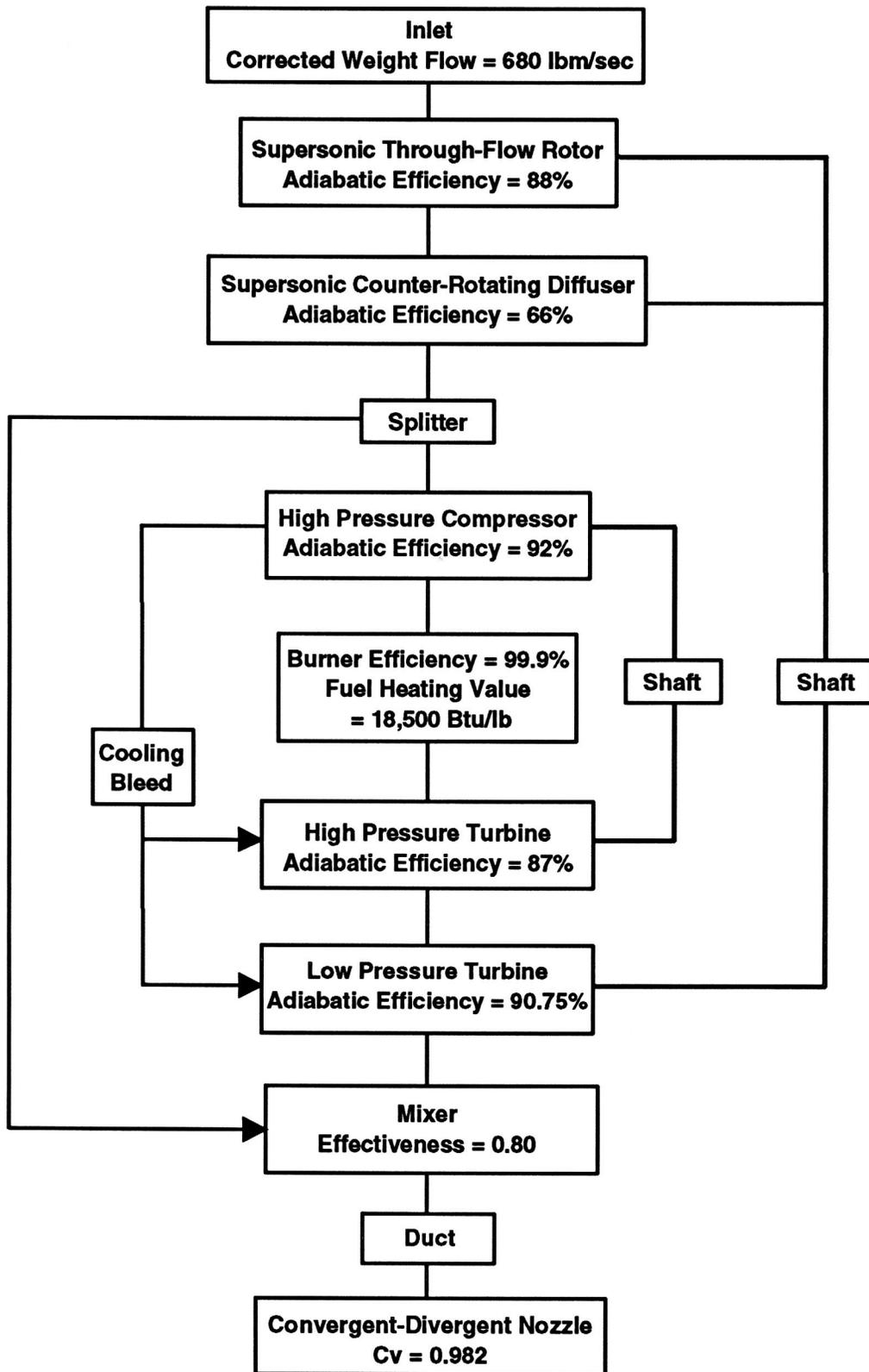
Figure 10.—Block diagram of Supersonic Through-Flow Rotor with Supersonic Counter-Rotating engine (SSTR/SSCRD).
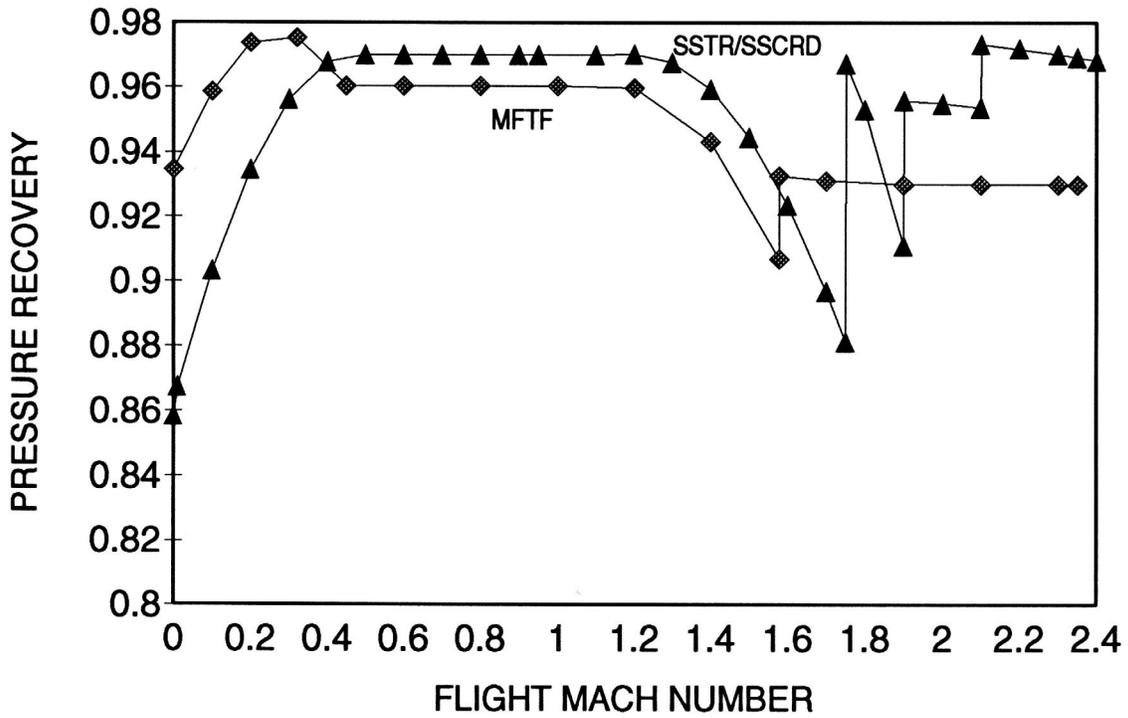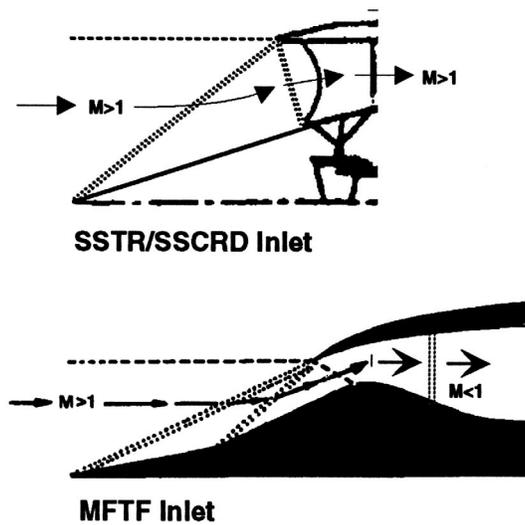
Figure 11.—Primary inlet pressure recovery.

SSTR/SSCRD Inlet

MFTF Inlet

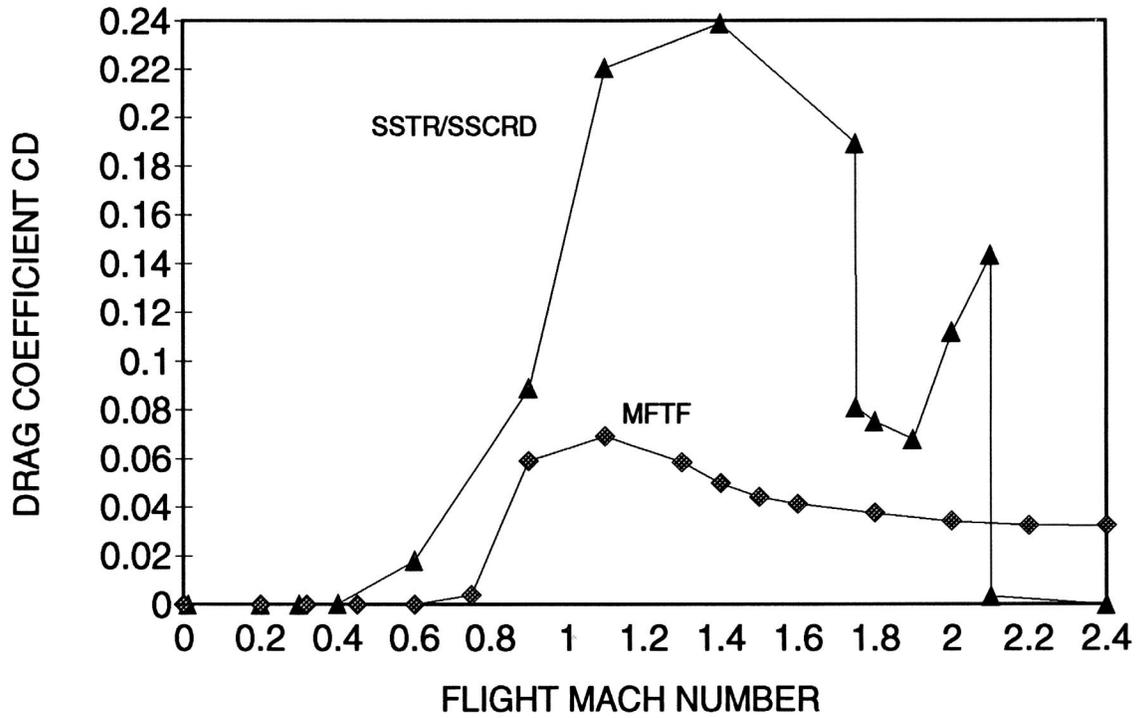Figure 12.—Comparison of shock waves of
SSTR/SSCRD and MFTF inlets.
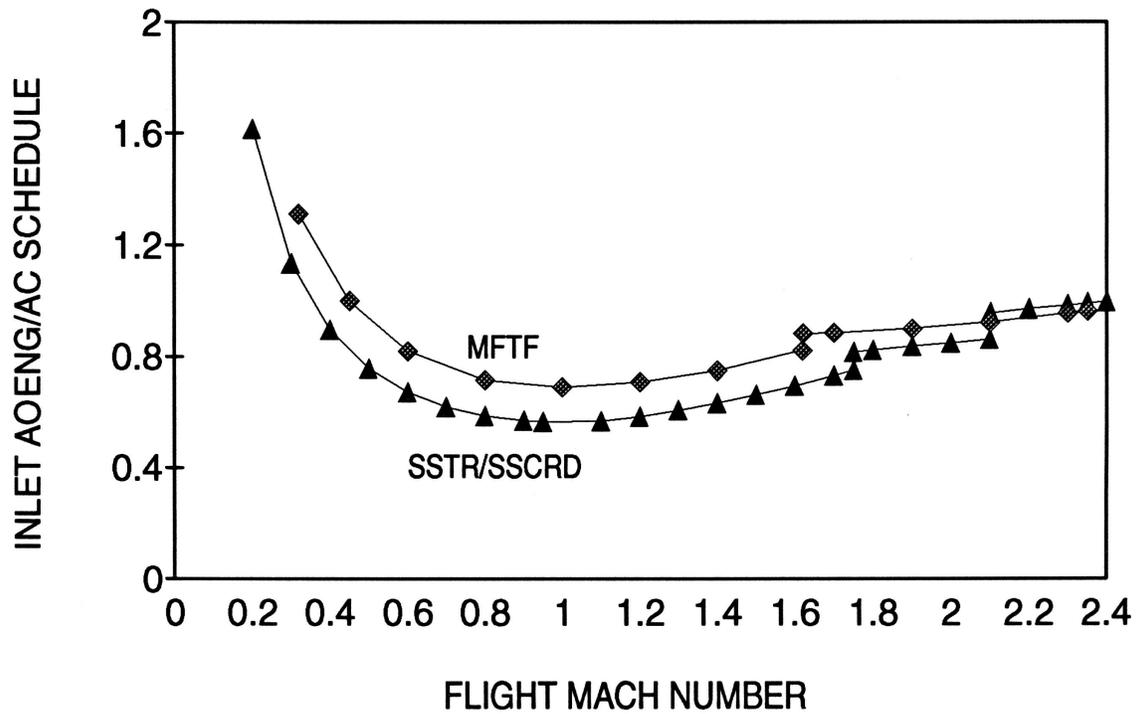
Figure 13.—Primary inlet drag coefficient.

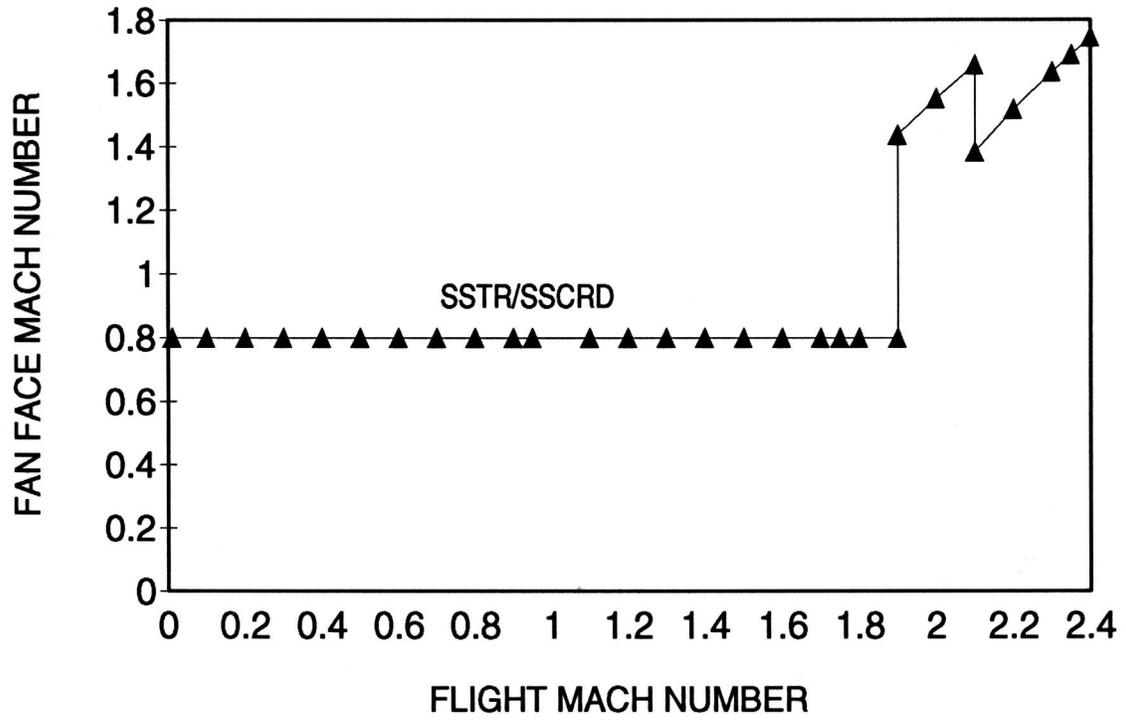
Figure 14.—Inlet AOENG/AC schedule.
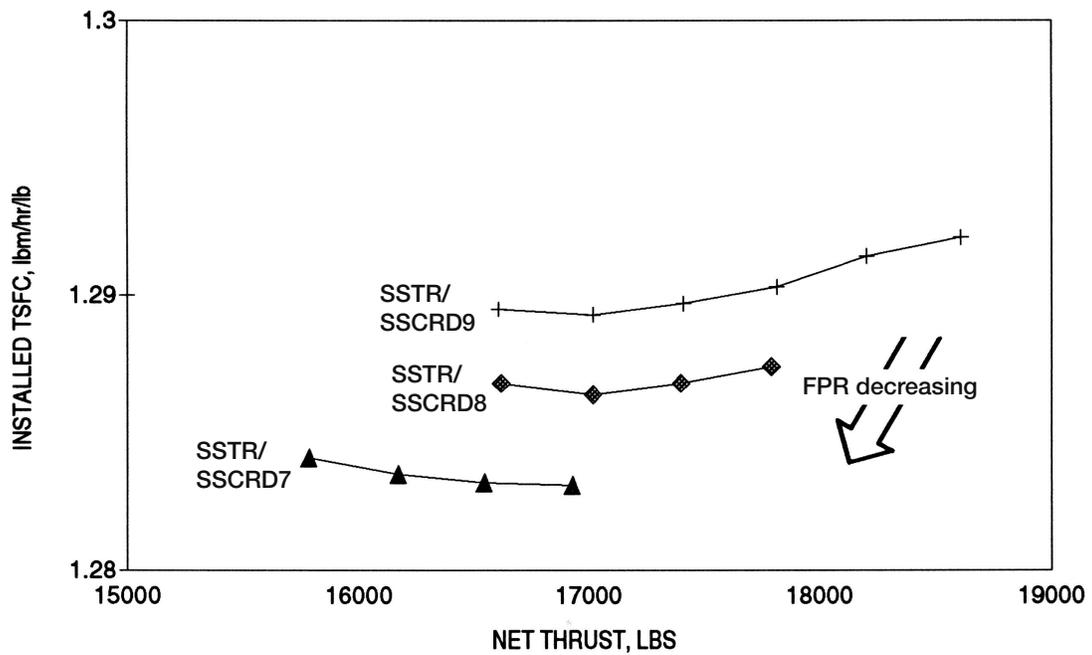
Figure 15.—Primary inlet fan Mach number.

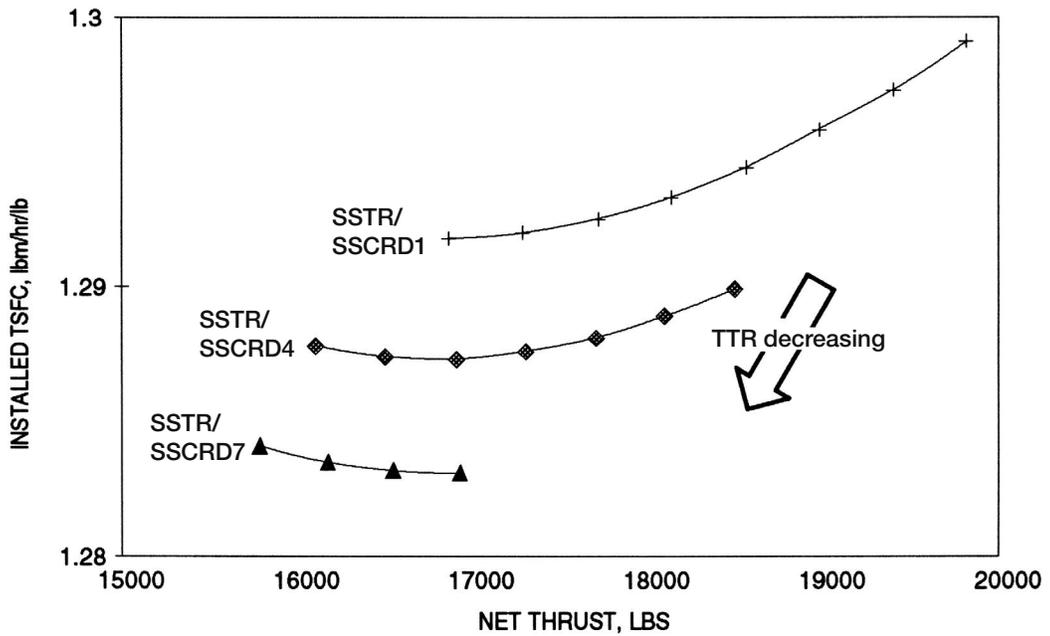Figure 16.—Impact of FPR on Mach 2.4, 60 000 ft performance (TTR = 1.183, k = 1.0).

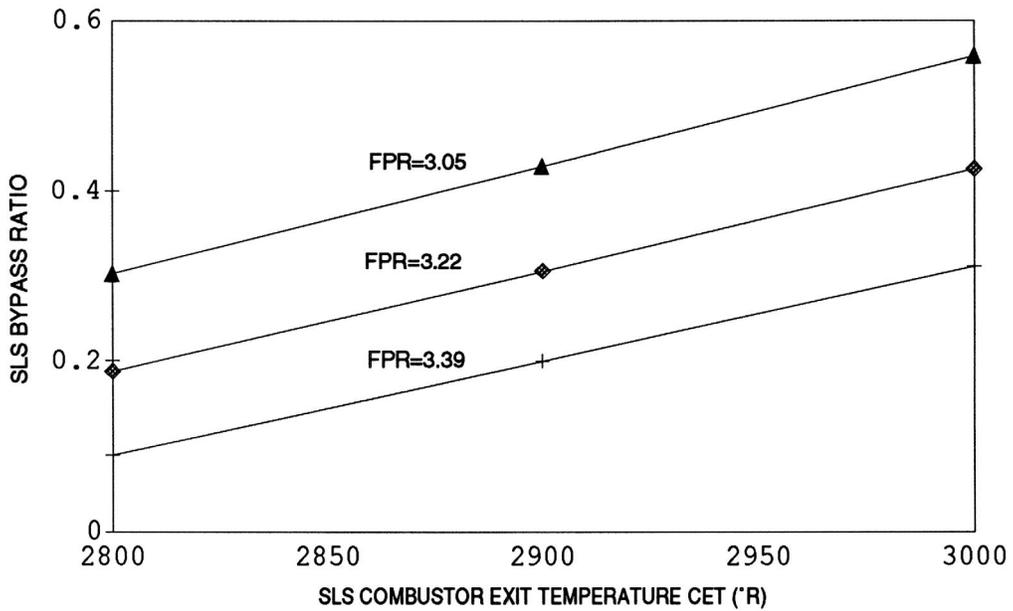Figure 17.—Impact of TTR on Mach 2.4, 60 000 ft performance (FPR = 3.05, k = 1.0).

Figure 18.—Relationship of SLS bypass ratio and combustor exit temperature for constant fan pressure ratio.
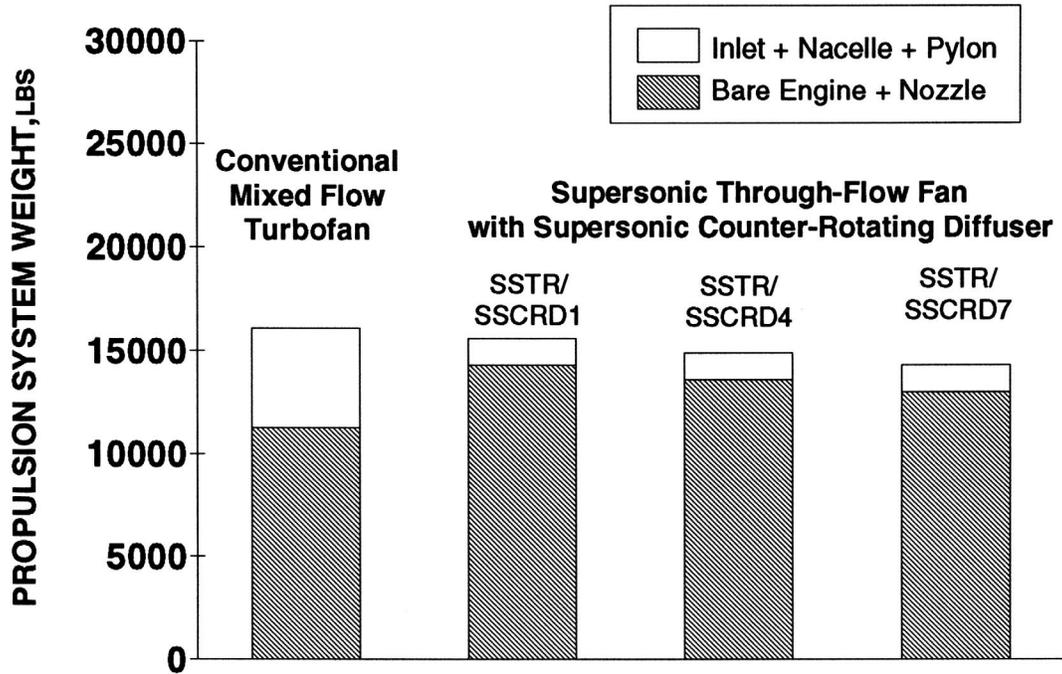
Figure 19.—Installed propulsion system weight per engine; sea level static airflow = 680 lbm/sec.
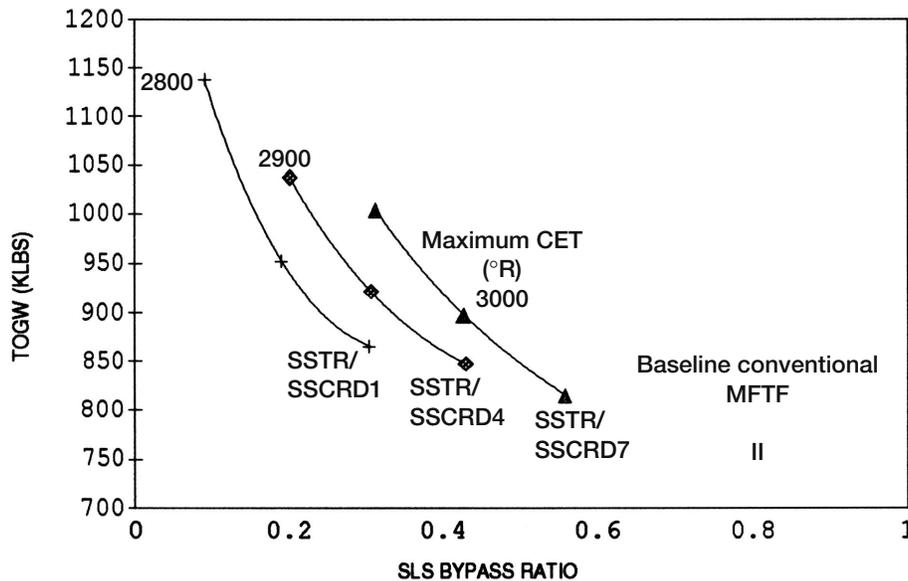

Figure 20.—Supersonic Through-Flow Rotor with Supersonic Counter-Rotating Diffuser turbofan TCA HSCT gross weights: influence of bypass ratio and combustor exit temperature.

|	Conventional MFTF	SSTR/ SSCRD7	% change in wt
Propulsion wt	85320	57284	–32.85%
OEW	385261	372492	–3.31%
Taxi out fuel wt	1649	6387	
Takeoff fuel wt	4980	5319	
Climb fuel wt	87824	77095	–12.21%
Supersonic cruise fuel wt	191113	225562	18.02%
Supersonic descent fuel wt	2889	7064	
Subsonic cruise fuel wt	35908	41416	15.33%
Subsonic descent fuel wt	4136	12445	
Reserves fuel wt	43950	66667	51.68%
Total fuel wt	372448	441954	18.66%
TOGW	757709	814446	7.48%
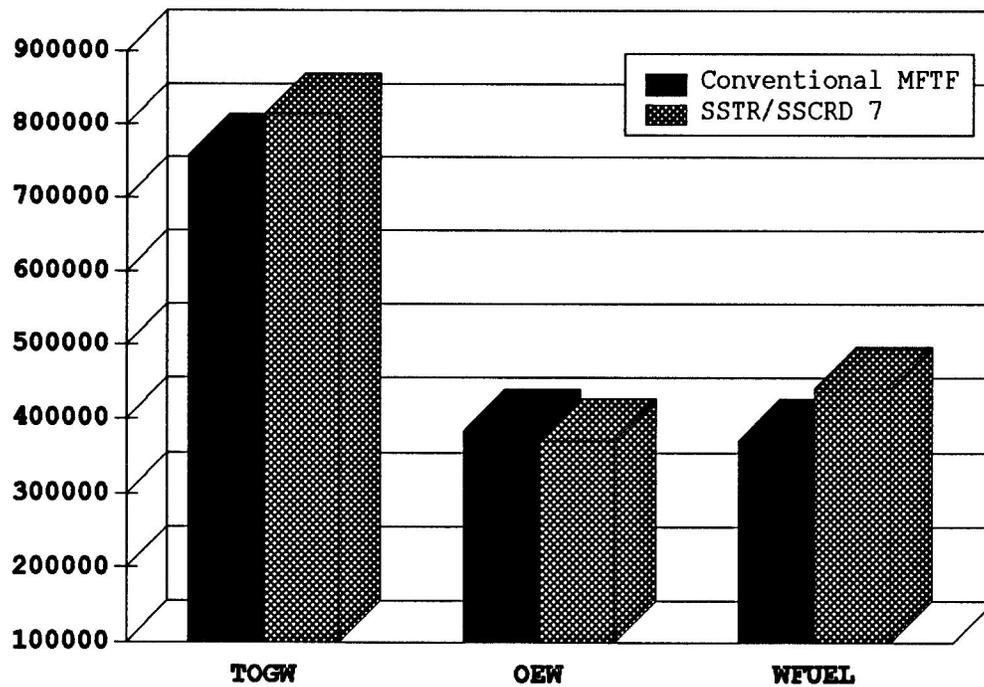
Figure 21.—Breakdown of SSTR/SSCRD aircraft TOGW.

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2004	Technical Memorandum

4. TITLE AND SUBTITLE

Parametric Study of a Mach 2.4 Transport Engine with Supersonic Through-Flow Rotor and Supersonic Counter-Rotating Diffuser (SSTR/SSCRD)

5. FUNDING NUMBERS

WBS–22–714–09–46
NAS3–27235

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–14653

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—2004-213139

11. SUPPLEMENTARY NOTES

This research was originally published internally as HSR049 in February 1997. Responsible person, Donald H. Tran, organiztion code 2400, 216–977–7025. Contact, Diane Chapman, organization code 2100, 216–433–2309.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category: 07   Distribution: Nonstandard

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A parametric study is conducted to evaluate a mixed-flow turbofan equipped with a supersonic through-flow rotor and a supersonic counter-rotating diffuser (SSTR/SSCRD) for a Mach 2.4 civil transport. Engine cycle, weight, and mission analyses are performed to obtain a minimum takeoff gross weight aircraft. With the presence of SSTR/SSCRD, the inlet can be shortened to provide better pressure recovery. For the same engine airflow, the inlet, nacelle, and pylon weights are estimated to be 73 percent lighter than those of a conventional inlet. The fan weight is 31 percent heavier, but overall the installed engine pod weight is 11 percent lighter than the current high-speed civil transport baseline conventional mixed-flow turbofan. The installed specific fuel consumption of the supersonic fan engine is 2 percent higher than that of the baseline turbofan at supersonic cruise. Finally, the optimum SSTR/SSCRD airplane meets the FAR36 Stage 3 noise limit and is within 7 percent of the baseline turbofan airplane takeoff gross weight over a 5000-n mi mission.

14. SUBJECT TERMS

Gas turbines; Axial flow turbines; Turbine exhaust nozzles; Gas turbine engines; Turbine engines; Supersonic turbines; Supersonic flight; Supersonic commercial air transport

15. NUMBER OF PAGES
28

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	