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

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August 2004
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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

\[ \frac{A_{\text{eng}}}{A_{\text{c}}} \] ratio of engine airflow to inlet capture area

\( A_{\text{rotor}} \) rotor entrance area, ft\(^2\)

\( \text{BPR} \) bypass ratio

\( \text{CET} \) combustor exit total temperature, \( ^\circ \text{R} \)

\( \text{C}_v \) nozzle velocity coefficient

\( \text{C}_m \) mixer momentum coefficient

\( \text{dcm} \) supersonic counter-rotating diffuser choke margin

\( \text{dcp} \) parameter indicating margin of maximum fan pressure ratio limit

\( \frac{E}{W_s} \) mixer effectiveness

\( F/W_s \) specific thrust, lb/lbm/s

\( \text{FPR} \) fan overall pressure ratio

\( k \) ratio of mixer secondary to primary total pressure

\( \text{LHV} \) lower heating value, Btu/lbm

\( \text{MFTF} \) mixed-flow turbofan

\( m_{\sqrt{\theta}/(\delta A_{\text{rotor}})} \) rotor specific flow, lbm/s/ft\(^2\)

\( N/\sqrt{\theta} \) rotor corrected speed

\( \text{OEW} \) operating empty weight, lb

\( \Delta P/P \) frictional relative total pressure drop

\( \text{PTR1} \) supersonic rotor pressure ratio

\( \text{PTR2} \) supersonic rotating diffuser pressure ratio

\( \text{SLS} \) sea level static

\( \text{SSCRD} \) supersonic counter-rotating diffuser

\( \text{SSTR} \) supersonic through-flow rotor

\( \text{scm} \) stator choke margin

\( \text{TOGW} \) takeoff gross weight, lb

\( \text{TSFC} \) thrust specific fuel consumption, lbm/hr/lb

\( \text{TT3} \) compressor exit total temperature, \( ^\circ \text{R} \)

\( \text{TT41} \) high-pressure turbine rotor inlet total temperature, \( ^\circ \text{R} \)
T8\textsubscript{max} maximum nozzle exit total
temperature, °R
TTR ratio of maximum CET over sea
level static CET
V\textsubscript{j} jet velocity, ft/s
W\textsubscript{corr} corrected airflow, lbm/s
w\textsubscript{b}, w\textsubscript{i} fraction of air not heated in the
burner but allowed to mix at exit,
reducing the exit temperature
\delta ratio of total pressure at
supersonic rotor face to SLS
total pressure
\theta ratio of total temperature at
super sonic rotor face to SLS
total temperature
\eta efficiency

Subscripts:
ad adiabatic
b burner
c cowl
gen engine
p polytropic
0 ambient

**Method of Analysis**

The engine cycle performance was calculated
using the NASA Engine Performance Program
(NEPP)\textsuperscript{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.\textsuperscript{15}

The inlet performance data were obtained
using the Inlet Performance Analysis Code
(IPAC)\textsuperscript{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.\textsuperscript{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)

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**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.\textsuperscript{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\textsuperscript{8} and NASA
Glenn.\textsuperscript{9,11} The engine (fig. 1)\textsuperscript{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\textsubscript{x} emissions. Economic viability is
defined as achieving a balance between the aircraft
cost and the commercial value.\textsuperscript{13}
corrected airflow of 680 lbm/sec, had the same capture area of 23.6 ft², the same rotor area of 14.3 ft², 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) 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). 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) 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. 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). 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 supersonic 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 supersonic 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 (dp), 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/SSCRD 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 takeoff thrust by providing better pressure recoveries from sea level static to Mach 0.4 with the same $A_{\text{eng}}/A_C$. 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 throughput 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 McDonnell 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.

**References**


20. High Speed Civil Transport (HSCT) Technology Concept Airplane Configuration Description
<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet</td>
<td>$W_{corr} = 680 \text{ lbm/s at SLS, recoveries given in figure 11}$</td>
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<tr>
<td>Fan/LPC</td>
<td>$\eta_p = 0.895 \text{ at SLS}$</td>
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</table>
| HPC       | $\eta_p = 0.920 \text{ at SLS}$  
$T_{3\text{ max}} = 1200 \degree \text{F (1660} \degree \text{R)}$ |
| Combusstor| $\eta_b = 0.999$  
$LHV = 18500 \text{ BTU/lb}$  
$\Delta P/P = 0.060$  
$w_t/w_t = 0.14$ |
| HPT       | $\eta_{ad} = 0.920 \text{ (peak)}$  
$T_{41 \text{ max}} = 2800 \degree \text{F (3260} \degree \text{R)}$ |
| LPT       | $\eta_{ad} = 0.925 \text{ (peak)}$ |
| Mixer     | $E = 0.80 \text{ (forced mixers)}$  
$C_M = 0.95$ |
| Ducts     | $\Delta P/P = 0.010 \text{ (duct, splitter, or VABI)}$  
$\Delta P/P = 0.005 \text{ (turbine exit frame)}$ |
| Nozzles   | $T_{8 \text{ max}} = 1700 \degree \text{F (2160} \degree \text{R)}$  
$C_v = C_v \text{ (NPR)}$ |
| Parasitics| 200 hp high spool power extraction  
1.0 lb/s customer bleed (ref.: 650 lb/s airflow) |

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<tr>
<th>Component</th>
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### TABLE 3.—CANDIDATE SSTR/SSCRD CYCLES WITH SLS PARAMETERS

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<td>15.2</td>
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<td>BPR</td>
<td>0.303</td>
<td>0.188</td>
<td>0.09</td>
<td>0.429</td>
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<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
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<td>1.2675</td>
<td>1.2675</td>
<td>1.2675</td>
<td>1.2237</td>
<td>1.2237</td>
<td>1.2237</td>
<td>1.183</td>
<td>1.183</td>
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<tr>
<td>$V_{\text{ jet}}, \text{ ft/s}$</td>
<td>2082</td>
<td>2193</td>
<td>2299</td>
<td>2064</td>
<td>2172</td>
<td>2276</td>
<td>2047</td>
<td>2154</td>
<td>2256</td>
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<tr>
<td>$\left(W\sqrt{\theta / \delta}\right)_{\text{ engine}}$</td>
<td>680</td>
<td>680</td>
<td>680</td>
<td>680</td>
<td>680</td>
<td>680</td>
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<td>Combustor exit temp., °R</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
<td>2900</td>
<td>2900</td>
<td>2900</td>
<td>3000</td>
<td>3000</td>
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<tr>
<td>HPT rotor inlet temp., °R</td>
<td>2550</td>
<td>2552</td>
<td>2554</td>
<td>2637</td>
<td>2639</td>
<td>2641</td>
<td>2724</td>
<td>2726</td>
<td>2728</td>
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<tr>
<td>Installed $F_N$, lb</td>
<td>38470</td>
<td>40612</td>
<td>42687</td>
<td>38075</td>
<td>40161</td>
<td>42160</td>
<td>37706</td>
<td>39763</td>
<td>41721</td>
</tr>
<tr>
<td>Installed TSFC, lb/hr/lb</td>
<td>0.8548</td>
<td>0.8791</td>
<td>0.9035</td>
<td>0.8407</td>
<td>0.8641</td>
<td>0.8867</td>
<td>0.8276</td>
<td>0.8507</td>
<td>0.8729</td>
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<tr>
<td>$F_N(2.4)/F_N(\text{ SLS})$</td>
<td>0.5259</td>
<td>0.5226</td>
<td>0.5202</td>
<td>0.4859</td>
<td>0.4832</td>
<td>0.4811</td>
<td>0.449</td>
<td>0.4475</td>
<td>0.446</td>
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<tr>
<td>Thermal eff., %</td>
<td>30.14</td>
<td>30.80</td>
<td>31.34</td>
<td>30.43</td>
<td>31.09</td>
<td>31.69</td>
<td>30.71</td>
<td>31.36</td>
<td>31.96</td>
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**TABLE 4.—CANDIDATE SSTR/SSCRD CYCLES WITH M = 2.40, 60 000 FT PARAMETERS**

<table>
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<tr>
<th></th>
<th>SSTR/SSCRD1</th>
<th>SSTR/SSCRD2</th>
<th>SSTR/SSCRD3</th>
<th>SSTR/SSCRD4</th>
<th>SSTR/SSCRD5</th>
<th>SSTR/SSCRD6</th>
<th>SSTR/SSCRD7</th>
<th>SSTR/SSCRD8</th>
<th>SSTR/SSCRD9</th>
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<tr>
<td>Installed $F_n/W_s$</td>
<td>50.4</td>
<td>52.9</td>
<td>55.3</td>
<td>46.0</td>
<td>48.3</td>
<td>50.5</td>
<td>42.1</td>
<td>44.3</td>
<td>46.3</td>
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<tr>
<td>PTR1</td>
<td>1.80</td>
<td>1.80</td>
<td>1.80</td>
<td>1.80</td>
<td>1.80</td>
<td>1.80</td>
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<tr>
<td>PTR2</td>
<td>1.21</td>
<td>1.21</td>
<td>1.21</td>
<td>1.21</td>
<td>1.21</td>
<td>1.21</td>
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<tr>
<td>FPR</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
<td>2.20</td>
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<tr>
<td>OPR</td>
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<td>8.6</td>
<td>8.6</td>
<td>8.6</td>
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<td>BPR</td>
<td>0.394</td>
<td>0.320</td>
<td>0.253</td>
<td>0.538</td>
<td>0.459</td>
<td>0.388</td>
<td>0.688</td>
<td>0.602</td>
<td>0.526</td>
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<td>$k$</td>
<td>1.16</td>
<td>1.12</td>
<td>1.08</td>
<td>1.25</td>
<td>1.21</td>
<td>1.16</td>
<td>1.3661</td>
<td>1.30</td>
<td>1.25</td>
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<td>$(W/\sqrt{\theta/\delta})_{engine}$</td>
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<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
<td>512</td>
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<tr>
<td>HPC exit temp, °R</td>
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<td>1660</td>
<td>1660</td>
<td>1660</td>
<td>1660</td>
<td>1660</td>
<td>1660</td>
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<td>1660</td>
</tr>
<tr>
<td>HPT rotor inlet temp, °R</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
<td>3260</td>
</tr>
<tr>
<td>$V_{in}$, ft/s</td>
<td>3887</td>
<td>3961</td>
<td>4033</td>
<td>3758</td>
<td>3826</td>
<td>3891</td>
<td>3639</td>
<td>3704</td>
<td>3766</td>
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<tr>
<td>Installed FN, lb</td>
<td>20232</td>
<td>21224</td>
<td>22207</td>
<td>18500</td>
<td>19410</td>
<td>20283</td>
<td>16933</td>
<td>17794</td>
<td>18610</td>
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<tr>
<td>Installed TSFC, lb/hr/lb</td>
<td>1.301</td>
<td>1.3099</td>
<td>1.3193</td>
<td>1.2899</td>
<td>1.2963</td>
<td>1.3033</td>
<td>1.283</td>
<td>1.2874</td>
<td>1.2921</td>
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<tr>
<td>Thermal eff., %</td>
<td>58.97</td>
<td>59.22</td>
<td>59.41</td>
<td>58.33</td>
<td>58.65</td>
<td>58.9</td>
<td>57.56</td>
<td>57.95</td>
<td>58.3</td>
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<tr>
<td>Propulsion eff., %</td>
<td>74.81</td>
<td>73.93</td>
<td>73.09</td>
<td>76.4</td>
<td>75.55</td>
<td>74.76</td>
<td>77.92</td>
<td>77.08</td>
<td>76.3</td>
</tr>
<tr>
<td>Overall eff., %</td>
<td>44.11</td>
<td>43.78</td>
<td>43.42</td>
<td>44.56</td>
<td>44.31</td>
<td>44.03</td>
<td>44.85</td>
<td>44.66</td>
<td>44.48</td>
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</table>
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.

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.

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.
Table: Breakdown of SSTR/SSCRD aircraft TOGW.

<table>
<thead>
<tr>
<th>Component</th>
<th>Conventional MFTF</th>
<th>SSTR/SSCRD7</th>
<th>% change in wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion wt</td>
<td>85320</td>
<td>57284</td>
<td>−32.85%</td>
</tr>
<tr>
<td>OEW</td>
<td>385261</td>
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<td>−3.31%</td>
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<tr>
<td>Taxi out fuel wt</td>
<td>1649</td>
<td>6387</td>
<td></td>
</tr>
<tr>
<td>Takeoff fuel wt</td>
<td>4980</td>
<td>5319</td>
<td></td>
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<tr>
<td>Climb fuel wt</td>
<td>87824</td>
<td>77095</td>
<td>−12.21%</td>
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<tr>
<td>Supersonic cruise fuel wt</td>
<td>191113</td>
<td>225562</td>
<td>18.02%</td>
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<tr>
<td>Supersonic descent fuel wt</td>
<td>2889</td>
<td>7064</td>
<td></td>
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<tr>
<td>Subsonic cruise fuel wt</td>
<td>35908</td>
<td>41416</td>
<td>15.33%</td>
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<td>Subsonic descent fuel wt</td>
<td>4136</td>
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<tr>
<td>Reserves fuel wt</td>
<td>43950</td>
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<td>Total fuel wt</td>
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<td>TOGW</td>
<td>757709</td>
<td>814446</td>
<td>7.48%</td>
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Figure 21.—Breakdown of SSTR/SSCRD aircraft TOGW.
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.