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Design and Performance of the Propulsion System for the Quiet Short-Haul Research Aircraft

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This paper describes the design and performance of the Quiet Short-Haul Research Aircraft (QSRA) propulsion system. A discussion of the mixed-flow boundary-layer control (BLC) system, which uses high and low pressure engine bleed air, is included. This system seriously affected propulsion system performance, particularly engine acceleration characteristics, requiring an integration of BLC system and powerplant controls. Funding limitations for the QSRA project prevented extensive full-scale testing and systems mockups, resulting in a high reliance on small-scale tests and analytical techniques. Ground tests of the actual aircraft systems showed that the extrapolation of small-scale tests and analytical techniques were in good agreement with measured full-scale results.

Introduction

In January 1974, NASA decided to embark on the Quiet Short-Haul Research Aircraft (QSRA) Project[1] as the culmination of 20 years of research in powered-lift short takeoff and landing (STOL) aircraft. The object was a low-cost, versatile, quiet jet research aircraft with next generation STOL performance. The powered-lift system selected for the QSRA was a four-engine hybrid upper surface blowing concept, which was to yield high lift coefficients and very low sideline noise levels. The aircraft design goals included: usable lift coefficient greater than 4.6 with the critical engine inoperative, maintaining normal safety margins while in a steep descent; capability to conduct terminal-area research, including operation from field lengths ranging from 457.2 to 1219.2 m (1500 to 4000 ft): 152.4 m (500 ft) sideline noise levels of 92 EPNdB at takeoff and 90 EPNdB on landing: and high roll control power at low approach speeds for research with the critical engine inoperative.

These goals had a significant impact on the design of QSRA systems, particularly the propulsion, boundary-layer control, and flight control systems. The performance of these systems are highly interdependent. This required a much greater degree of system integration than for conventional transport aircraft.

A design-to-cost philosophy was used in the development of the QSRA systems as opposed to other criteria such as design for maximum performance or other features such as improved maintainability. Performance goals were established, but firm specifications were not. Large-scale or laboratory tests and mockups were used only in areas of high technical risk. Heavy reliance was placed on analytical prediction techniques and the extrapolation of small-scale test data to full-scale systems.

In addition, a high level of information flow between QSRA project groups was emphasized. In this way propulsion engineers had an open line of communication not only between design and analysis, but also with other discipline groups such as systems and structures, and with the Boeing and NASA technical staffs.

This paper describes the design and development of the QSRA propulsion system and includes a discussion of the mixed-flow boundary-layer control (BLC) system which had a significant impact on the propulsion system design. The analytical predictions of fan performance, core performance, and installed thrust are compared to measurements made during the ground test of the aircraft. The discussion includes a brief summary of the engine/inlet stability tests and some comments on the propulsive-lift flow turning tests.

Airplane Description

The QSRA is shown configured for a STOL approach in Fig. 1. The fuselage is that of a deHavilland C-8A Buffalo with structural reinforcement in the aft section and new fairings at the wing-body intersection. The C-8A empennage was used without structural or aerodynamic modification. Stability Augmentation System (SAS) actuators were added to both the rudder and the elevator. The C-8A landing gear was modified to increase the sink rate capability of the aircraft.

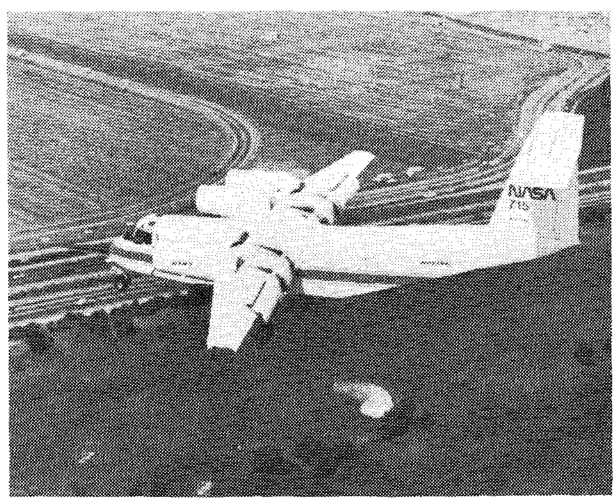

Fig. 1 The Quiet Short-Haul Research Aircraft performing a STOL approach.

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The QSRA wing was designed and fabricated by Boeing with a wingspan of 22.4 m (73.5 ft), a wing area of 55.74 m^2 (600 ft^2), and quarter chord sweep of 15 deg. The center section of the wing is sealed to form two integral fuel cells which contain a total of 4535.9 kg (10,000 lb) of Jet A-1 (JP-5) fuel. Fixed leading-edge flaps are blown by a mixed flow boundary-layer control system. The trailing edge on either side of the centerline consists of two upper surface blowing (USB) flaps, a double-slotted flap, and a drooped, blown aileron.

Propulsion System

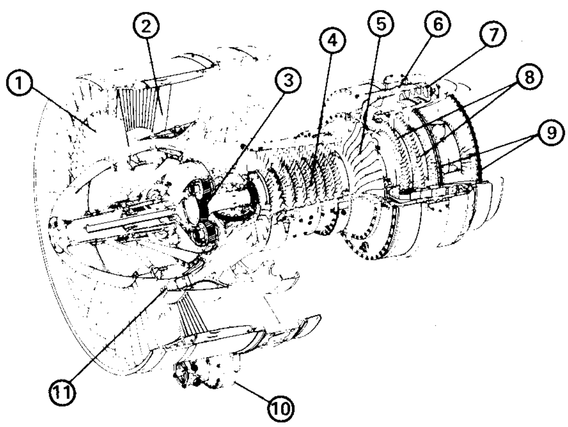
The QSRA main propulsion system consists of four AVCO-Lycoming YF-102 (QSRA) engines mounted in above-the-wing nacelles. These prototype engines, acquired from the USAF A-9A program, were refurbished and updated in a program managed by the Lewis Research Center. The principal elements of this update include a fan containment ring, combustor case high-pressure air bleed ports, new oil coolers, and improved shafting material.

A cutaway view of the engine is shown in Fig. 2. The low-pressure spool incorporates a single-stage fan which provides bypass and core air to the engine. The core airflow is further compressed by a single-stage supercharger attached to the fan. The fan is driven by a two-stage, uncooled turbine through a single planetary reduction gear (2.3 speed ratio) located in the fan module.

The gas producer section of the engine is essentially a T-55 core with slight modifications. The high-pressure components include an axial/centrifugal compressor, a reverse-flow combustor, and a two-stage air-cooled turbine to drive the compressor. The high-pressure compressor has seven axial stages followed by a centrifugal stage. It features variable inlet guide vanes (VIGV's) and a sixth-stage bleed band to minimize the possibility of compressor stall during transient operations.

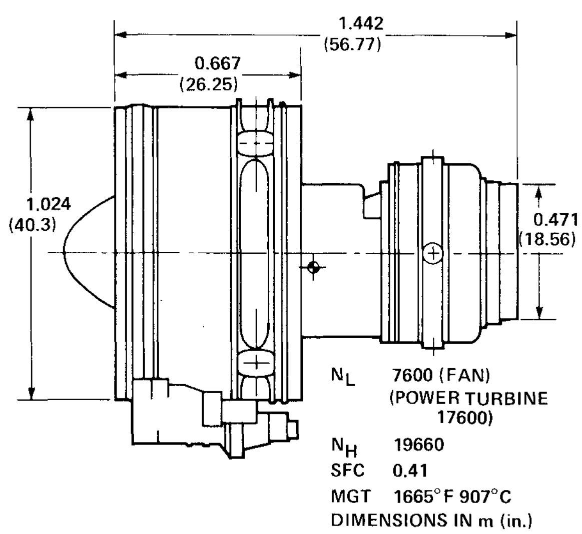
The engine weighs 5412 N (1215 lb) and has a basic diameter of 1.077 m (42.4 in.) with an overall length of 1.621 m (63.8 in.), including the fan spinner, while the fan has a diameter of 1.024 m (40.3 in.). The engine geometry and rated performance are shown in Fig. 3.

The nacelle is shown in Fig. 4. The external nacelle is composed of two main assemblies. The structural cowl and nozzle assembly is attached to the wing front spar and the engine build-up assembly is mounted to this structure. A nose cowl is attached to the engine as shown in Fig. 4 and serves as both the inlet and outer nacelle. Engine-driven accessories are airframe mounted in this nose cowl. Fire protection behind the nacelle is provided by an external heat shield attached to



1. FAN STAGE
2. FAN STATOR
3. REDUCTION GEAR ASSY
4. CORE AXIAL COMPRESSOR
5. CORE CENTRIFUGAL COMPRESSOR
6. CUSTOMER BLEED PORTS
7. COMBUSTOR
8. GAS PRODUCER TURBINES
9. POWER TURBINES
10. ACCESSORY GEARBOX
11. SUPERCHARGER

Fig. 2 Cutaway view of the YF-102 (QSRA) engine.



MAX. THRUST	7500 lb	33409.1 N
WEIGHT DRY	1215 lb	551.1 kg
TOTAL AIRFLOW	267 lb/sec	121.1 kg/sec
CORE AIRFLOW	37 lb/sec	16.8 kg/sec
B.P.R.	6.2	

Fig. 3 YF-102 (QSRA) engine layout.

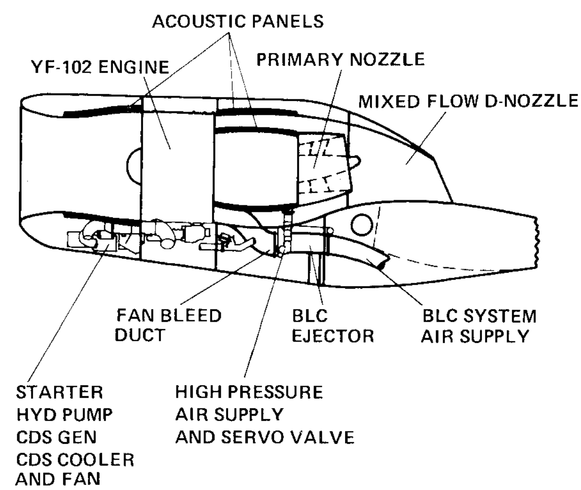


Fig. 4 Systems layout in the QSRA nacelle.

Table 1 QSRA propulsion system installation losses

Inlet pressure recovery	$P_T/P_{T0} = 0.995$
Fan duct pressure loss	$\Delta P/P = 0.016$
Accessory power extraction	22.371 kW (30 shp)
Boundary-layer control bleed	3.0% constant fan bleed 0 to 10% high-pressure bleed
Environmental control system bleed	6.8 kg/min (15 lb/min) high-pressure bleed (inboard engines only)
Nozzle performance and characteristics	
Fan stream effective area at mixing plane	0.44 m^2 (682.5 $in.^2$) ($C_D = 0.96$)
Core stream effective area at mixing plane	0.161 m^2 (250.0 $in.^2$) ($C_D = 0.92$)
Final geometric area	0.433 m^2 (671.0 $in.^2$) ($C_D = 0.966$)

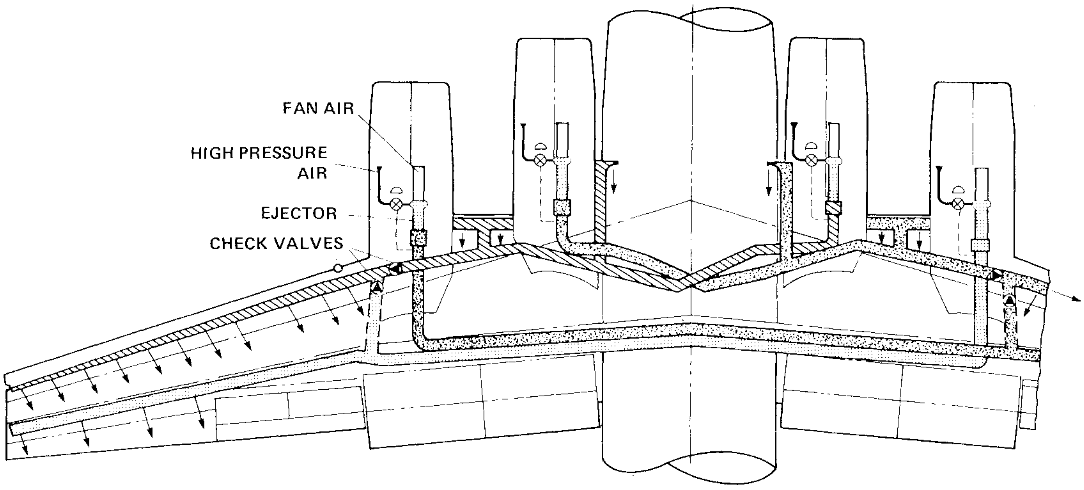


Fig. 5 The layout of the QSRA boundary-layer control (BLC) system.

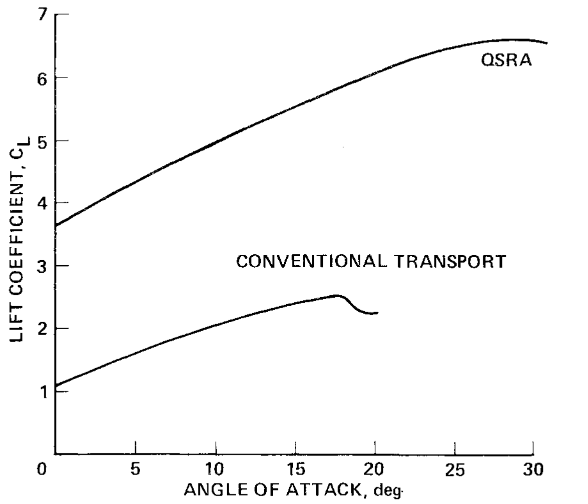


Fig. 6 QSRA approach lift coefficient compared to a conventional transport.

the upper surface of the wing, together with the use of heat-resistant materials in the wing flaps and trailing edge.

The exhaust system is a confluent-flow design with both primary and fan streams discharging through a common D-shaped exit nozzle having an aspect ratio of 3.5. As indicated in Fig. 4, the core exhaust diffuses as it passes through the primary nozzle and then mixes with the surrounding fan stream before exiting through the D-shaped upper-surface blowing nozzle. The core nozzle is canted upward 9.4 deg relative to the engine centerline to minimize heat effects on the wing.

The flow areas in the fan duct and core-nozzle exit plane (mixing plane) were sized to provide adequate performance without significantly affecting surge margins. The main control on surge margins and engine match, however, is provided by the final exit area of the D-nozzle, which is designed to spread the exhaust into a thin sheet, which is then turned by the Coanda effect over the USB flaps, providing propulsive lift. The efficiency of the jet sheet to provide this propulsive lift is highly dependent on the design and shape of the D-nozzle exit. For the QSRA this flow spreading is enhanced, especially with one engine inoperative, by a cutout or door that opens toward the adjacent nacelle.

The QSRA D-nozzle cutout design was determined empirically by small scale tests and besides enhancing flow spreading, it also increases the nozzle effective area. This makes it difficult to determine actual nozzle exit area; however, as a convention, D-nozzle geometric area is defined as the projected area on a plane perpendicular to the flow axis at the nozzle exit without including the cutout. The effective area of the D-nozzle is predicted from small scale tests of geometrically similar nozzles. A summary of mixing plane and nozzle areas is given in Table 1.

Boundary-Layer Control System

A unique feature of the QSRA is the mixed-flow boundary-layer control (BLC) system for the wing leading edges and ailerons.[2] Air for the BLC system is bled from both the fan and the engine core and mixed in an ejector. A schematic of the BLC system is shown in Fig. 5.

The BLC air is distributed by crossducting from each engine to the opposite side of the wing leading edge or aileron surfaces to minimize engine-out effects. For design simplicity as well as reliability, the use of independent BLC ducts and associated nozzles for each engine was a design objective. However, results from the Ames 40×80 ft wind tunnel tests indicated the desirability of boundary-layer control on the wing leading edge outboard of the engines to prevent premature stall at high angle of attack with an inboard engine inoperative. This was incorporated by adding an interconnecting duct between the aileron and leading edge BLC systems and two check valves. This permits outboard leading-edge blowing at all times, at the expense of a reduction in blowing to the aileron for the opposite inboard engine-out case. For that situation, however, the aileron will be deflected upward to balance the rolling moments, so that aileron performance is not affected by reduced blowing. The aileron ducting is located in a cavity aft of the rear spar; however to reduce costs, the leading-edge ducting was located externally behind the leading-edge flaps and crosses over inside the fuselage, under the wing.

This fairly complex arrangement of ducting resulted from the research requirements for propulsive-lift performance. The QSRA will operate at approach lift coefficients in excess of 5.5 with normal commercial transport safety margins. A comparison of the QSRA lift performance with that of a conventional commercial transport is given in Fig. 6. To accomplish these performance goals, the airflow over the wing and control surfaces of the QSRA must be fully attached at angles of attack in excess of 25 deg. In addition, it is necessary to prevent stall on the outboard portions of the wing to maintain aileron control effectiveness throughout the QSRA operating range. One of the most effective ways of maintaining this high performance is to provide blowing or boundary-layer control along the leading edge of the wing and ailerons.[3] It is, however, undesirable to duct hot, high-pressure air throughout the airplane, and the fan pressure is only sufficient at high power settings. The QSRA provides the required BLC pressure by a unique system utilizing both the high-pressure core bleed air and the fan air, providing a BLC

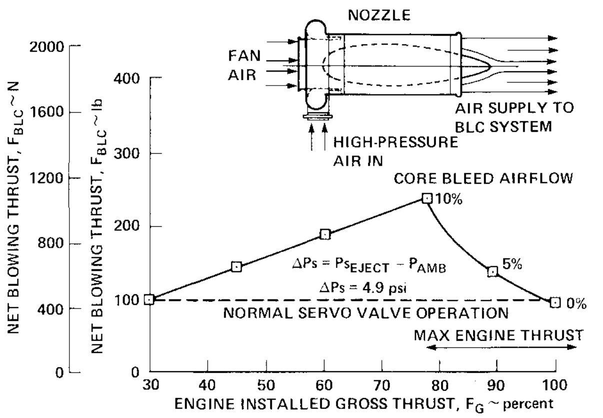


Fig. 7 The performance of the QSRA aileron BLC system shown as a function of engine thrust. The BLC ejector that combines the fan and core air from the engine to provide the BLC system air flow is shown in the insert.

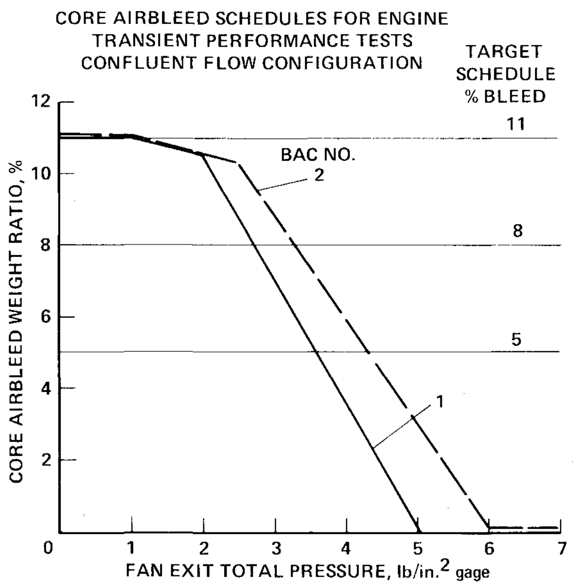


Fig. 8 Core airbleed schedules submitted to Lewis Research Center for ground test.

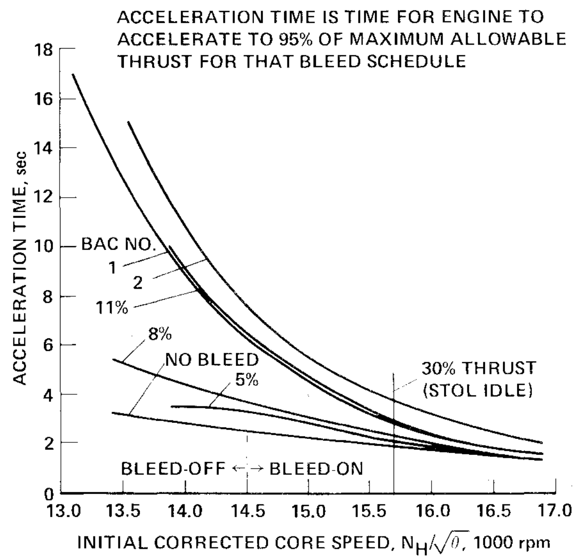


Fig. 9 YF-102 (QSRA) engine acceleration times for various bleed schedules.

air supply that is nearly constant at all power settings between flight idle and full power. Each fan duct contains a scoop that diverts 3% of the fan air to an ejector where it is mixed with high-pressure bleed air to provide the correct pressure and rate of flow for the BLC system.[4]

The mixing ejector and servo-regulator valve are located as shown in Fig. 4. The ejector, shown in Fig. 7, has a fixed-geometry section with an elliptical center body and 42 circumferentially distributed ejector nozzles. These convergent-divergent nozzles, with length-to-diameter ratios of 5:1, limit the high-pressure bleed to a nominal 10% of the engine core flow, and fan bleed is limited to 3% due to duct size. Figure 7 shows the effect of this ejector design on net blowing momentum of the aileron nozzles. The upper curve represents the performance of the ejector without any pressure regulation (constant 10% core flow). The servo-regulator valve limits the downstream duct pressure to a preset value, however, and the regulated system follows the lower curve of Fig. 7, yielding a nearly constant value of blowing momentum over the entire engine thrust range. This valve regulates high-pressure flow from the compressor so that it is zero at high power settings where the fan pressure ratio is high, and about 10% of the core airflow at low power settings. The right-hand curve shows the maximum available engine thrust (temperature limit) for various values of core bleed airflow. Although there is a loss in engine thrust at all power settings, this loss is negligible at the higher power settings that would be required under emergency conditions.

BLC/Propulsion System Interactions

The BLC concept just described raises two fundamental questions. First, what happens to the normal engine operating performance, particularly acceleration, with a modulated high-pressure bleed schedule? Second, what happens to normal engine operating performance in the event of a BLC system failure?

During the design phase of the QSRA these questions were addressed in several different ways. Concurrent with this design effort the Lewis Research Center ran a series of ground tests with a YF-102 engine to develop and verify safe engine operational procedures.[1] Lewis ran several hundred engine transients consisting of accelerations, decelerations, bodies, and sudden bleed demand tests. Four different constant bleed values were used during these transients (0,5,8, and 10%) in addition to the two modulated bleed schedules shown in Fig. 8. These modulated schedules were representative of those required for the QSRA BLC system.

During these transient tests it was found that the engine acceleration was unacceptably slow from low core speeds at the high bleed levels. Further testing determined engine speed ranges and fuel control adjustments that would provide acceptable QSRA performance: 3.5 s acceleration time from 30% (STOL flight idle) to 95% maximum thrust with the modulated bleed schedule. Although an increase in fuel control acceleration schedule provided faster acceleration rates, it was necessary to determine the effect by this increased fuel flow on component life and engine stability. Based on computer simulation and a 500 flight-hour program design goal, the effect of increased transient temperatures on component life was not considered a major problem. However, the question of engine stability and surge margin, especially during bleed-off accelerations, needed to be resolved.

Subsequent testing at Lewis confirmed that the QSRA objectives could be met with this increased fuel schedule with no adverse effects on the engine's operation with bleed-off. A summary of the data from the Lewis acceleration tests is shown in Fig. 9. Acceleration times increase greatly below 30% thrust and become excessive as the engine approaches its ground idle setting. Because one or more of the engines will be operated at ground idle to simulate engine-out conditions during the QSRA flight research program, this lack of acceleration capability could be very serious in the event of a system failure or other emergency while operating in this mode. Hence, a control switch was designed to sense engine core speed and to shut off the high-pressure bleed to the ejector when the core is operating below 74% of its maximum speed.

The acceleration response of the QSRA engines from ground idle to maximum power is shown in Fig. 10. These engines are supplying high-pressure bleed air on a modulated schedule above 74% core speed and require from 5 to 7 s to accelerate to 95% thrust. Engines 3 and 4 appear to have a 1 to 2 s lag before they begin to accelerate. This is believed to be caused by the fuel control design in conjunction with the ground idle setting and it is considered acceptable for the research program. Engine 2 has a break in its acceleration curve around the 60% thrust level. This change in acceleration rate is caused by an interaction between the engine's acceleration bleed schedule and the modulated high-pressure bleed schedule. Again, this is considered acceptable. Future operational propulsive-lift transports would probably have either reduced BLC requirements or integrated BLC/propulsion system controls. Research in both of these areas will be conducted during the QSRA program.

In the event of a BLC system failure such as a burst duct or servovalve failure (fail open is the normal mode), the engine turbine inlet temperature would increase rapidly leading to eventual hot section damage. A failure of the servovalve or of the ducting aft of the ejector would result in this overtemperature condition occurring only at high power settings because of the flow limitations imposed by the ejector nozzles. Therefore, a second control was designed to limit high-pressure bleed to core speeds less than 94%. Figure 7 shows that high-pressure bleed is not required at high power settings and that this control would have no effect on normal BLC system performance. As this control could not protect the engine in the event of a duct failure between the engine and ejector, that ducting was designed to safe life criteria so that the probability of a failure in one of these ducts is approximately the same as a failure in the engine case. This, of course, results in a slight weight penalty in these ducts.

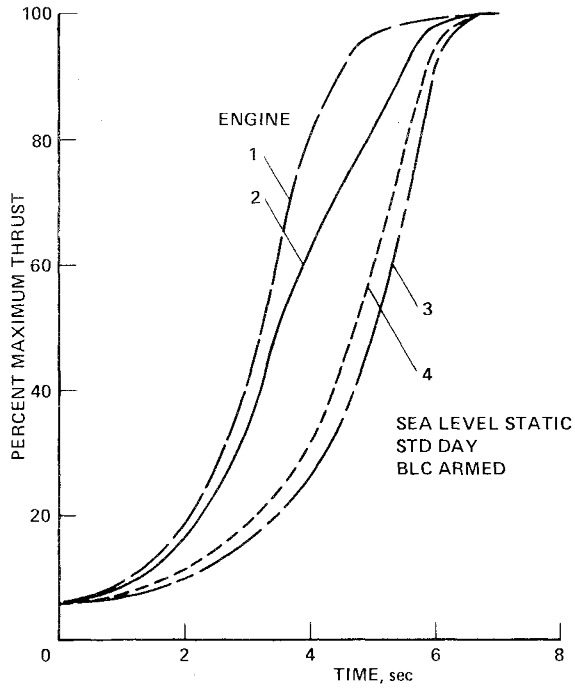


Fig. 10 YF-102 (QSRA) engine acceleration time from ground idle to maximum power.

Propulsion System Performance

Most of the measurements of propulsion system characteristics were made during aircraft ground tests.[5] The primary objectives of this ground test were to: 1) determine the component map characteristics and verify adequate surge margins (nozzle trim); 2) measure engine performance with and without the BLC system operating; 3) trim and adjust the engine fuel controls for idle, takeoff power, and acceptable acceleration characteristics; and 4) measure flaps-up thrust and flaps-down flow turning.

An installation loss summary is given in Table 1 and represents the numbers used in the final analytical performance predictions made by Boeing in June 1977.[6] As most of the hardware was not tested full scale, extensive use was made of these analytical predictions to verify the operation of the QSRA propulsion system and, more importantly, to serve as a baseline or standard against which the measured data would be compared. Significant deviation between the expected and measured performance required an immediate and thorough evaluation to determine its cause. Although in most cases these deviations were caused by instrument or similar problems, in a few cases they indicate potential system problems. For example, the BLC valve failed to close during engine start due to insufficient pneumatic pressure in the valve actuator. (An electric motor-driven valve was designed and installed prior to first flight.)

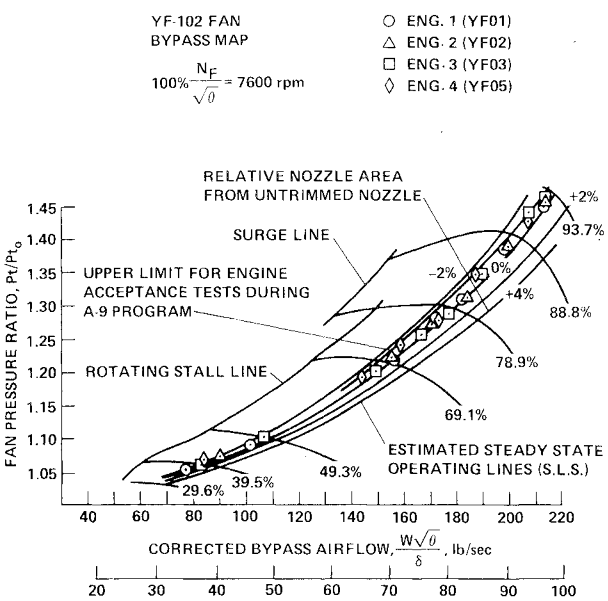


Fig. 11 YF-102 (QSRA) engine fan map showing the results of the airplane ground test.

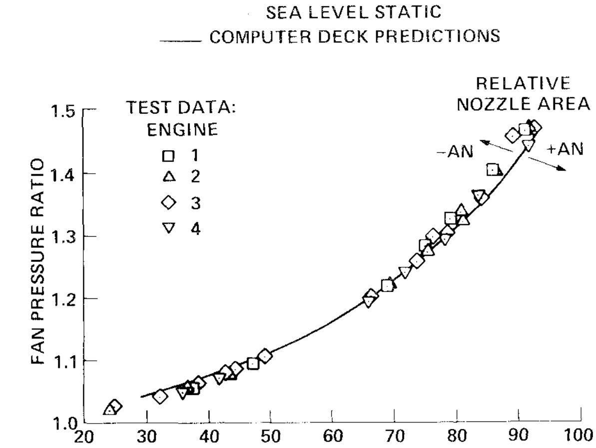


Fig. 12 YF-102 (QSRA) engine fan pressure ratio vs corrected fan speed.

Fan Performance

Fan surge margin was monitored on all engines using the instrumentation discussed in Ref. 5. Engine 2 was dedicated to engine performance measurements and contained additional fan discharge pressure probes and instrumentation at engine stations 2.08 (intercompressor) and 3 (compressor discharge). Therefore, supercharger and HP compressor operation were monitored on engine 2.

Corrected airflow, pressure ratios, and corrected rotor speeds were calculated from engine measurements using an "on line" data system. Pressure ratio vs corrected airflow were plotted on Lycoming supplied component maps for each condition and compared to predicted operation. To correlate these parameters with rotor speed, additional plots of pressure ratio and corrected flow vs corrected rotor speed were constructed. Predicted engine operation is documented in Ref. 6.

Figure 11 shows test data from all four engines plotted on the YF-102 fan map. This map includes predicted operation for a range of relative nozzle areas with the base area corresponding to the untrimmed nozzles. The test data were plotted using fan pressure ratio and corrected bypass flow as primary parameters with corrected fan speed as a secondary parameter. The test data indicated good correlation with predictions up to fan speeds of 70%; at higher speeds, these data indicated a nozzle under-area condition of up to 2%. This nozzle area data spread was considered acceptable in light of rather limited instrumentation and nozzle trim was not required. The upper limit for fan operation used during the A-9A program's YF-102 acceptance tests is also shown in the figure for reference.

Test data plotted on the fan pressure ratio vs corrected fan speed curve (Fig. 12) indicates that fan pressure ratio correlates well with predictions up to a fan speed of about 70%. Above this fan speed range the measured fan pressure ratio increased above predictions indicating an under-area condition. However, analysis of the additional fan discharge instrumentation provided on Engine 2 indicated an apparent pressure profile distortion occurred above fan speeds of approximately 70%. This resulted in the probe used for the pan pressure ratio measurement to read high by about 1.2%. Since all engines exhibited a similar jump in fan pressure ratio above 70%, the change in the pressure profiles was assumed to be configuration dependent. Hence, all of the pressure ratio measurements were adjusted down by 1.2% above a fan speed of 70% before they were plotted on Fig. 11.

Inlet airflow was calculated during the ground test program using the measurements from four static pressure taps located 1½ in. downstream of the inlet throat. Static inlet airflow using this inlet pressure instrumentation was determined for each engine during the ground test program and compared to computer deck predictions. Figure 13 presents this comparison between measured and predicted airflow. The dashed line in Fig. 13 is a curve fit using the test data from all the engines. There was close agreement between predictions and measurements above approximately 50% fan speed for engines 1,2, and 3. Engine 4 operated at airflow levels about 3% lower than the other engines.

A comparison between predicted and test data for the relationship between corrected fan speed and corrected core speed is shown in Fig. 14. For engine operation below 72% corrected core speed (sixth stage bleed band open) the predicted data does not compare well with the test data. This indicates the inability of the computer program to simulate engine operation at low engine power levels. Above 72% corrected core speed the test data are within ±2% of predicted results.

Thrust Performance

The installed takeoff thrust performance was estimated by using three data sources: 1) 1/6-scale cold flow model tests, 2) YC-14 full-scale data, and 3) 0.55-scale 40×80 ft wind-tunnel tests. The gross thrust at the flap trailing edge was estimated by applying a velocity coefficient (C_V) for the inboard and outboard installations to the ideal engine thrust at the QSRA mixing plane. The 1/6-scale QSRA "cold flow" model C_V's were adjusted downward to reflect YC-14 "real engine" effects and the increased wing scrubbing with the QSRA installation.

The flaps-up thrust performance measured for each outboard engine is shown on Fig. 15. The performance is presented as corrected resultant thrust vs corrected fan speed. The resultant thrust includes the thrust due to the lift vector (approximately 14 deg) measured with the airplane mounted on three two-component force balances. The data was

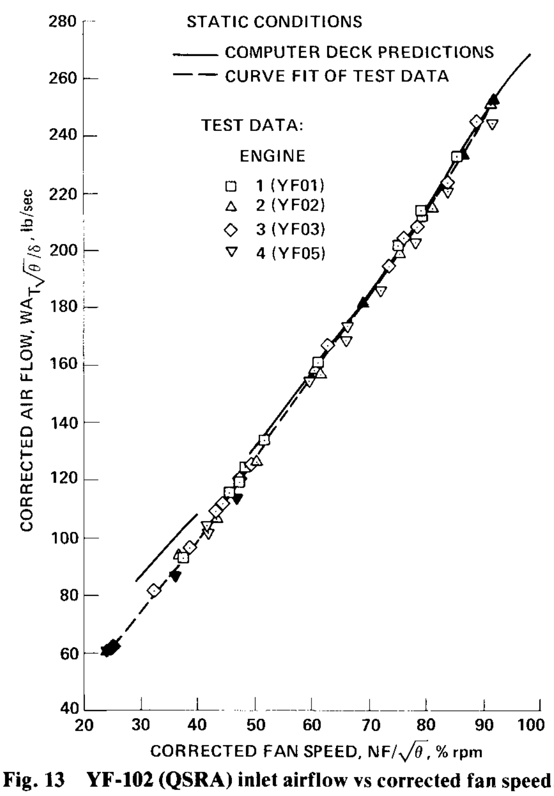


Fig. 13 YF-102 (QSRA) inlet airflow vs corrected fan speed.

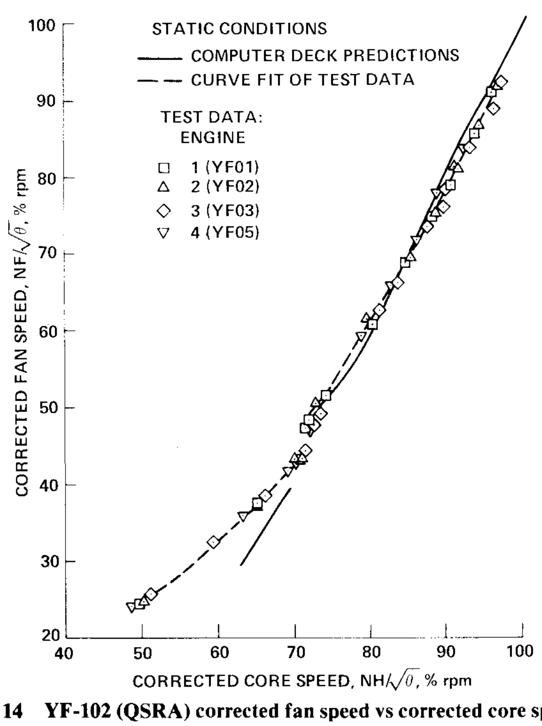


Fig. 14 YF-102 (QSRA) corrected fan speed vs corrected core speed.

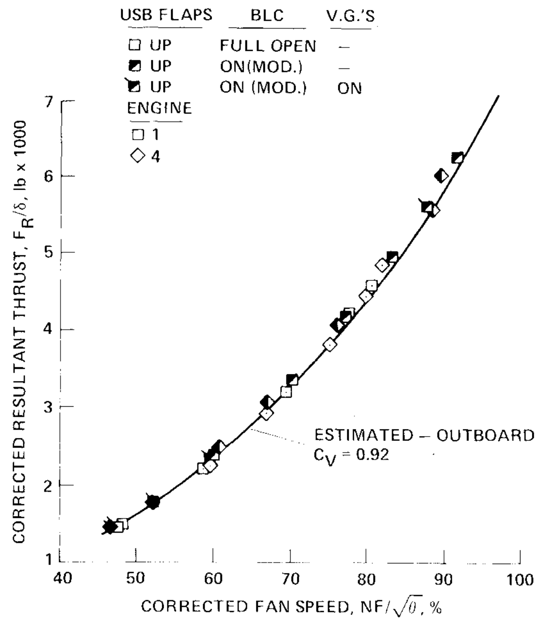


Fig. 15 Outboard engine gross thrust with USB flaps retracted.

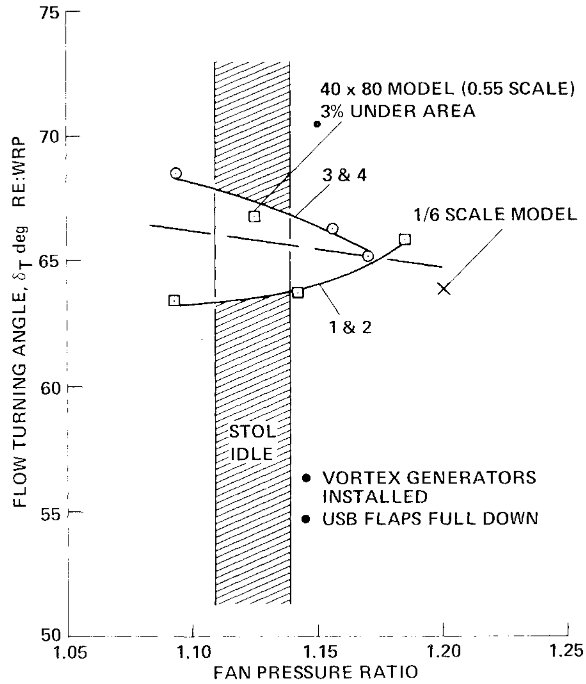


Fig. 16 Dual engine flow turning with vortex generators attached to the wing surface.

acquired with the BLC valve open and with BLC regulator modulating.

Because the thrust performance represents only the thrust due to engine exhaust, the thrust produced by the BLC nozzles was subtracted from the total balance force. The BLC nozzle thrust was estimated from BLC duct mass flows, pressure ratios and application of an internal nozzle loss coefficient (C_V) and an external (scrubbing) loss factor.

As indicated on Fig. 15, the outboard installation data is in close agreement with estimated levels. The inboard engines have about 3% less thrust, however, due to increased scrubbing losses. A similar effect was noted in the 0.55 scale (JT-15D) model data. As just explained, the C_V estimates include fan duct and nozzle losses (internal) and wing scrubbing losses (external). The few data points obtained with vortex generators installed indicate that they cause a slight loss in thrust at maximum power and no measurable loss at low power.

Flow Turning

The flow turning angle attained by the engine exhaust resultant thrust vector is an indication of how well the exhaust flow is attached to the USB flaps under static conditions. It is simply a measure of the effectiveness of the system to convert the axial thrust vector of the engine exhaust into a lift vector. The flow turning angles presented here are relative to the wing reference plane which is 4.5 deg (pitched up) relative to the body.

With the QSRA installed on three two-component force balances, the flow turning angles were measured by setting the USB flaps at the full down position (66 deg rotation) and operating the engines individually and in pairs through a range of power settings that bracketed the estimated approach thrust levels. Although these flow turning measurements were restricted to approach power settings because the jet/ground interactions caused by higher power settings yield questionable results, it was believed that they would provide a basic insight into the performance characteristics of the USB propulsive-lift design.

The mean flow turning angle for individual engines at STOL idle is about 69 to 70 deg. This level is slightly higher than the mean level measured with the 40 × 80 ft wind-tunnel model, but was expected due to the smaller relative USB nozzle height on the QSRA untrimmed exhaust. The slightly higher levels measured on the 1/6-scale model suggest a small flow turning penalty is incurred on the airplane installation due to canted-up primary exhaust or exhaust swirl.

The flow turning angles measured with the engines operating in pairs and with vortex generators installed are presented in Fig. 16, where flow turning angle is plotted vs fan discharge pressure ratio in order to compare with data from other facilities. The mean flow turning level is down from the individual engine turning levels by 3 to 4 deg. This effect was experienced with the 1/6-scale model also, and is believed to be caused by interference between the spreading exhausts from adjacent engines.

Although the turning angle difference between the left- and right-hand sides was not understood at the time of the ground tests, later investigation during the flight tests at Ames confirmed that this difference was real. Additional studies showed that its most probable cause was rotating exhaust flow induced by swirl in the primary exhaust. The vortex generators were repositioned to account for the presence of these rotational components, resulting in nearly symmetric aircraft performance during recent flight tests.

Engine Stability

Stability tests were conducted on all engines to demonstrate acceptable inlet operation and acceptable surge margins with increased fuel control acceleration schedules. These tests were conducted with modulated bleed off and the fuel control increased by 5% (TEST position for compressor surge detection). To check stability under severe operating conditions a series of transients, consisting of rapid accelerations, decelerations, and bodies, were performed on the engines. No adverse engine operation was noted and the engine operated surge free during this entire series of tests.

One final stability test was conducted on the engine to check inlet and fan operation at high angles of attack. A wind machine was positioned to provide a 36 m/s (72 knot) wind at 51 deg to the inlet centerline which was estimated to be the most critical inlet inflow condition. Tests were run on Engines 1 and 2 using the same procedures as in the previous tests and also with the engines at ground idle (low mass flow) in a crosswind, which is expected to be the worst condition for inlet separation. Again no adverse engine operation was detected.

Concluding Remarks

The Quiet Short-Haul Research Aircraft is a four-engine, upper surface blowing jet research airplane with very low sideline noise levels. Although this research aircraft operates only in the low-speed regime, the wing and nacelles were designed to be conceptually representative of a high-speed commercial transport aircraft. This advanced powered-lift system contains many of the elements that would be required in the design of an operational commercial propulsive-lift transport of the 1990s. The aircraft's propulsion system embodies more of a systems approach than is currently required in the design of today's transports, with engine, boundary-layer control (BLC) system, and to a limited extent, flight controls all being integrated.

Extensive use of BLC was required to prevent flow separation during high angle-of-attack flight to maintain adequate safety margins, especially during engine-out operation on steep descent paths. Another propulsive-lift requirement, the Coanda turning, dictated the propulsion system's mixed-flow D-nozzle design and the vortex generator pattern on the wing surface behind the engines. Funding limitations often prevented extensive use of full-scale system tests, resulting in a high reliance on analytical prediction and small-scale tests. These prediction techniques and small-scale tests played an especially important role in the critical design areas of the propulsion system. In addition, the BLC system bleed air requirements impacted the engine performance, particularly in engine acceleration characteristics and temperature safety limits, requiring an integration of BLC system and engine controls.

A comparison of the predicted and measured performance of the propulsion system components and of the total system showed that, in general, the extrapolation of small-scale tests and analytical techniques to the full-scale hardware was adequate and yielded very good results. In some cases, the predictions aided in the discovery and solution of potentially serious system problems with minimal cost impact.

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