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F-12 Series Aircraft Propulsion System Performance and Development

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The F-12 aircraft propulsion system elements are described. Flight performance of the inlet, engine, and ejector are treated, and the importance of flowfield simulation and engine nacelle leakage are demonstrated. The inlet design philosophy is discussed along with the importance of inlet control to the whole propulsion system. The inlet unstart is described, followed by a brief development history of the control schedules and their effect on the frequency of unstarts. Close cooperation between the airframe and engine manufacturers allowed an interface beneficial to the propulsion system.

Nomenclature

AB = afterburning
G = normal acceleration
Btu = British thermal units
$LVDT$ = linear voltage differential transducer
C_L = lift coefficient based on wing reference area
C_D = drag coefficient based on wing reference area
C_{fp} = ejector gross thrust minus pressure drag over ideal primary gross thrust
rpm = revolutions per minute
α = angle of attack measured from the wing reference plane
Engine Face Mass Flow Ratio = ratio of engine face station mass flow to the flow through an area equal to the inlet capture area at freestream conditions
Engine Face Total Pressure Recovery: total pressure at the engine face station divided by freestream total pressure calculated with a specific heat ratio of 1.4
Distortion: maximum pressure minus minimum pressure divided by the average pressure at the engine face
Mach number: velocity divided by the local speed of sound

Introduction

THE F-12 series of aircraft were designed in the early 1960's by the Advanced Development Projects group (the "Skunk Works") of Lockheed. The YF-12 set speed and sustained altitude records in 1964 which stand unchallenged to this day. These aircraft have unique propulsion system components required for sustained cruise above Mach 3.0 and at altitudes in excess of 80,000 ft. The propulsion system consists of an axisymmetric mixed compression inlet, the Pratt & Whitney J-58 bleed bypass turbojet engine, and a fuselage mounted blow-in-door ejector.

The purpose of this paper is to describe the F-12 propulsion system with particular emphasis upon the airframe mounted components. The airframe portion of this system interacts with the aircraft flowfields to significantly affect the performance of the aircraft in flight. Flight test results have been compared with various ground tests to confirm these effects and will be presented. The aircraft design objectives included efficient high-altitude cruise at maximum or part afterburning power. The aircraft angle of attack range was to be modest so the inlets were expected to accept air over a limited range of angle of attack. At supersonic speeds above Mach 1.6, the inlets operate in the internal compression mode, and supersonic flow within the inlet can become unstable, breaking down in what is known as an inlet unstart. This phenomenon requires careful control of the inlet geometry and the airflow passing through the inlet. The success of this propulsion system in avoiding unstarts is discussed in terms of inlet control; however, the care taken in minimizing engine airflow transients by the engine designers is equally important.

Propulsion System Description

The F-12 aircraft (Fig. 1) is clearly dominated by the propulsion system, with nacelles larger in diameter than the basic fuselage. The propulsion system depicted in Fig. 2 is made up of three major elements: 1) inlet and inlet control, 2) engine and its control, and 3) self-actuating airframe mounted ejector nozzle. Ready engine access is provided by hinging the outer wing about the upper outboard nacelle split line. The hinged portion of the nacelle and ejector is depicted separately for clarity.

Inlet

The inlet is axisymmetric with a translating spike. When the spike is retracted to its high Mach number position, the inlet contains an internal throat typical of a mixed compression inlet. Boundary-layer control on the spike is provided by a porous centerbody bleed with the bleed air passing overboard through louvers located at the ends of the centerbody support struts (Fig. 3). Cowl boundary-layer bleed is taken off through a "shock trap" bleed, oversized to provide sufficient pressure to feed the air through the engine secondary compartment and into

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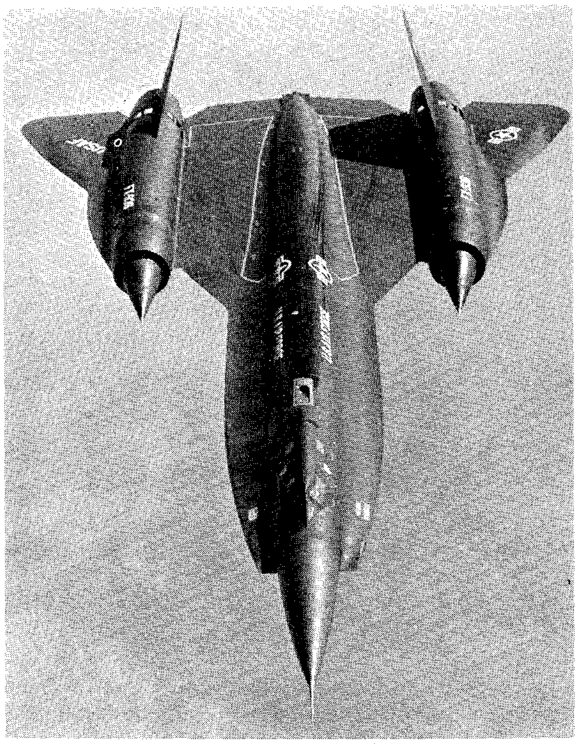

Fig. 1 YF-12A aircraft.

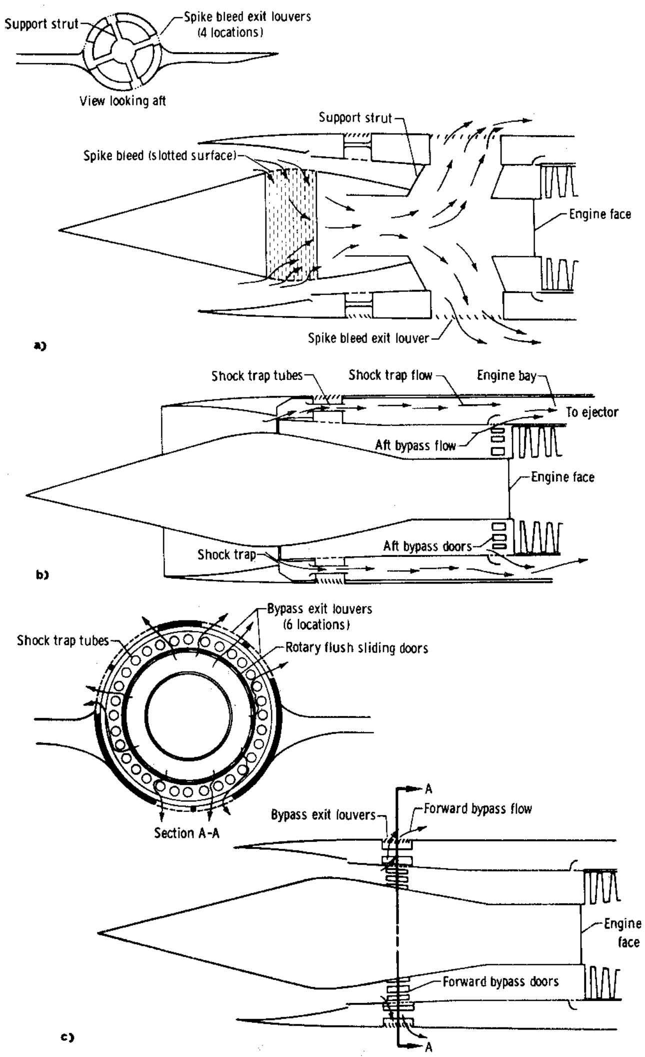

Fig. 3 Inlet flows.

the ejector. This cowl bleed air serves the dual purpose of stabilizing the terminal shock and cooling the engine and nozzle. The inlet is fitted with a forward bypass door, controlled by an inlet control to pass excess airflow overboard, matching the inlet to the engine. Aft bypass airflow joins the cowl bleed air passing through the ejector. This flow must be limited in order to avoid backing up the bleed and unstarting the inlet. It is manually scheduled. The aft bypass was added after initial flight test indicated forward bypass airflow was insufficient to allow idle operation. Also, judicious use of the aft bypass during acceleration reduces drag of forward bypass flow.

Engine

The engine is the Pratt & Whitney JT11D-20 designated the J-58 by the military. This engine is a single-spool afterburning turbojet with a fourth-stage bleed bypass which ducts air into the afterburner. This bleed system is operated at high Mach numbers to provide increased compressor stall margin. The bleed air re-enters the engine ahead of the afterburner where the air is used for cooling and increased thrust augmentation. The engine fuel control maintains a ratio of primary fuel flow to burner pressure as scheduled by compressor inlet temperature, rotor speed and power lever. Fuel flow ratio is trimmed by exhaust gas temperature to maintain high cycle efficiency. Engine airflow is controlled by scheduling engine rpm as a function of inlet total temperature. Engine rpm is maintained by modulating the exhaust nozzle. This arrangement provides nearly constant airflow at a given Mach number from below military power to maximum *AB*, which is very desirable when operating behind a supersonic mixed compression inlet. The J-58 engine is unique being designed to operate continuously even at maximum afterburning for high-altitude high Mach cruise.

Ejector Nozzle

The ejector nozzle is a blow-in-door ejector nozzle with free floating trailing edge flaps (Fig. 4) developed by Pratt & Whitney and modified as required to install it on the airframe. Airframe mounting of the ejector facilitates the passage of large secondary airflows and allows aircraft structural provisions to pass through the ejector. Airframe mounting allows a smooth transition from the aircraft contours into the ejector contours and facilitates engine

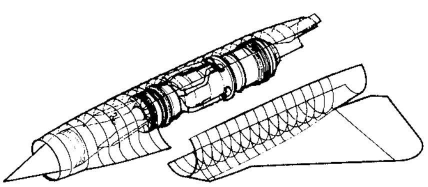

Fig. 2 F-12 propulsion system.

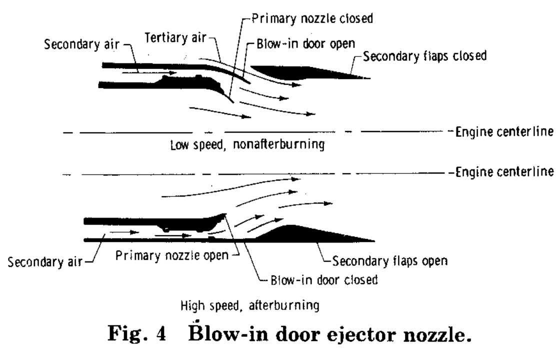

Fig. 4 Blow-in door ejector nozzle.

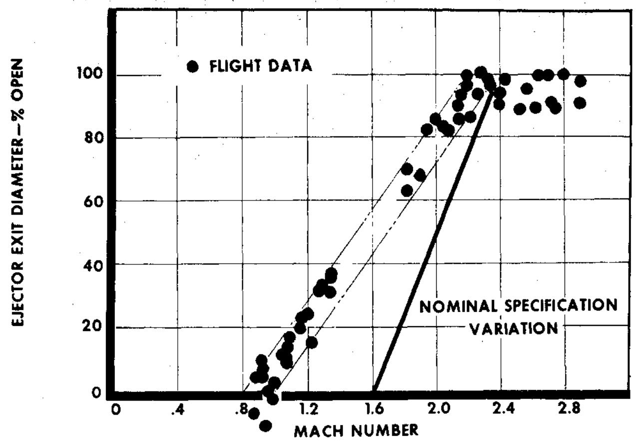

Fig. 5 Ejector exit area variation. Ejector exit diameter vs Mach number.

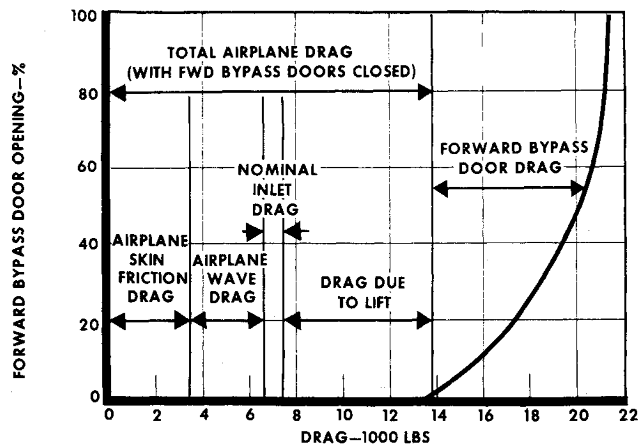

Fig. 6 Forward bypass door drag at cruise.

removal. The blow-in-doors provide tertiary air to fill the ejector nozzle at airspeeds below Mach 1.1. The trailing edge flaps open up between Mach 0.9 and Mach 2.4, in order to provide a divergent shroud around the primary nozzle and the secondary stream at high Mach numbers (Fig. 5). In order to understand the importance of each of the three propulsion system components, it is interesting to note the proportion of the thrust which is supplied by each component while operating in maximum afterburner. Table 1 indicates how the actual thrust forces are distributed while the engine is inducing flow and heating it up with maximum afterburner. If the *AB* is reduced to minimum *AB*, the engine would actually be dragging on the engine mounts at high Mach numbers. Further reduction of engine thrust below military power will result in no propulsive thrust on the aircraft.

Table 1 Propulsive thrust distribution

Mach no.	Inlet	Engine	Ejector
2.2	13	73	14
3.0+	54	17.6	28.4

Propulsion System Philosophy

The propulsion system was optimized to provide maximum thrust at relatively high angles of attack for maximum altitude capability while operating at high Mach number cruise. The inlet was sized to provide good transonic performance and excellent high speed cruise performance. With increasing flight Mach number, the engine air inlet tends to increase in size and complexity. The inlet becomes a potentially more significant part of the propulsion system and can affect the aircraft flying qualities. Figure 6 indicates the relative importance of the inlet forward bypass door to the other elements of aircraft drag. Obviously, when operating at a stabilized condition of thrust equal drag, motion of the forward bypass door can disturb the aircraft. This is particularly noticeable when one bypass door is full closed, and the other door is moving in response to atmospheric variations and causing yaw oscillations on the aircraft. At this point, a brief explanation of the inlet control as it is presently mechanized will be expounded (Fig. 7).

Inlet Spikes

Each inlet centerbody has a spike which moves forward at low speeds to provide a large throat area required to match engine airflow and spill excess airflow ahead of the inlet. As the Mach number increases above Mach 1.6, the spike is retracted to capture more airflow and restrict the throat as required to slow the flow for efficient compression. The inlet control senses flight Mach number at the nose boom of the aircraft. Angle of attack and angle of sideslip are sensed by an attitude probe on the left side of the pitot static boom.[1] Spike position is scheduled by Mach number and biased by angle of attack (α), angle of sideslip (β), and normal acceleration. Normal acceleration was selected in order to compensate for the effects of structural bending. The nose of the aircraft containing the α sensor may deflect up or down during elevated "*g*" conditions depending upon fuel loading in the aircraft.

If an inlet should unstart, a sensor is provided to note the rapid drop in duct pressure. This unstart signal overrides both inlet spikes and drives them forward in order to remove the internal contraction sufficiently to allow the inlet to restart. The spike then returns to its normal position. Both inlets are restarted in order to balance the forces produced upon the airframe by the unstarted inlet.

In the event of a control system malfunction, the spike can be set manually in accordance with a Mach schedule on the cockpit control provided hydraulic pressure is

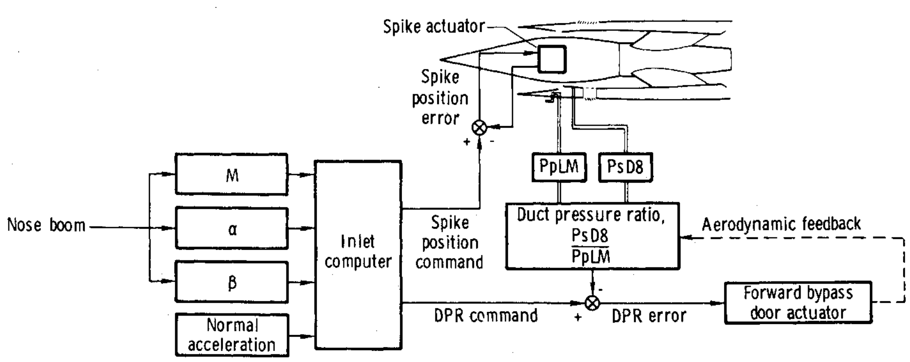

Fig. 7 Inlet control schematic.

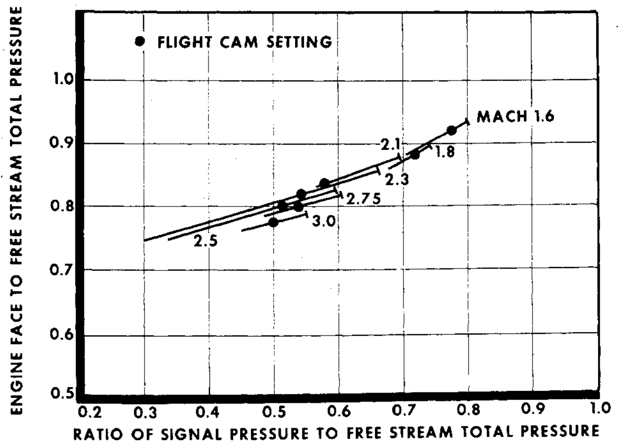

Fig. 8 Effect of signal pressure on enging face pressure recovery. Control signal pressure vs recovery. $\alpha = 3°$.

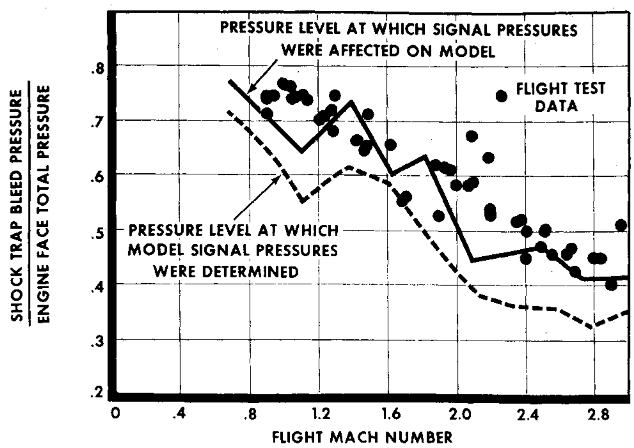

Fig. 10 Shock trap bleed pressure.

available and the spike *LVDT* is functional. If the spike *LVDT* fails, the spike may be moved full forward with a solenoid.

Forward Bypass Control

With the spike properly positioned, the inlet is capable of producing a pressure ratio of 40:1 at Mach 3.0+, provided the terminal shock is properly positioned within the inlet. The terminal shock moves in response to changes in airflow. The forward bypass door in each inlet consists of a series of openings in a rotating band located a short distance aft of the inlet throat. Rotation of the band uncovers matching openings in the inlet duct and allows airflow to pass overboard through louvers.

Operating automatically the bypass doors are open on the ground to allow additional air to enter the inlet at static conditions. The doors are closed upon retraction of the landing gear. At Mach 1.4, the bypass may modulate as required to produce a scheduled pressure ratio between a duct wall static pressure slightly aft of the inlet throat and a cowl pitot pressure. Figure 8 presents the relationship between the signal pressure and the inlet pressure recovery for a low angle of attack. The signal pressure ratio, like the spike position, is scheduled as a function of Mach number, biased by angle of attack, angle of sideslip, normal acceleration, and in addition, spike position error. If the signal pressure is below the pressure ratio set by the control cam, the bypass door will close, reducing the airflow from the duct.

During rapid transients, if the spike is out of position as indicated by a large voltage to the spike electro-hydraulic valve, an open bias is applied to the forward bypass door.

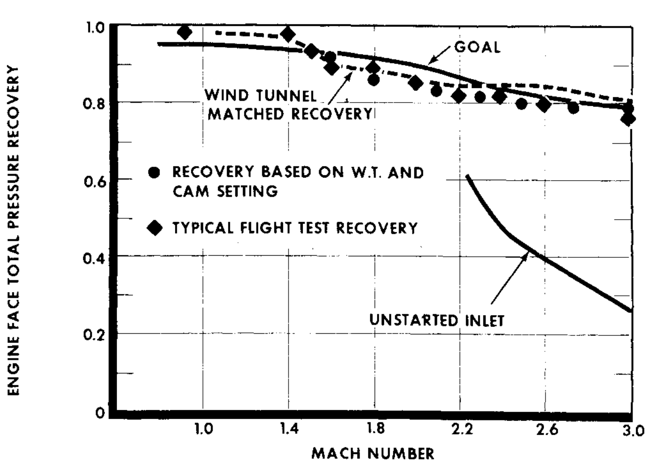

Fig. 9 Engine face total pressure recovery.

This adds tolerance during dynamic situations and makes provision for the fact that the spike is out of its scheduled position.

When the bypass door is commanded closed beyond its stop, the hydraulic valve and electronics would tend to integrate to a condition which would not allow rapid response to a door open transient. This tendency is overcome by providing a capacitor circuit which charges in response to a large door closed signal and opposes the door closed signal.

Large unsatisfied forward bypass door open commands are sensed and used to double the door open signal gain and provide added response to the bypass doors in a direction to avoid unstarts.

In the event of a malfunction of the bypass control, manual control of the door is possible by cockpit control knob or an open override solenoid switch.

Flight Performance

The propulsion system and aircraft flight performance were evaluated in relationship to component tunnel tests and over-all aircraft drag. The following elements were studied: a) Inlet total pressure recovery and mass flow, b) Engine as a gas generator, and c) Ejector momentum balance.

Inlet

The inlet engine face total pressure recovery is presented in Fig. 9. The original goal estimate was made for preliminary performance estimates. The wind tunnel matched recovery data came very close to the goal. The actual flight performance met the goal and the wind-tunnel performance at high Mach numbers, but dropped below the wind-tunnel matched performance from Mach 2.1 to 2.8. The reason for this lower performance was the apparent necessity to lower the inlet duct pressure ratio controlling the forward bypass door in order to avoid inlet unstarts. The effect of signal pressure on recovery is shown in Fig. 8. When the flight signal pressure points are plotted on wind-tunnel data, the recovery agrees with flight experience as presented in Fig. 9.

The shock trap secondary bleed pressures in flight were high requiring a signal pressure reduction from the wind tunnel derived signal pressures (Fig. 10). The inlet mass flow ratio was hard to pin down due to the characteristic of the inlet with the cowl shock trap bleed feeding the ejector. Figure 11 presents the wind-tunnel data with various bleed restrictions. Note the large variation in engine face mass flow ratio as a function of cowl bleed exit cover position. This is contrasted to the same inlet with a ram bleed designated by the square symbols.

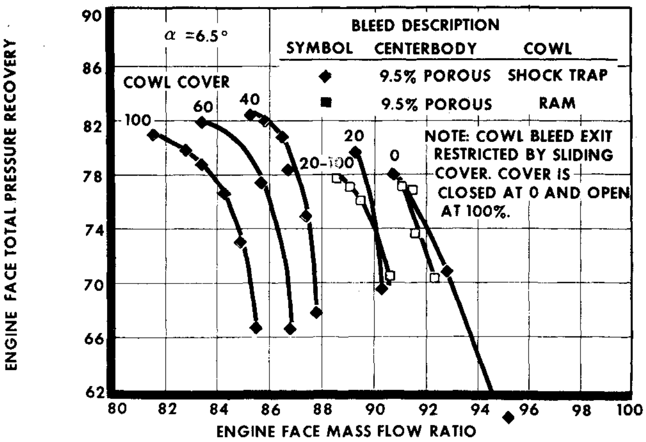

Fig. 11 Effect of cowl bleed restriction on enging face total pressure recovery.

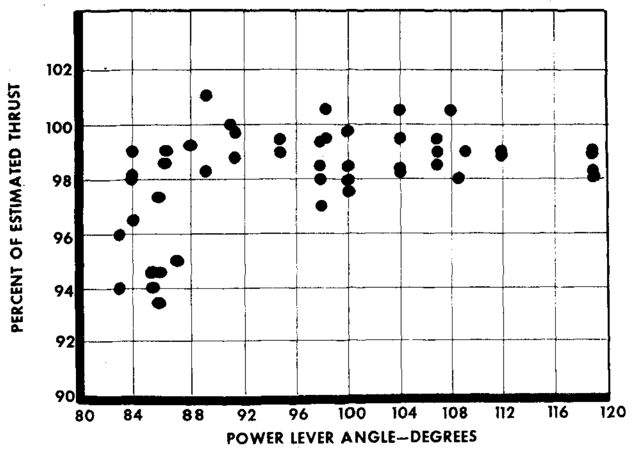

Fig. 13 Inflight engine thrust evaluation. Nominal estimated vs calculated net thrust from flight data comparison at cruise Mach number.

Note that after the cowl cover is 20% open, there is no further variation in inlet mass flow as the cover is opened to 100%. The shock trap bleed[2] was selected because it did provide a favorable compromise between inlet stability and good bleed recovery. However, the operating point depends on a number of variables, including the afterburner setting and aft bypass door setting, both of which affect the back pressure. In order to evaluate the inlet performance, an accounting system was set up assuming the nominal wind-tunnel mass flow data of Fig. 12 and flight measured pressure recovery. Overboard bleed and bypass drag were evaluated based on wind tunnel tests of a fullscale typical louver. Spillage drag was based on analytical calculations and empirical data. The secondary passage flow was matched based on flight test flow vs pressure drop data, and engine specification ejector characteristics. All the mass flow was accounted for and an inlet drag determined.

Engine

An instrumented engine was evaluated using the gas generator method. Cruise performance data (Fig. 13) indicated that the actual thrust was generally within 2% of the calculated thrust using measured exhaust gas temperature and rpm. Since this is within the expected accuracy of this method, calculated engine thrust is considered to be reasonably accurate for the following study.

Nozzle

The aircraft nozzle was pressure tapped, the flight ejector thrust was calculated and the thrust from the engine performance report was subtracted to provide the increment plotted in Fig. 14. A decrement in excess thrust was noted at transonic speeds on the aircraft, and this ejector performance represents a portion of this thrust loss. Chase pilots noted that the ejector trailing edge flap position started open sooner than expected, Fig. 5. A wind-tunnel investigation simulating the wing and rudder confirmed that the ejector was suffering from higher than freestream Mach number at transonic speeds.

After many accelerations for which the thrust was calculated, there appeared a discrepancy based on early drag estimates. As indicated in Fig. 15, the nominal discrepancy increment reached 80 drag counts at Mach 1.0. The early drag estimate was based on a straight sting model and an estimated boattail drag. Later model tests included a blade sting which improved the boattail representation as indicated in Fig. 16. Applying flight measured pressures across the blade sting area improved the representation further. However, without the ejector tertiary blow-in-doors flowing on the model, a drag the equivalent of $\Delta C_p = 0.002$ was missed between Mach 0.95 and Mach 1.0. In addition, the wing pressure drag was measured to determine the effect of the actual ejector configuration in flight, and an additional drag increment determined. Figure 17 indicates that the losses associated with the mutual interference of the ejector and boattail of the fuselage and wing accounts for the major portion of the transonic decrement. At higher Mach numbers, the thrust and drag agreement is excellent.

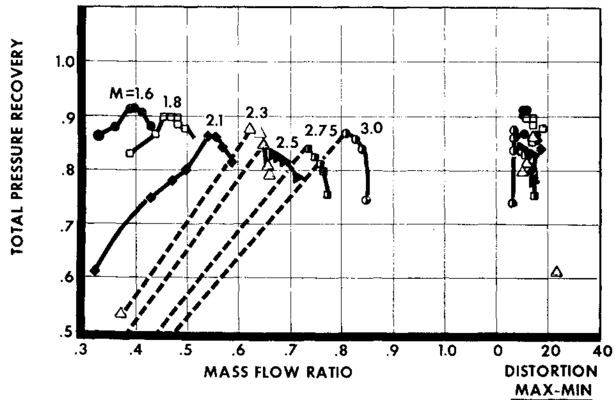

Fig. 12 Wind-tunnel engine face total pressure recovery. Nominal wind tunnel data.

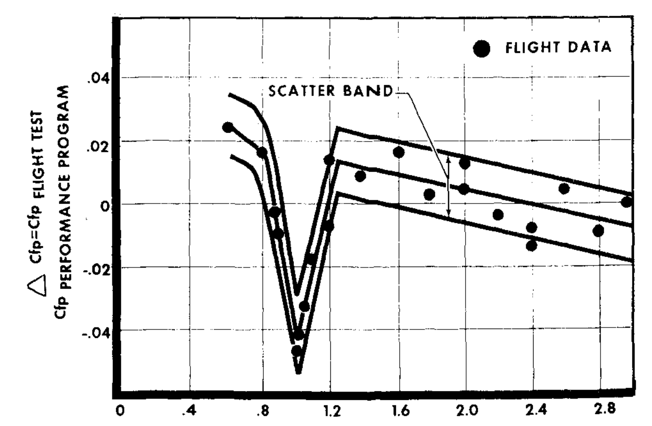

Fig. 14 Comparison of flight test ejector performance with specification prediction.

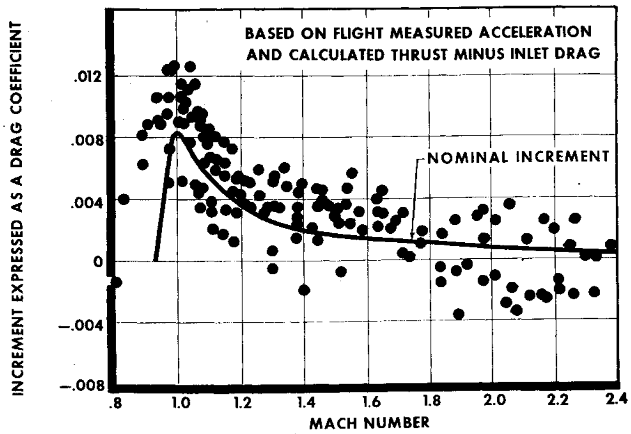

Fig. 15 Increment between flight test and initial drag estimate.

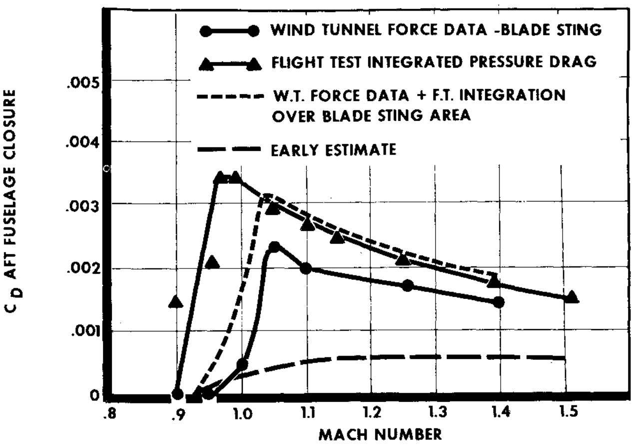

Fig. 16 Aft fuselage pressure drag.

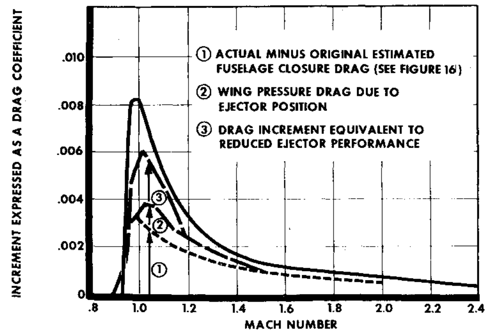

Fig. 17 Buildup of drag increment to match flight data.

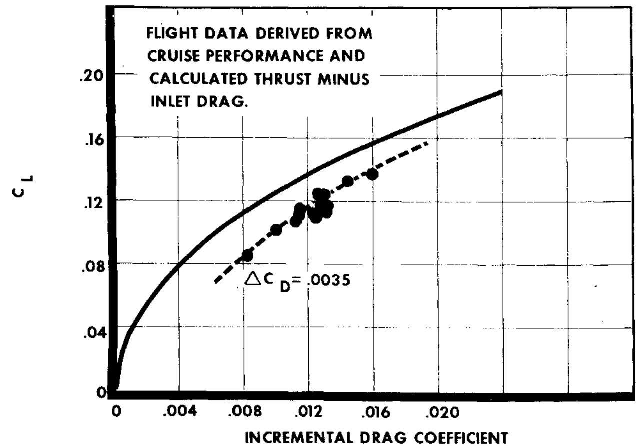

Fig. 18 Drag increment between flight test and estimated at cruise. ΔC_D vs C_L cruise Mach.

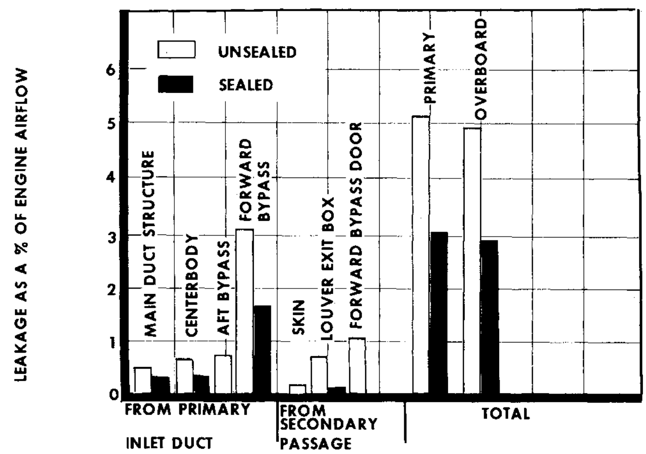

Fig. 19 Nacelle leakage at cruise. Nominal cruise leakage one nacelle.

Cruise Performance and Duct Leakage

As noted in the previous section, the thrust minus drag was approaching very close to the estimated value as Mach number increased toward Mach 2.4. At higher Mach numbers near cruise, the performance fell below the predicted by the equivalent of $C_D = 0.0035$ as indicated by Fig. 18. Although the containment of air at high pressure ratios across the structure had been considered seriously from the beginning of the design, this factor was still suspected. The forward bypass doors originally had a light spring steel lip seal which was quite effective, but had to be replaced when the seal began to break up and go into the engine. In order to establish the location and magnitude of various leaks, an aircraft nacelle was tested under air pressure. As part of the program, seal improvements were made and the leakage from the sealed and unsealed nacelle are presented in Fig. 19. Note that the largest single source of leakage is the forward bypass doors. Since the forward bypass door is open at Mach numbers above 1.6. no drag penalty due to door leakage is observed until the forward bypass door closes near cruise. In fact, using the mass flow accounting system mentioned earlier, the leakage flow was accounted for as bypass or secondary flow through the ejector. However, early estimates assumed the bypass would be closed and we were expecting door closed performance. Leakage from the aft nacelle has had ram drag charged to it; however, the ejector is given credit for the momentum of this air. Therefore, an ejector loss due to leakage must be accounted. The original fuel heating value was to be 19,100 Btu/lb, but a more realistic value of 18,500 Btu/lb reduces the performance slightly.

Centerbody bleed drag was estimated on an ideal exit thrust at $C_D = 0.0007$. When louver data became available, the value used in calculations was $C_D = 0.00125$ for the best thrust louver configuration. This configuration was only tested on one aircraft together with improved sealing and the reduced bleed drag was realized. The centerbody bleed drag used in the present configuration is the wind tunnel louver drag for production louvers which can pass more airflow than the low drag louver.

The present propulsion system performance can be calculated based on ground measured leakage flows from the nacelle bypass and secondary passage, measured louver drags, measured fuel heating value, and the flight measurement of engine thrust. This has been done and the results tabulated in Table 2. By subtracting the "value esti-

Table 2 Drag buildup of flight test drag increment at cruise

Item	Present	Attainable
Centerbody bleed	0.0014	0.00125
Nacelle leakage	0.0023	0.0011
Ejector with leakage	0.0007	0.0007
Engine down 1%	0.0002	0.0002
Fuel heating value	0.0002	0.0002
Total	0.0048	0.00345
Less value estimated	0.00125	0.00125
Δ from estimated thrusts	0.00355	0.00220
Δ Found in flight	0.0035	0.0022

mated," a discrepancy from the simply calculated inlet bleed drag is obtained which agrees well with the discrepancy found in flight using the same calculated bleed drag. A further test was made with sealed nacelles and improved centerbody louvers, and compared to a calculation of attainable performance. Again, good agreement was found to exist.

Inlet Unstarts

When supersonic flow entering an inlet breaks down due to the expulsion of a normal shock, the inlet is said to have unstarted. The shock system separates the spike boundary layer as indicated in the schlierin photograph of an unstarted inlet (Fig. 20). The total pressure in the inlet during unstart is equivalent to the pressure required to separate the spike boundary layer. This pressure, presented in Fig. 9, can be lower than normal shock recovery.

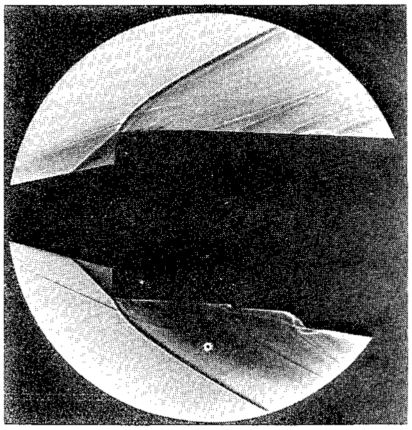

Fig. 20 Schlieren of an unstarted inlet.

The inlet must go through a restart cycle, removing the inlet contraction area and opening the bypass door to allow a restart. When an unstart occurs, the aircraft experiences a yaw and tendency to roll off on one wing. The thrust loss is very large, and therefore is very undesirable. During the development phase, it was found to be desirable to restart both inlets to minimize the unsymmetrical loads on the aircraft. However, the greatest effort went into reducing the frequency of inlet unstarts. This was accomplished by adjusting the inlet control signal pressure levels and the spike schedule on one hand while working to eliminate hardware problems from the control system. A statistical record of unstarts was maintained during the implementation of improved hardware and schedules, indicating a reduction of flights with unstarts by a third.

Conclusions

The F-12 propulsion system is now developed and the performance of this system has generally met predictions when the predictions were based on accurate simulation. The following are conclusions regarding some of the requirements needed to obtain accurate simulation and good design for supersonic propulsion systems:

1) Model testing required to develop propulsion system performance should include provision for the simulation of external flowfields.

2) The simulation of ejector configuration and also ejector flows may be required to properly evaluate the combined system drag. This is especially true at transonic speeds.

3) Nacelle leakage is a real problem which must be met from the beginning of design, and allowed for realistically in performance estimates.

4) When selecting a nozzle type, proper account must be made for auxiliary inlet flows. The ejector nozzle, for example, allows bleed flow to ventilate the engine compartment and be used in the nozzle rather than being passed overboard.

5) Optimum propulsion system performance requires control over the engine airflow to eliminate the drag penalty of bypassing airflow.

6) High reliability components combined with ample unstart margins make the mixed compression inlet a practical device capable of efficiently reducing the velocity of the engine airflow from freestream to engine face conditions.

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