Thrust Reverser Exhaust Plume Reingestion Model Tests

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The flow characteristics of lower reverser jets in ground effect were investigated on an advanced fighter aircraft model using flow visualization techniques Initial testing, with noncanted reverser jets, showed that aircraft velocity at ingestion onset was close to touchdown velocity However, the introduction of outboard jet cant significantly reduced the ingestion onset velocity For example canting the jets outboard by 30 deg reduces this velocity by half A data set is presented which can be used to predict reverser efflux penetration over a range of jet axial and cant angles for models of similar configuration

Nomenclature

A_{JET}	= reverser lower jets total effective area
d	= reverser equivalent jet diameter $\sqrt{4A_{JET}/\pi}$
h	= height of lower reverser exit above ground
NPR	= effective nozzle pressure ratio
P_{JET}	= effective total pressure at reverser exit
P_∞	= freestream static pressure
q_{JET}	= reverser dynamic pressure $P_{JET} - P_\infty$
q_∞	= freestream dynamic pressure $\frac{1}{2}\rho_\infty V_\infty^2$
V_{AX}	= freestream or tunnel velocity along model x axis knots
V_{ING}	= freestream or tunnel velocity at ingestion onset knots
V_R	= relative velocity $\sqrt{q_\infty/q_{JET}}$
V_∞	= freestream or tunnel velocity knots
X	= exhaust plume upstream penetration distance
X_{LIP}	= value of X at inlet lip
α	= angle of attack, deg
β	= angle of sideslip, deg
θ	= reverser jet axial angle measured anticlockwise from x axis to jet vector projection in x z plane deg (Fig 2)
ϕ	= reverser jet cant angle measured from z-axis to jet vector projection in y z plane deg (Fig 2)
γ	= reverser jet azimuth angle measured from x axis to jet vector projection in x y plane deg (Fig 10)

Introduction

CURRENTLY there is considerable interest in the development of advanced tactical fighter aircraft which may be required to operate from bomb damaged runways A short takeoff and landing (STOL) aircraft with a reversing exhaust nozzle may be necessary to satisfy this shortened runway requirement Thrust reversing is an effective approach for decelerating an aircraft both in flight and during ground roll It provides rapid deceleration reduced landing distances and improved survivability

Although thrust reversing can substantially reduce landing distances, a potential problem associated with reversing during aircraft ground roll is the ingestion of hot exhaust gases into the engine inlet Temperature distortion generated by these hot gases can significantly reduce engine performance and cause serious engine stability problems Thus the amount of useful reverse thrust is a function of the aircraft speed at which inlet reingestion occurs Hence, for effective thrust reverser operation it is essential to design for a low ingestion speed

The reverser exhaust gas reingestion problem during aircraft landing ground roll has received some attention during recent years both for commercial[1] and military[2] aircraft However, the need still exists for a detailed study of this problem for advanced STOL fighter aircraft with reversing nozzles Also development of a detailed exhaust plume reingestion test data base is essential for effective thrust reverser design In order to develop this data base a novel flow visualization water and wind tunnel test program was conducted in the Northrop test facilities Both test results and the parametric data base which was developed are presented in this paper This data base can be used to establish the orientation of the lower reverser ports in order to give acceptable ingestion onset speeds for models of similar configuration

Two modified F 18 models fitted with simulated lower nozzle jets were tested A 0 025 scale model was used for the water tunnel test This was primarily an exploratory test intended to provide the key simulation parameters for subsequent wind tunnel tests conducted with a 0 08 scale model The primary emphasis was on flow visualization in order to determine the forward extent of the efflux front during its propagation towards the inlets Both canted and noncanted jet orientations were tested The detailed reingestion test data base discussed in this paper was obtained from the 0 08 scale wind tunnel test

Test Approach

In order to investigate the reverser plume reingestion flow characteristics only the lower reverser jets were simulated The trajectory and forward penetration characteristics of jets expanding into free air are well documented[3] and show that the flow from the upper ports will not be critical as far as ingestion is concerned A 6 ft diameter ground board was used to simulate the ground plane Its size was minimized to reduce boundary layer and tunnel blockage effects

The upstream penetration and ingestion characteristics of the lower reverser plume during ground roll are likely to depend on: 1) the physical dimensions of the jet and its

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orientation 2) aircraft configuration 3) nozzle pressure ratio 4) the ratio of jet momentum to freestream momentum 5) effects arising from the temperature difference between the reverser efflux and freestream flow and 6) the modification of the flowfield due to inlet suction

To achieve complete similarity at model scale it would be necessary to use a hot jet However, for a given flow area and nozzle pressure ratio jet momentum is essentially independent of jet temperature since its velocity is proportional to the square root of temperature and the density varies inversely as temperature Hence, the principle of momentum similarity can be preserved using a convenient cold jet simulation at model scale, as in this test series Also, a comparison of model ingestion results from both hot and cold jets in Ref 1 shows that the ingestion velocities derived from both techniques agree to within 10% indicating that temperature effects such as buoyancy are small The presence of a ground board boundary layer at model scale would result in a freestream momentum deficiency aiding jet upstream penetration, thus resulting in overestimated ingestion onset velocities. For these tests the ground plane boundary layer growth was minimized by keeping the ground board as small as possible

In order to simulate the large inlet capture ratios during ground roll inlet suction was provided as a function of nozzle pressure ratio The reverser port geometry was preserved at model scale

For a typical test run, the wind tunnel velocity was reduced in stages from the maximum velocity of interest at constant nozzle pressure ratio and at the required inlet air flows With each reduction in tunnel velocity plume progress towards the inlet and beyond was observed and recorded through flow visualization For these tests it was assumed that ingestion occurred when the plume reached the inlet lip The tunnel velocity at ingestion (V_{ING}) was defined as the aircraft ingestion onset velocity

Model Test Description

Model Details

Figure 1 shows the schematic of the model as tested in the Northrop 7×10 ft low speed wind tunnel It represents an advanced fighter twin engine configuration fitted with four simulated nozzle reverser ports on the lower aft fuselage

The distance from port centerline to the inlet lip was 20 6 in and the reference nozzle exit height for ground roll was 4 8 in Model height was adjustable and variable length landing gear legs enabled the wheels to be kept in close proximity to the ground board The ground board was of circular plan form (6 ft diam) in order to preserve the geometry in sideslip when the model and ground board were yawed together Its size was minimized in order to reduce boundary layer and tunnel blockage effects

High pressure air at ambient temperature was supplied to the reverser ports through flexible hoses feeding a plenum chamber The plenum chamber and nozzle assembly were pivoted close to the nozzle centerline in order to allow axial variation of the reverser efflux angle Canting of the jets laterally was achieved by suitably cut interchangeable inserts of aluminum honeycomb Jet flow axial and cant angles were calibrated to within 5 deg of accuracy. The pressure loss through the honeycomb was determined and the reverser jet exit pressure ratio was subsequently monitored using a calibrated transducer in the plenum chamber Provision was made to measure reverser port and inlet mass flows

Reverser Plume Flow Visualization

The reverser exhaust plumes were made visible by injecting water into the high pressure air through spraybars upstream of the plenum chamber The resulting efflux mist was illuminated by a strong light source mounted under the ground board and directed through a 1 in wide slit in the longitudinal plane of the inlet as shown in Fig 1

The plume progress upstream with reducing tunnel velocity was monitored by photographing the mist pattern and the separation line between freestream and nozzle flows The separation lines were made visible on the ground board by the

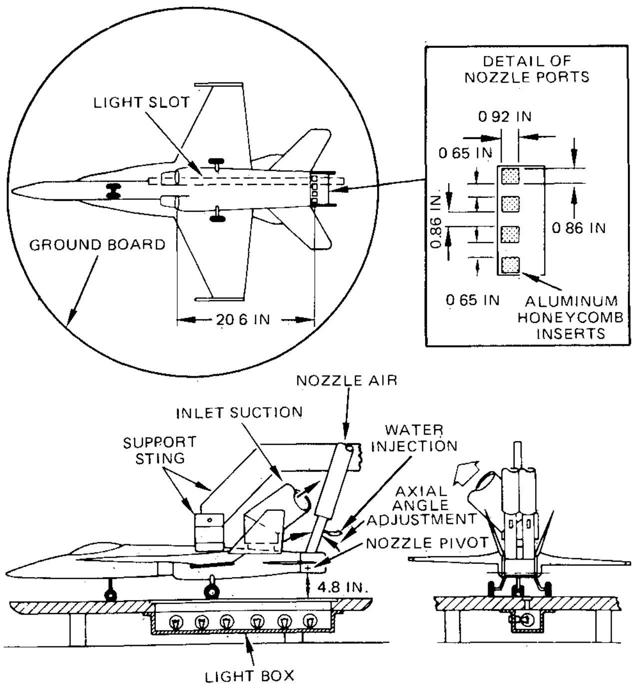

Fig 1 Wind tunnel model test schematic

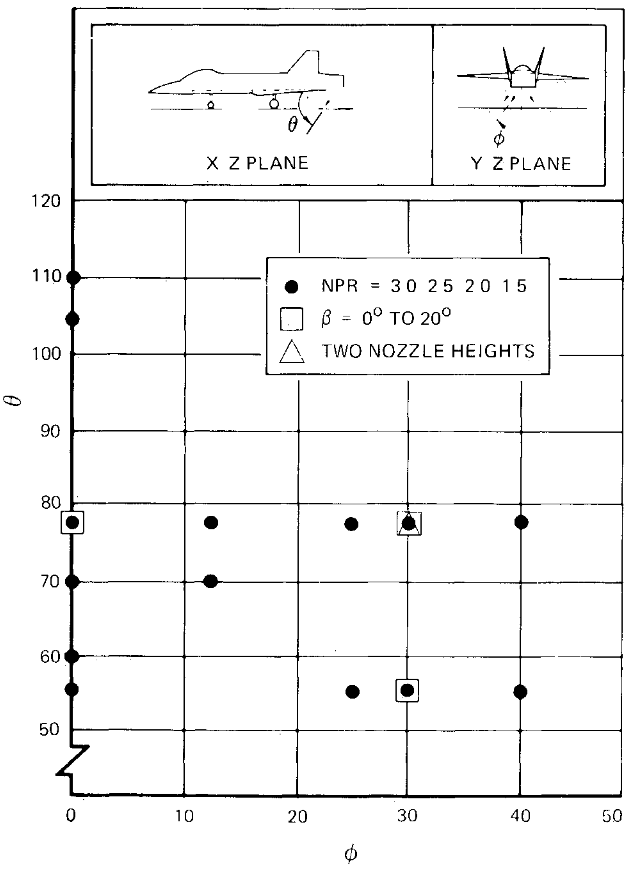

Fig 2 Test matrix

accumulation of water droplets from the jet Some observations were also made with ground board tufts

Test Matrix

Figure 2 shows the range of jet flow angles tested at the four reverser exit pressure ratios Plume upstream penetration and ingestion was investigated at axial angles from 55 to 110 deg with zero cant Effect of jet canting was obtained primarily at θ of 55 and 77 deg Sideslip effects were also obtained at θ/ϕ of 77/0 77/30 and 55/30 deg Two nozzle heights (baseline and baseline plus 20%) were tested at θ/ϕ of 77/30 deg

Test Results

An overview of how the test was conducted is shown in Fig 3 Data are presented for noncanted jets ($\theta/\phi = 77/0$ deg) at NPR of 3 0, 2 0 and 1 5 Wind tunnel velocity for a given efflux penetration distance is plotted against $X/X_{\rm LIP}$ The data set at each of the three NPR values represents a typical test run The tunnel velocity is reduced in stages from its maximum value at constant NPR and the corresponding inlet airflow Ingestion occurs when the plume reaches the inlet ($X/X_{\rm LIP} = 1\ 0$) These data indicate that at the noncanted axial jet angles and higher nozzle pressure ratios desirable for reverse thrust efficiency the ingestion velocities can be close to touchdown velocities This problem was also evident with the initial Tornado reverser design[2] and led to the investigation of jet canting

A more generalized data set is shown in Fig 4 Ingestion velocity $V_{\rm ING}$ is presented as a function of NPR for a series of nozzle axial angles It shows that reducing NPR at a fixed axial angle results in lower ingestion velocities

Data Correlations

All the basic test data in this paper are presented in a relative velocity form $V_R h/d$ This parameter, when expressed as $\sqrt{q_\infty h^2/q_{\rm JET} d^2}$ is seen to be proportional to the ratio of freestream momentum of a flow area h^2 and the momentum of a jet with equivalent diameter d The upstream penetration of the jet depends strongly on this ratio

The above parameter has been used to correlate extensive test results in Refs 1 and 4 It is demonstrated in Ref 4 that for a jet impinging on the ground but unconstrained by any airframe interference, the nondimensional upstream penetration distance X/h is a function of this parameter for a range of jet sizes and nozzle heights Furthermore this same parameter is used in Ref 1 to correlate extensive test results obtained from a series of model tests performed to determine the hot gas ingestion characteristics of the Concorde aircraft It is also shown that there is a good correlation for both hot and cold jet model tests conducted for a range of nozzle heights and reverser jet pressure ratios

Northrop wind tunnel test data obtained for noncanted reverser jets are presented in Fig 5 using the parameters discussed above Results are shown for three values of θ ranging from 55 to 105 deg and for all the NPR values tested These data correlate rather well Entering Fig 5 with a given $X_{\rm LIP}/h$ (i e 4 3 for the configuration tested) shows that the ingestion velocity substantially reduces with increasing reverser jet axial angles

The effect of jet canting is shown in Figs 6 and 7 for 55 deg and 77 deg axial angles respectively The canting range shown is 0 to 40 deg At each cant angle it was necessary to define a new value of the equivalent jet diameter because of the changing flow characteristic of the honeycomb inserts as the cant angle was increased Jet canting reduces ingestion velocity at both axial angles primarily by modifying the efflux trajectory It is also likely that some of the benefit of cant is due to the lateral separation of the jets at ground plane impingement This reduces the possibility of mutual jet interference and destroys the mechanism producing the " fountain" effect at impingement which was observed for the zero cant cases These data also show fairly good correlation for the two reverser jet heights tested at 30 deg cant angle The effect of jet height on ingestion velocity is discussed below

Effect of Reverser Exit Height

The effect on ingestion velocity of raising the reverser exit height 20% from the reference height is shown in Fig 8 As can be seen there is approximately a 10 knot reduction in ingestion speed at the increased height

Crosswind Effect

The effect of sideslip on efflux penetration was investigated at angles up to 20 deg for a limited range of axial/cant angles The magnitude of this effect will depend in part on the difference between the sideslip angle β and jet azimuth angle γ Figure 9 shows the effect of sideslip on efflux penetration at

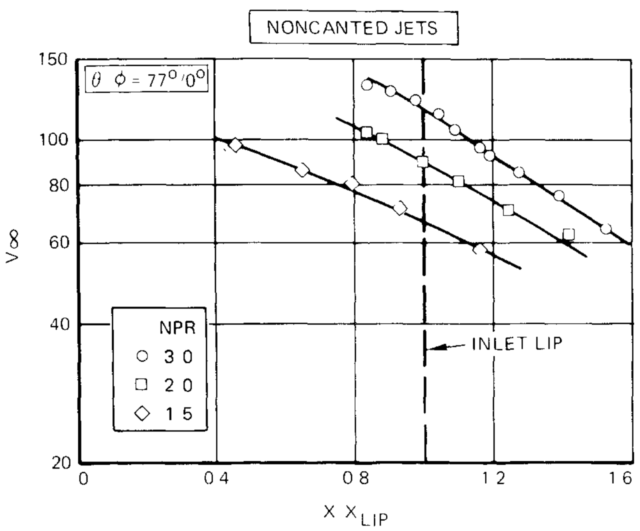

Fig 3 Efflux penetration characteristics

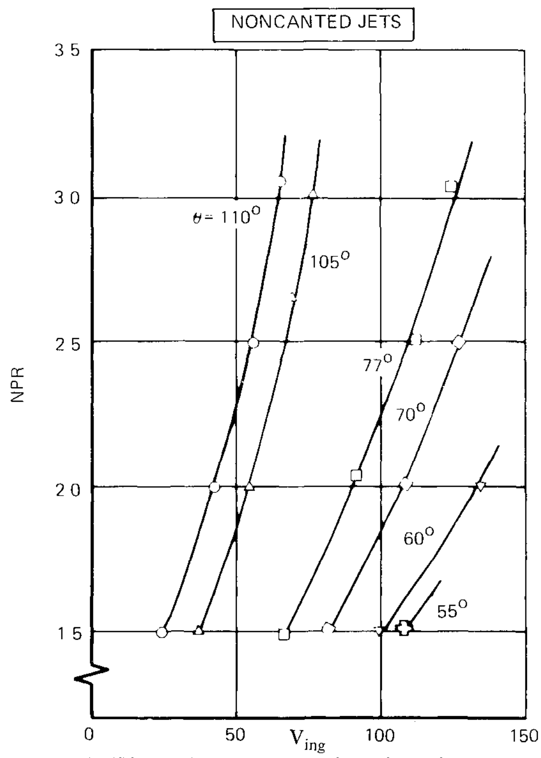

Fig 4 Effect of jet pressure ratio on ingestion velocity

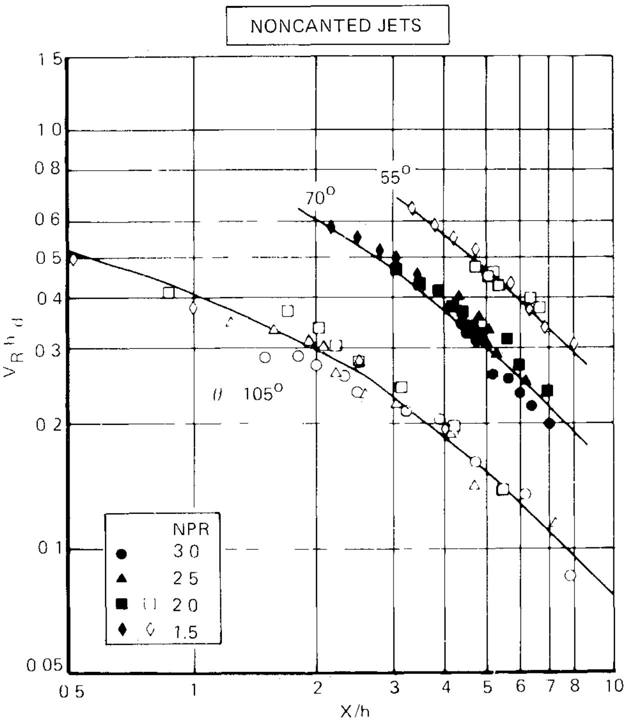

Fig 5 Jet axial angle effect on efflux penetration

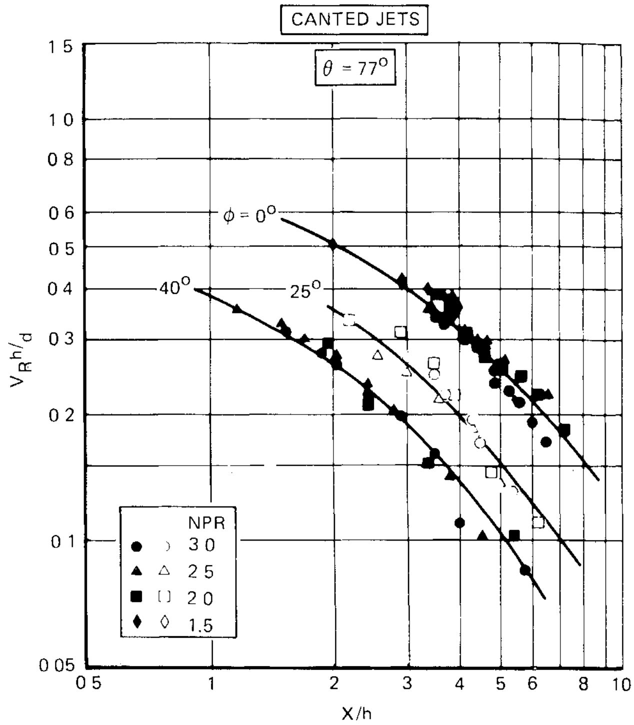

Fig 7 Jet cant angle effect on efflux penetration $\theta = 77$ deg

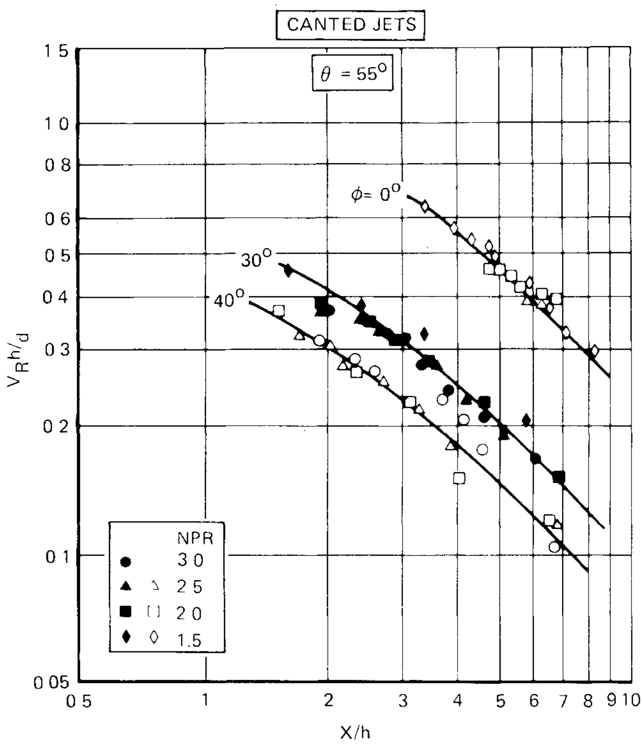

Fig 6 Jet cant angle effect on efflux penetration $\theta = 55$ deg

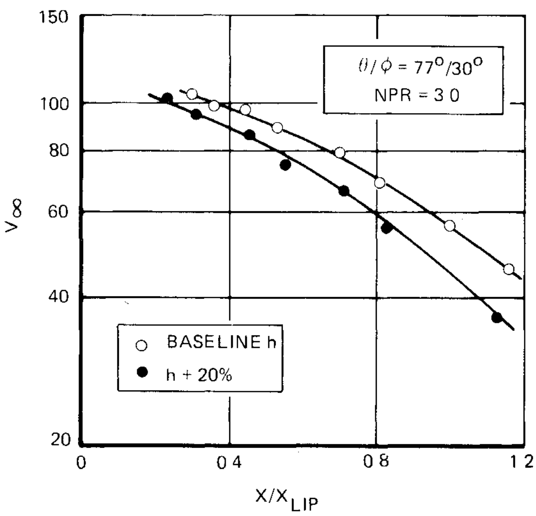

Fig 8 Effect of reverser port height on efflux penetration

zero cant and zero azimuth angle A significant reduction in efflux penetration with sideslip was observed due to introduction of an effective cant angle The results at 30 deg cant angle are presented in Fig 10 for axial angles of 55 and 77 deg For 55 deg there is a tendency for the efflux to penetrate further upstream as the sideslip angle becomes a significant part of the jet azimuth angle and the benefit of canting is effectively reduced No such trend is evident for θ of 77 deg where the maximum sideslip angle is a smaller proportion of the jet azimuth angle

Reverser Plume Ground Flow Contours

During the test the illuminated water droplets within the reverser jet plume not only provided a highly visible side profile but also produced an extremely well defined plume penetration boundary in the ground plane Both these contours were observed and recorded at each test point

Typical plume contours for canted (40 deg outboard) and noncanted reverser jets are shown in Figs 11a and 11b, respectively The plan view represents the separation lines dividing the reverser and freestream flows on the ground board Each contour shows the efflux front location at a specific tunnel velocity The set of contours shows its progress upstream as the tunnel velocity is reduced The impact of jet canting in reducing ingestion velocity can be easily seen by comparing the two velocities at ingestion onset The lateral dispersion of the efflux with canted jets contrasts with the concentration of the noncanted flow pattern

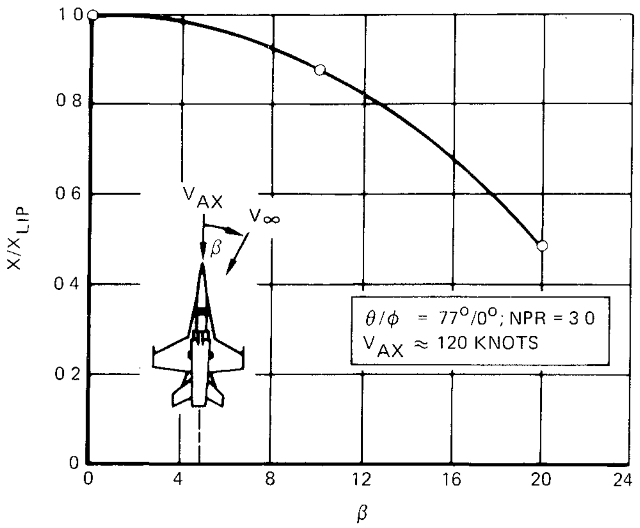

Fig 9 Effect of crosswind on efflux penetration—zero cant

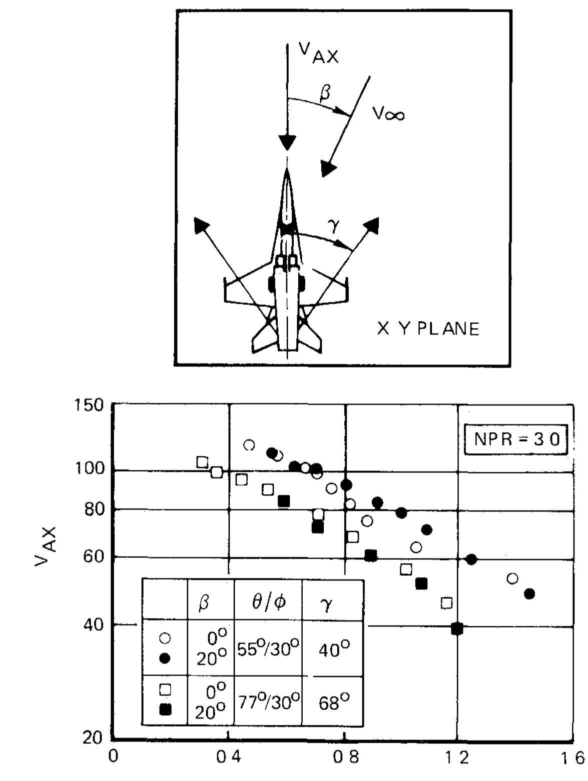

Fig 10 Effect of crosswind on efflux penetration—30 deg cant

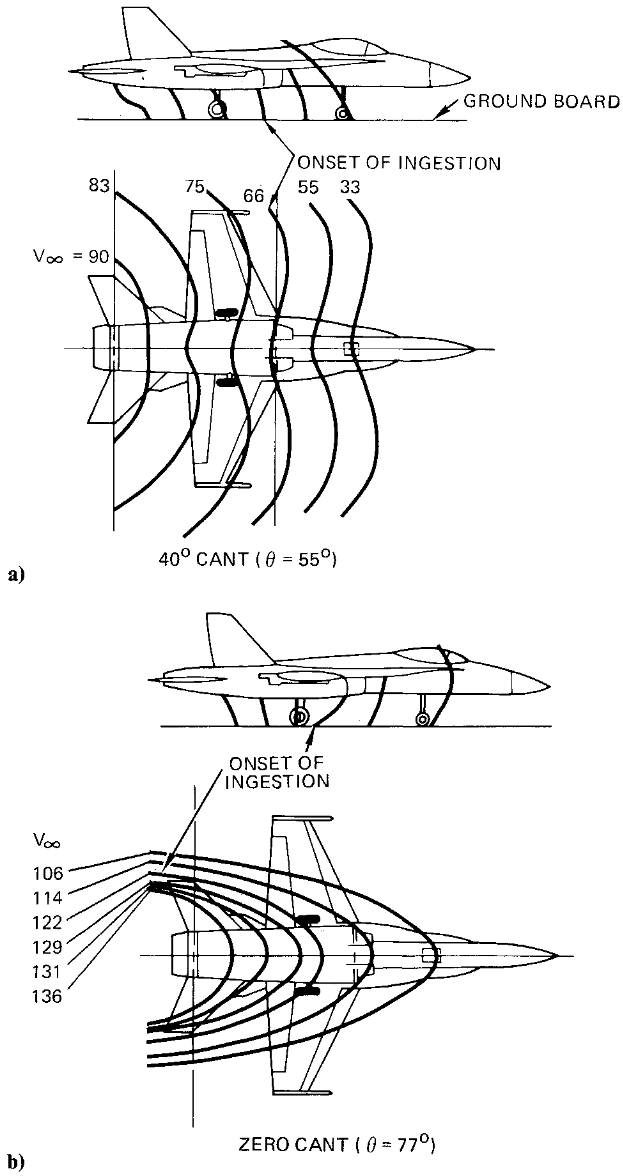

Fig 11 Ground flow pattern schematic at NPR = 3 0

Comparison of Results

Water Tunnel Test

Prior to the wind tunnel testing, some exploratory work was performed in the Northrop water tunnel on a 0 025 scale model mounted as shown in Fig 12 The model was can tilevered from the tunnel wall and a minimum length tran sparent ground board was attached to the landing gear Inlet suction corresponding to NPR of 3 0 was also provided A colored dye injected into the reverser jet was used as the flow visualization technique Figure 13 shows that at θ of 60 deg the water tunnel results compared well with those obtained in the wind tunnel.

Wind Tunnel Test

A comprehensive thrust reversing model test program was conducted for the Concorde aircraft during its development phase and reported in Ref 1 The model test results are also compared with flight test data obtained on the production aircraft This extensive noncanted reingestion data base for the Concorde is compared with the model test data in Fig 14

Figure 14a shows the Concorde test data obtained using three models with hot and cold jets and a range of ground heights and nozzle pressure ratios Also included are some data with the ground plane boundary layer eliminated by testing with a moving model An inset aircraft schematic shows the position of the auxiliary inlets with an X_{LIP}/h at that location of 3 8 It can be seen that the data correlates well about the average line shown

Figure 14b shows the data obtained from this model test The model schematic also shows the inlet lip location and the corresponding X_{LIP}/h of 4 3 which is reasonably close to the 3 8 value for the Concorde The data for jet axial angles of 60 and 70 deg are plotted along with the Concorde data average line for the nominal axial angle of 65 deg Despite the dif ference in model planforms the results are similar However the data show a higher rate of change of slope as the efflux front approaches the inlet lip station For the model tested the

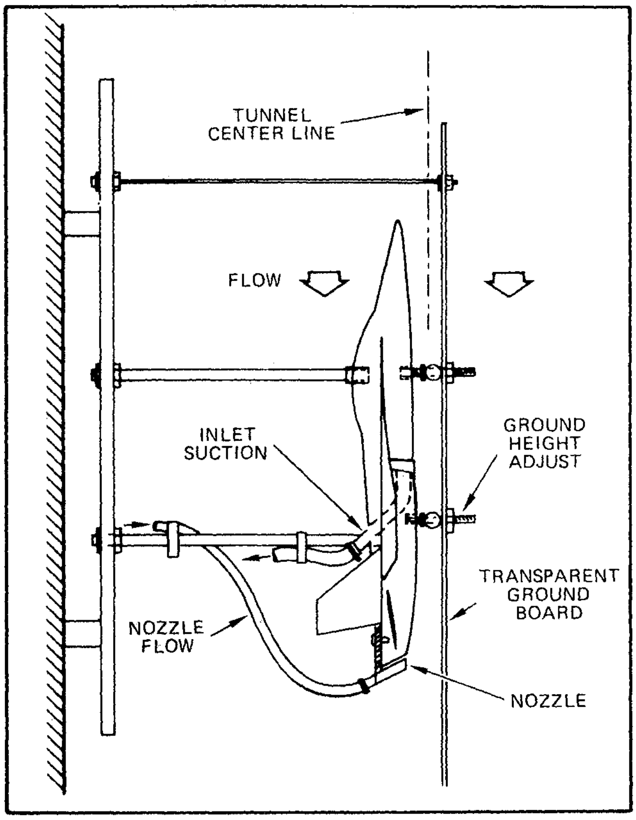

Fig 12 0 025 scale model in water tunnel

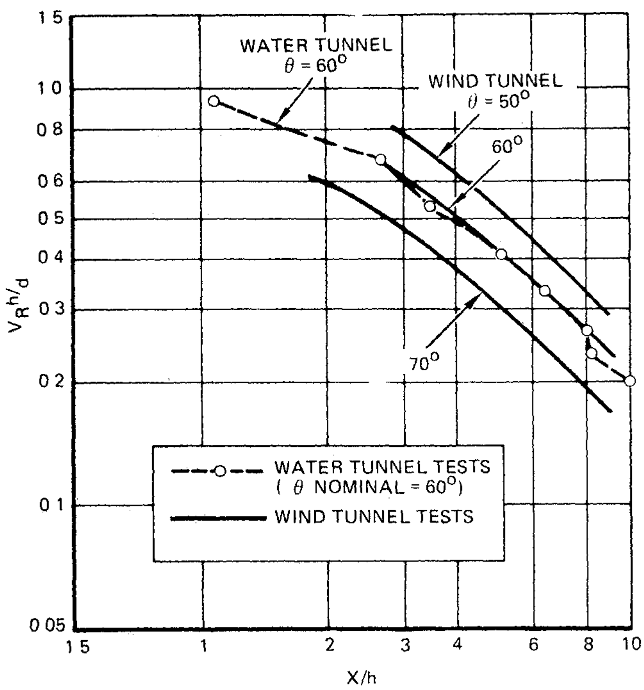

Fig 13 Comparison of water tunnel and wind tunnel results

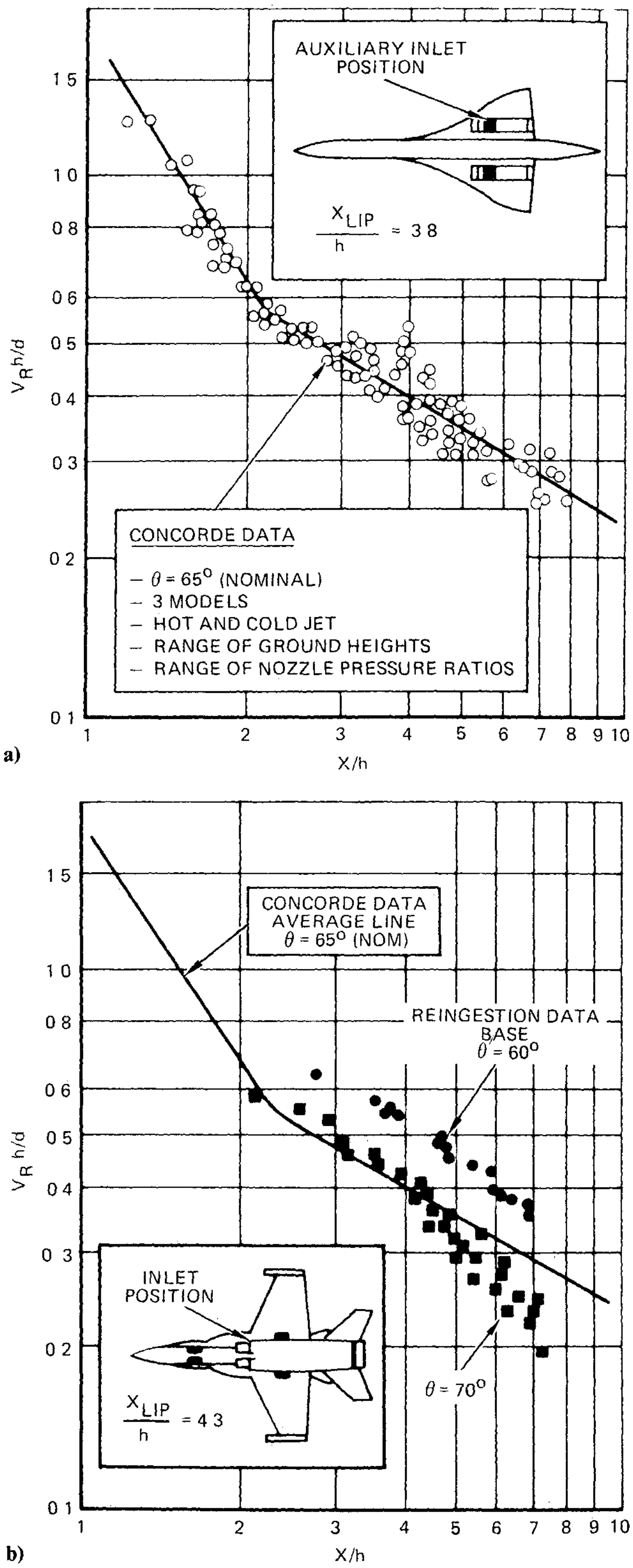

Fig 14 Comparison with Concorde data—zero cant

inlet lip is located at the wing leading edge It is suggested that beyond this point the wing's interference effect on the plume may be diminishing with the data correlation along a curve more like an unconstrained diffusing plume which would tend to penetrate less The reason why the Concorde data do not behave similarly may be due to the different aircraft wing planforms The auxiliary inlets on the Concorde are located well back under the wing with the reverser plume essentially still constrained by the wing for X/h values greater than 3 8

Application of Results

The correlated test data results presented earlier in Figs. 5 to 7 have been used to establish an overall reverser plume reingestion test data base This data base is presented in Figure 15 The noncanted data are shown in Fig 15a for an axial angle range of 50 to 110 deg Figure 15b shows the effect of canting the reverser jets

These data can be used for other models of similar con figurations Using the given $X_{\rm LIP}$ h d and the reverser NPR

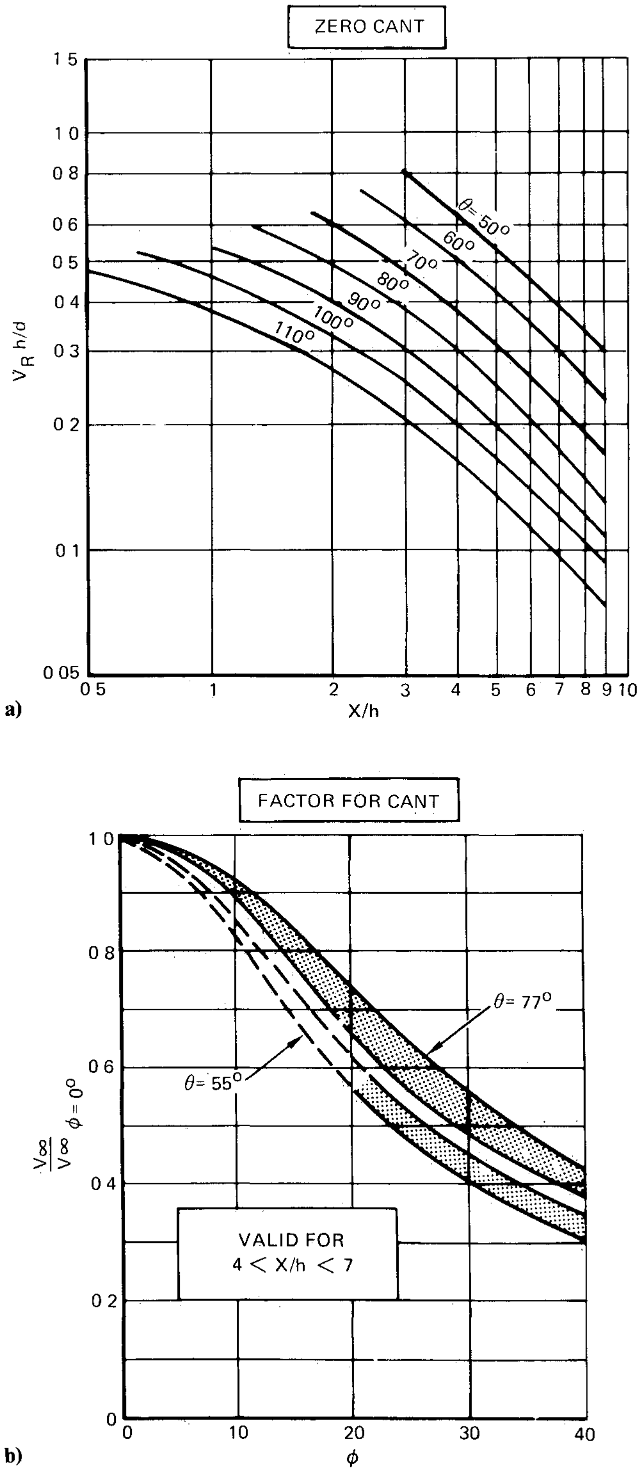

Fig 15 Efflux penetration data base

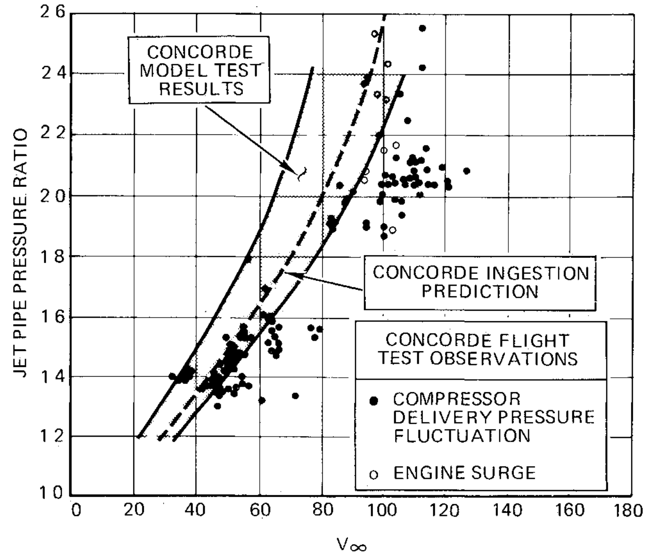

Fig 16 Concorde model ingestion prediction using data base

Fig 15a is entered at the selected θ in order to obtain aircraft ingestion velocity for noncanted jets Figure 15b is then entered at the selected ϕ to obtain the factor for jet cant This figure shows the substantial reduction obtained in ingestion velocity through jet canting Note that the benefit of cant is greater at the lower jet axial angle At shallow jet angles the initial jet impingement with the ground plane occurs further upstream and hence, the influence of cant on jet trajectory will be greater It should be noted that canting the lower reverser jets at a given jet axial angle will result in a loss in reverser thrust efficiency arising from purely geometrical considerations and a possible increase in flow turning losses

Neglecting turning losses this thrust reduction is approximately 10% at 30 deg and 20% at 40 deg cant for typical jet axial angles However it can be shown that the effect of this thrust loss on ground roll distance is more than compensated for by the increased time at full reverse thrust due to the reduction in ingestion velocity

Figure 16 shows the Concorde model ingestion prediction using the test data base presented in Fig 15 The data base is used with the relevant Concorde parameters as inputs in order to predict the Concorde ingestion velocities as a function of internal jet pipe pressure ratio It can be seen that both the trend and level of the results from this study compare well with the Concorde model results Note that Concorde production flight test data show a higher ingestion-onset velocity prediction than the model test results However, no attempt can be made to explain this difference here due to limited information on the flight test data

Conclusions

The penetration characteristics of a reverser jet in ground effect have been investigated at model scale on an advanced fighter aircraft configuration with particular emphasis on the aircraft velocity at onset of ingestion A data set is presented which can be used to predict efflux penetration over a range of jet axial and cant angles for models of similar configuration The test results discussed above provide the following conclusions: 1) initial testing with noncanted jets at axial angles and nozzle pressure ratios required to produce the desired reverse thrust levels showed that aircraft velocity at ingestion onset was close to typical aircraft touchdown velocities and 2) the introduction of jet cant significantly reduces ingestion onset velocity; for example canting the jets outboard by 30 deg reduces this velocity by half

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