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Ground Effects Testing of Two-, Three-, and Four-Jet Configurations

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Ground effects of V/STOL aircraft are dependent on the number and arrangement of the propulsive flows. Extensive tests of a generalized powered model have parametrically measured suckdown, buoyant fountain effects, and reingestion as a function of height above the ground. The number and the location of the propulsion simulators were varied to represent two-, three-, and four-fan configurations. Two nacelle-mounted ejectors at the aircraft center of gravity represented the two-fan arrangement; a nose fan and two nacelle-mounted fans gave the three-poster arrangement; and two ejectors ganged in tandem in nacelles represented the four-fan configuration. These tests were conducted at the Vought Ground Effects Facility. Comparisons of the test results show that the four-poster configuration is buoyant near the ground. The effects of the thrust magnitude, thrust direction, differential thrust, aircraft attitude with respect to the ground, and fountain control devices on the underside of the fuselage are identified. Inlet temperature rise compares the reingestion characteristics of the two-, three-, and four-poster arrangements. Several means of reducing reingestion such as nozzle position, wing location, canting the thrust direction, and inlet shielding are compared.

Introduction

V/STOL aircraft designs are sensitive to both the number and arrangement of propulsion jets in ground effect. Propulsion flowfields developed from these jets in proximity to the ground cause suckdown, buoyant fountains, and reingestion. For example, multijet configurations form well-defined flowfields near the ground. These exhaust flows impinge on the ground and form upflows along the stagnation lines between the jets. These upflows can intersect and form a fountain, producing a buoyant force strong enough to counter the effect of suckdown. However, this upward force can also produce aircraft moments, depending on the point of fountain flow impingement on the fuselage. In addition, these upflows can carry hot exhaust gases which can be ingested into the inlets, decreasing the propulsive force available.

V/STOL designs should be configured to minimize or eliminate suckdown, induced moments, and reingestion. The size of the propulsion units can then be minimized, resulting in lower gross takeoff weight. Numerous studies have shown the impact of these ground effects on the design of a specific configuration.

This experimental study was conducted to measure propulsion-induced effects on a generalized V/STOL model with two-, three-, and four-propulsion simulators. These data provide parametric trends to aid the designer in integrating the propulsion system with the airframe.

Model Description

Model construction permitted a wide range of test variables. The ejector-powered arrangement was a 0.06 scale model of a 40,000-lb V/STOL aircraft. The number of propulsion simulators could be varied. One configuration with two fuselage-mounted nacelles and a nose jet simulated two- and three-jet configurations (Fig. 1). A four-jet configuration consisted of two propulsion simulators, one mounted forward and the other aft, in nacelles on each side of the fuselage (Fig. 2).

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Nacelle and exhaust location could be varied for each multijet configuration. Four nozzle locations were available for the three-jet configuration by lengthening the nacelle. The nozzle located at the wing quarter chord with the nose jet covered simulated the two-jet arrangement. The other positions were wing trailing edge, flap trailing edge, and a half-chord length behind the wing trailing edge. The nacelles for the four-jet arrangement were tested in two chordwise, two spanwise, and two vertical locations, as shown in Fig. 2.

Other model geometric variables included high and low wing positions, high and low horizontal tail positions, vectorable exhaust flow, and attachment of trailing edge flap.

Propulsive flows were simulated by ejectors. Each ejector was connected to separate air lines and could be modulated independently. The Tech Development TD-405 ejectors, (Fig. 3) gave nozzle exit pressure ratios from 1.1 to 1.6, covering the range of interst for high bypass ratio propulsion systems. The ejectors were independently mounted with small gaps between the ejectors and the airframe, thereby separating the propulsion forces from the induced forces measured on the airframe.

Test Facility

Tests were conducted at Vought's Small Ground Effect Facility. The Small Ground Effects Facility is adjacent to and uses the Vought High Speed Wind Tunnel air supply and data acquisition system. The model was mounted vertically forward of a movable-track-guided ground plane (Fig. 4). The airframe was mounted on a six-component internal balance. The nonmetric propulsion system was attached to the model support. A 10-ft square vertical ground plane was moved toward and away from the model to vary height above the ground. Tilting the ground board from the vertical provided positive angles of attack. Negative angles of attack and roll angles were achieved by rotating the model on its support to 180 and 90 deg, respectively.

Test Procedure

Forces and moments on the model were measured as a function of height above the ground. The test procedure was to set the thrust on the propulsion simulators out of ground effect. If temperature data were to be taken, the ejector supply air temperature was adjusted and monitored until it

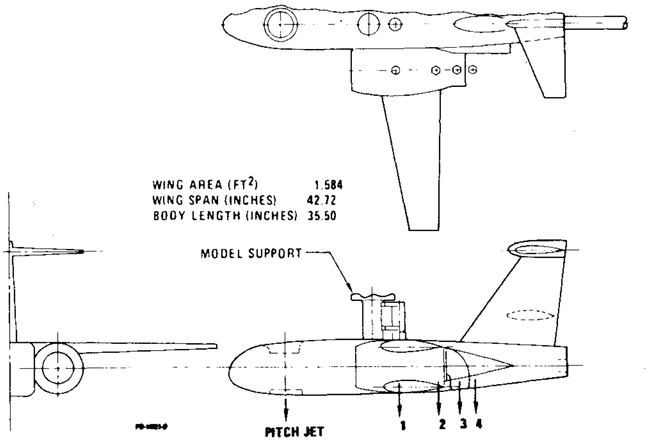

Fig. 1 Nozzle location can be varied to simulate two- and three-jet configurations.

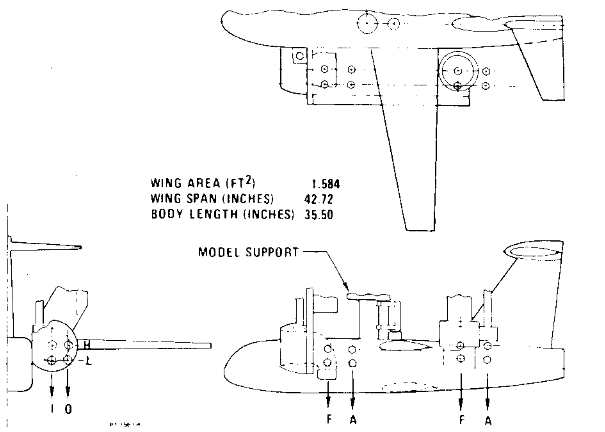

Fig. 2 Nozzle location can be varied on the four-jet configurations.

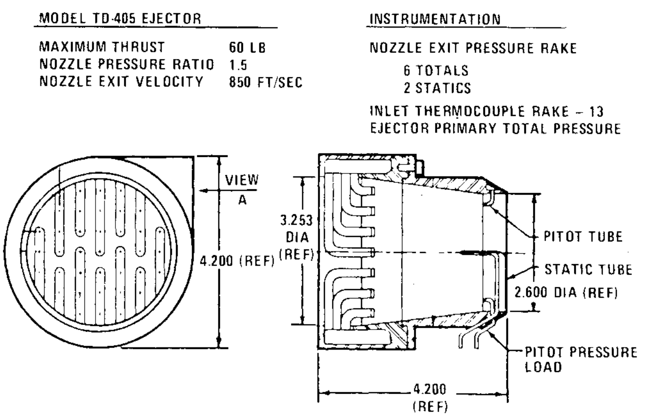

Fig. 3 Ejectors simulate propulsive flows.

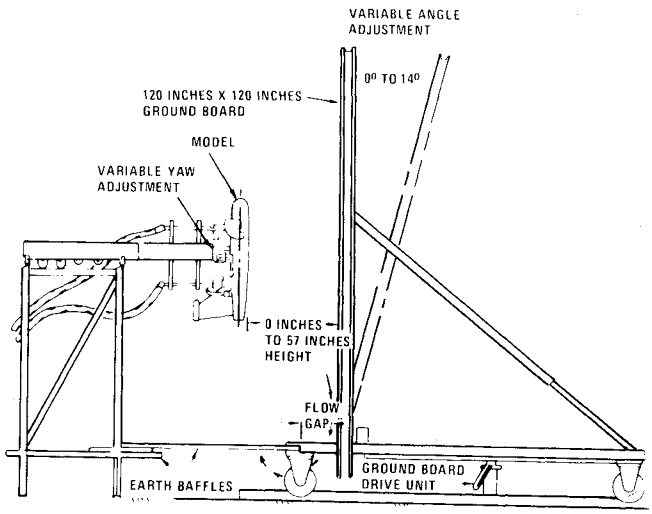

Fig. 4 The Small Ground Effects Facility varies aircraft heights above the ground.

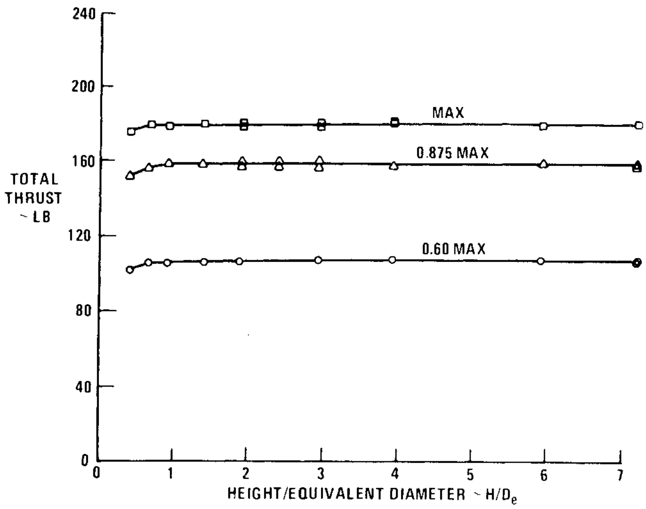

Fig. 5 The ground plane does not affect thrust above $H/D_e = 1.0$.

stabilized at the desired level. The ground board was then cycled through the vertical takeoff and landing range from a maximum height to equivalent diameter ratio (H/D_e) of 8 to a minimum of 0.3 (out of ground effect to less than wheel height). Data were taken at various heights. Propulsion-induced forces on the airframe were measured by the internal balance. Thrust was computed from a calibration relating the ejector primary drive airflow and ejector performance. The calibration was performed prior to the test with each ejector mounted separately on a test stand. The nozzle exit instrumentation permitted determination of back-pressure effects on thrust close to the ground (Fig. 5). The ground plane did not affect the thrust for height/diameter ratios greater than 1.0. Thermocouple rakes in the inlets measured reingestion temperature rise. The tests described above are detailed in Refs. 1 and 2. A geometrically similar model was tested with the same ejectors attached to the airframe, so the total propulsive and induced forces were measured. This model was constructed for tests in the wind tunnel but also was tested on the ground effects facility. The results from this test (Ref. 3) substantiate the data obtained with the metric airframe and grounded propulsion system discussed in this paper.

Test Results

A comparison of test results in Fig. 6 shows the four poster with a strong fountain producing a buoyant effect down to wheel height ($H/D_e \simeq 0.75$). The three-jet arrangement produces a weaker fountain with an associated increase in suckdown. The upflow formed along the stagnation line of the two-jet configuration is too weak to effectively counterbalance the suckdown, resulting in a large penalty near wheel height. Each configuration has about the same lift loss out of ground effect.

The corresponding comparison of induced pitching moments in Fig. 7 shows pitchup for the three-jet configuration as the ground is approached. The fountain is forward of the wing quarter-chord-moment reference point, requiring a change in the geometry or an increase in thrust to obtain a trim condition. The fountain for the four jets is near

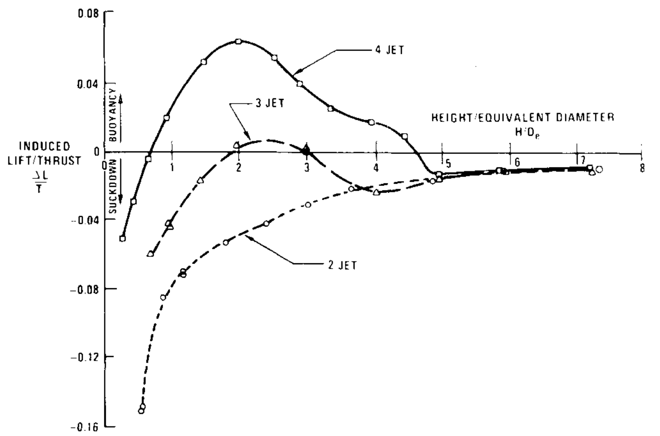

Fig. 6 The four-jet configuration is buoyant near the ground.

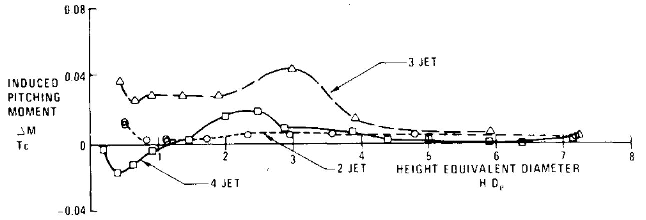

Fig. 7 The three-jet configuration has pitchup near the ground.

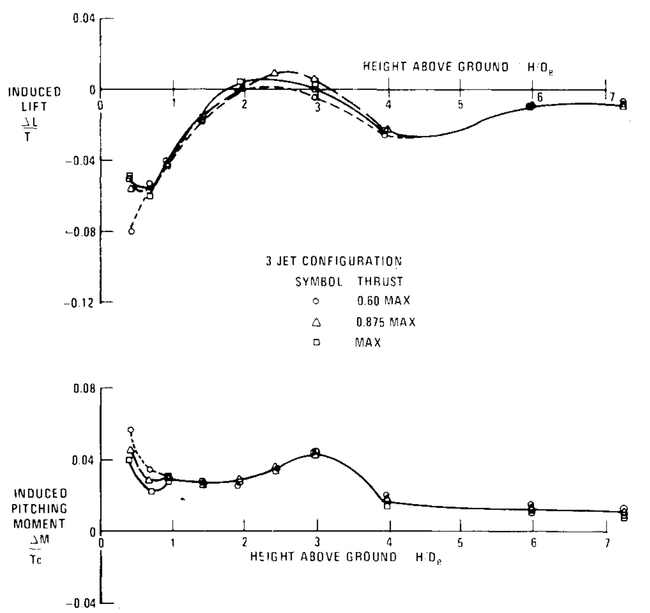

Fig. 8 Induced force and moment ratios are not changed by total thrust variation.

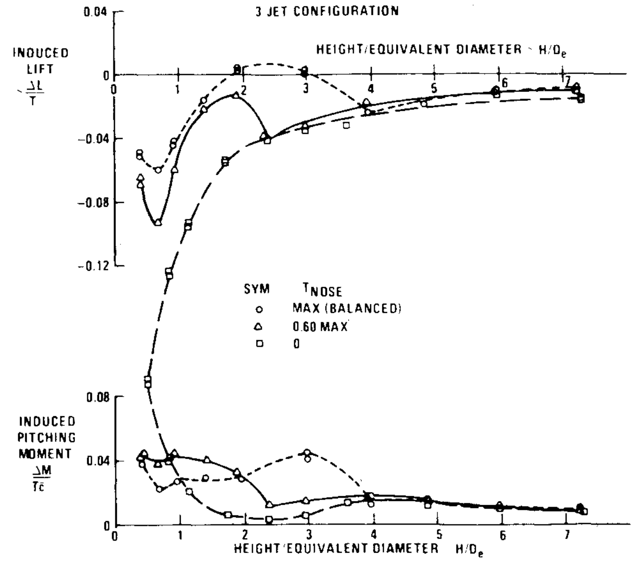

Fig. 9 Modulation of nose thrust varies fountain strength and position.

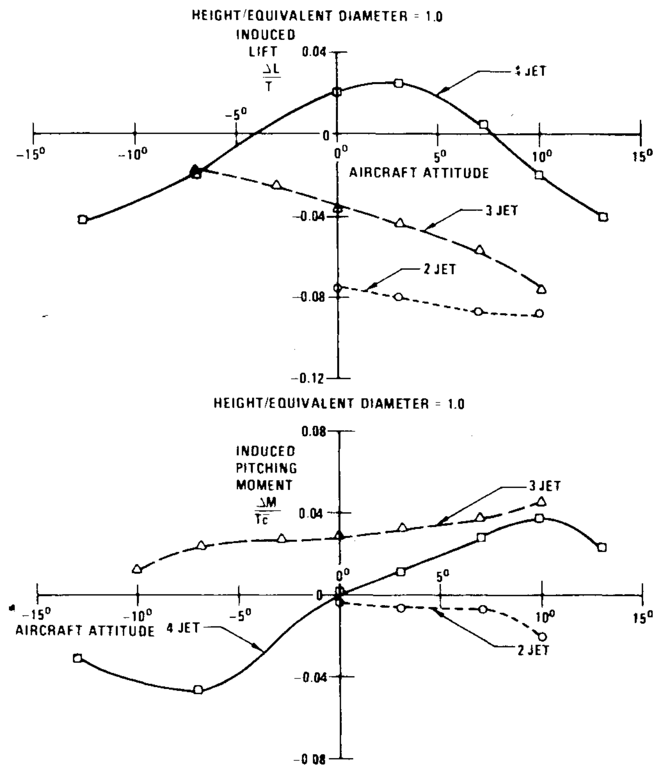

Fig. 10 Aircraft attitude shifts the fountain.

the reference center, producing a nose-up moment, then shifting aft to produce a nose-down moment close to the ground. No significant moments are generated by the weak upflow of the two-jet arrangment.

Reducing the total thrust an equal amount on each propulsion simulator did not change the nondimensionalized test results. The induced effects are shown to be reduced in proportion to the thrust in Fig. 8 for the three-jet arrangement. Similar results were measured on the two- and four-poster configurations. Although the total thrust level is greater with more jet simulators, these results confirm that the nondimensional results can be compared between the configurations.

Varying the thrust between the fore and aft jets, as would be done for pitch control, is shown in Fig. 9 to affect the fountain characteristics. As the strength of the forward jet descreases relative to the aft jets for the three poster, the fountain strength is reduced and the suckdown effect more pronounced. The fountain effect is not significant until the ground is approached. In the extreme condition with the nose jet off, typical two-poster suckdown results were measured, even though the lift/cruise jets are at the flap trailing edge.

Aircraft attitude with respect to the ground changes the geometry of the flowfield and fountain effects. A nose-up attitude with respect to the ground plane moves the fountain impingement point forward on the fuselage. Conversely,

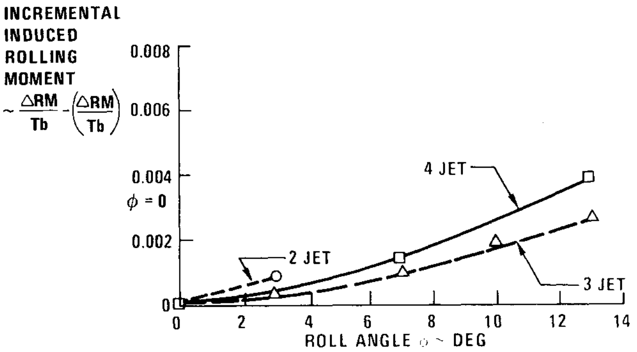

Fig. 11 Induced rolling moment increases with roll angle.

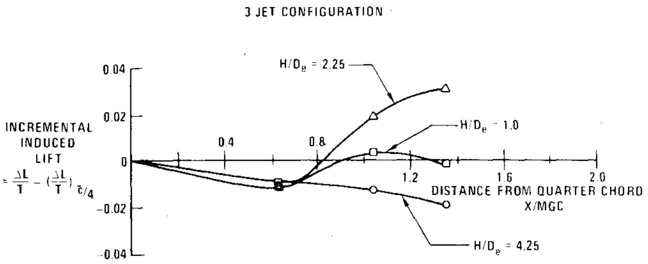

Fig. 12 A nozzle location aft of the wing increases buoyancy.

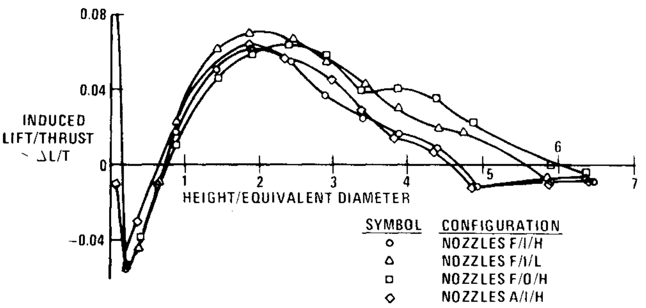

Fig. 13 Nozzle location is not a strong influence near the ground for the four-jet configuration.

nose-down pitch moves the fountain aft. The fountain strength is reduced because of the increase in jet mixing length from nozzle to impingement point. Figure 10 shows the loss in fountain buoyancy as the attitude of the four-jet arrangement is varied. A nose-down attitude for the three poster increases the fountain buoyancy, because the fountain moves aft with more effective area to act upon. The two-jet arrangement is not significantly affected.

The fountain is destabilizing and causes increased moments with aircraft attitude. The pitching moment increase with nose-up attitude shows the fountain moving forward, and a nose-down pitching moment increment shows aft fountain movement with nose-down attitude. The fountain moves about the wing quarter chord for the four poster. It moves toward the moment center as the three poster pitches down. Figure 11 shows that with the aircraft rolled, the fountain shifts outboard, increasing roll.

Moving the nozzle aft from the quarter chord increases the three poster's buoyancy as the ground is approached. The increment in induced lift is shown in Fig. 12. Out of ground effect there is an increase in lift loss. This same result is reported in Ref. 4 for a nozzle position aft of the wing compared to a position under the wing planform.

Induced lift for the four-jet configuration is not very sensitive to the nozzle position (Fig. 13). A low inboard position shows the greatest buoyancy, and an outboard, high position is less buoyant close to the ground. Inboard and high

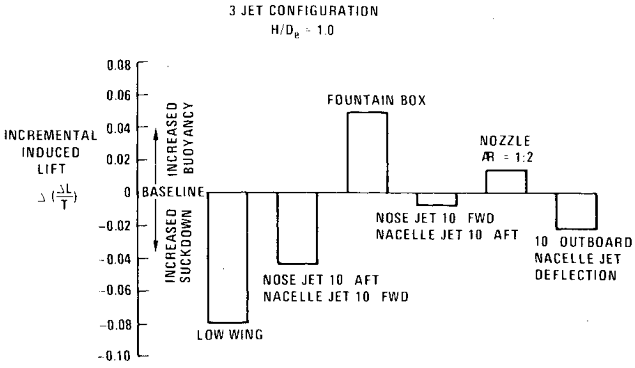

Fig. 14 Configuration variants alter suckdown levels near the ground.

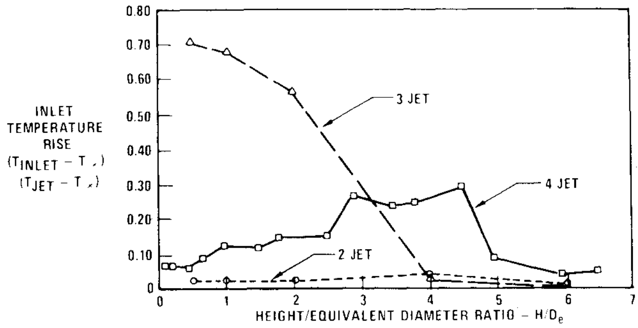

Fig. 15 The three-jet configuration has severe reingestion.

is slightly less buoyant down to the point of maximum fountain effect.

Several methods were investigated to reduce the suckdown effect (Fig. 14). The three-jet configuration was selected for the study, but the results show trends applicable to other configurations. A low wing reduces the channel between the wing and the ground and increases suckdown. Deflecting the nose jet and lift/cruise forward degraded the fountain strength with an associated suckdown penalty. Deflecting the nose jet forward and lift/cruise jets aft showed a small degradation in fountain buoyancy. Canting the jets laterally outboard also reduced the fountain effect. Capturing the fountain flow on the underside of the fuselage by strakes or channels was the most effective way of reducing the suckdown penalty. It was observed that the fountain can move out of the containing channels with a sudden loss of the favorable effect. Also the fountain impinging on the sides of these channels can induce destabilizing pitching moments, requiring additional corrective measures. Rotating the rectangular two-dimensional nozzle so that the long sides are parallel to the aircraft longitudinal axes was shown to be slightly effective.

An evaluation of the near-field reingestion was made during these tests. Inlet reingestion temperature levels were measured with thermocouple rakes at the simulated fan face station. Reingestion levels were found to correlate with the strength of the fountain flows. Temperature rise begins with the onset of the fountain and increases as the ground is approached. Close to the ground, fountain strength and reingestion decrease. The exhaust flows coalesce and a fountain is unable to form.

A comparison of reingestion for the two-, three-, and four-jet arrangements is given in Fig. 15. Reingestion is measured by the inlet temperature rise above ambient nondimensionalized by the average jet exhaust temperature level above ambient. The average jet exhaust temperature is the mass weighted average of all the exhaust nozzles. The "Y-shaped" flowfield of the three-jet configuration is shown to carry the hot exhaust to the inlets location tested. The four-jet arrangement forms a "plus pattern" with the stagnation lines

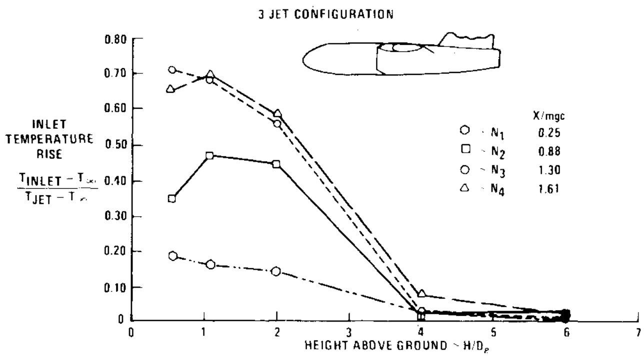

Fig. 16 Reingestion increases with aft nozzle location.

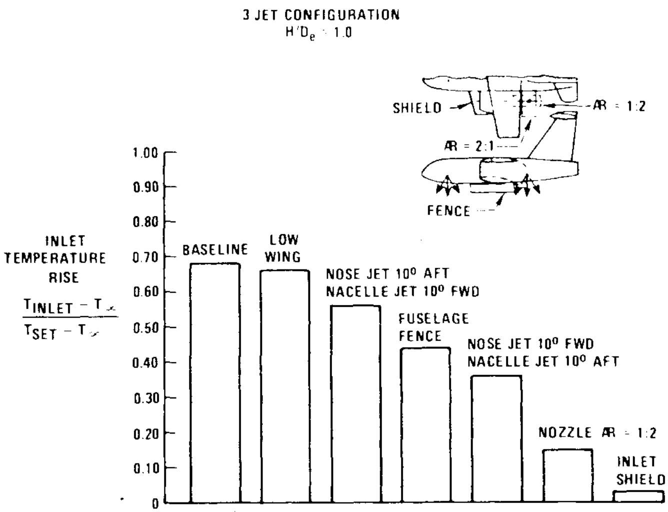

Fig. 17 Reingestion can be reduced by several methods.

fore and aft along the body and laterally along the wing. The weak upflow of the two poster does not pose a reingestion problem. More information on reingestion is given in Ref. 5.

Moving the lift/cruise nozzle aft on the three-jet configuration resulted in aligning the stagnation flows with the inlets (Fig. 16). The stagnation lines are forward of the inlets with the nozzles at the quarter chord. Nozzle positions aft move the fountain and stagnation flow lines rearward and in a position to pass under the inlets.

Several means were investigated to reduce reingestion using the three-jet configuration for the study (Fig. 17). A low wing did not help in this case, where the inlets were forward of the wing leading edge. Deflecting the jets toward each other and away from each other was beneficial. Fences on the side of the fuselage partially shielded the lift/cruise inlets. Nozzle aspect ratio is seen to give a large reduction in reingestion. But the most effective method was to shield the inlet with a small plate extending forward of the inlet lip. Inlets positioned over a wing planform would be similarly shielded.

Conclusion

These parametric tests have provided data covering a wide range of design trade-offs. Trends have been established on a common configuration for easy comparison. The four-jet configuration was seen to be buoyant down to about landing gear height above the ground. The two-jet arrangement without a strong upflow to counteract suckdown was severely penalized near the ground. The three-jet arrangement tested generated a fountain forward on the fuselage producing severe reingestion.

Various means of reducing adverse ground effects were tested. In general, those methods favorable to reducing suckdown were detrimental to the reingestion problem, and vice versa. For example, an inlet over a low wing would be shielded from reingestion, but the low wing increases the suckdown. Containment and channeling of the fountain flows impinging on the fuselage appears to reduce suckdown and control reingestion. However, careful tailoring is required. Flowfields and resulting induced effects are altered by aircraft attitude and thrust modulation for control. These tests have shown that the geometry of the aircraft and the arrangement of the propulsive jets can be shifted to reduce the adverse ground effects. The four-jet arrangement is shown to be an attractive solution because the flowfield causes buoyancy close to the ground, situates the fountain near the aircraft center of gravity (reducing induced moments), and carries the exhaust gases along paths that limit reingestion.

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