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GROUND EFFECTS ON V/STOL AND STOL AIRCRAFT--A SURVEY

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Abstract

The flow fields encountered by jet- and fan-powered Vertical/Short Takeoff and Landing (V/STOL) aircraft operating in ground effect are reviewed and their general effects on the aerodynamic characteristics are discussed The ground effects considered include 1) the suckdown experienced by a single jet configuration in hover, 2) the fountain flow and additional suckdown experienced by multiple jet configurations in hover, 3) the ground vortex generated by jet and jet flap configurations in Short Takeoff and Landing (STOL) operation and the associated aerodynamic and hot-gas-ingestion effects, and 4) the change in the downwash at the tail due to ground proximity After over 30 years of research on V/STOL aircraft, the general flow phenomena are well known and, in most areas, the effects of ground proximity can be estimated or can be determined experimentally. However, there are some anomalies in the current data base which are discussed.

Introduction

Aircraft that use powered lift augmentation to achieve short field or V/STOL performance must do so by deflecting significant masses of air (either directly from the engines or by assisting the wing in deflecting the free stream) downward to support the aircraft's weight at low speeds During takeoff and landing, the ground interrupts this downward flow, alters the flow field around the aircraft, and changes the aerodynamic forces on the aircraft Research and development work on V/STOL aircraft over the past 20 to 30 years has provided a broad understanding of the flow fields involved and the mechanisms by which the aerodynamic characteristics of these aircraft are changed by ground proximity Experimental techniques for determining these effects are available and, in some cases, methods for estimating them have been developed.[1-4] However, some anomalies in the available data base are not understood These differences in the data are not serious enough to justify delay in development of V/STOL and STOL aircraft, but they make it difficult to develop an orderly system of methods for estimating the aerodynamic characteristics of these configurations and require extra experimental programs in the development cycle

A workshop was held at NASA Ames Research Center in August 1985 to discuss these anomalies along with the current status of ground effect research and to develop recomendations for future investigations. In this paper, material used in the introduction to that conference is reviewed as an outline of the state of the art and highlights the current anomalies Unfortunately, the recommendations of the workshop could not be included, but can be found in the proceedings of the workshop (to be published as a NASA SP).[5]

Basic Flow Fields

The basic flow fields associated with hovering, transition, and STOL operation of jet- and fan-powered V/STOL and STOL aircraft are depicted in Fig 1 When hovering out of ground effect (upper left corner of Fig 1), the jet streams that support the aircraft entrain air, thereby inducing suction pressures on the lower surfaces. These pressures produce a small download, usually less than 2% of the jet thrust Because these downloads are small, the available empirical methods for estimating them (Ref 2, Section 2.2 1) are adequate

As the hovering aircraft descends into ground effect, the jet stream (or streams) impinges on the ground to form a radial wall jet flowing outward from the impingement point(s) These wall jets also entrain air and significantly increase the induced suction pressures and the resulting loss in lift as the height above the ground is reduced

With multiple-jet configurations, the radial wall jets flowing outward from their respective impingement points meet and form an upflow or "fountain " The impingement of the fountain on the aircraft produces an upload which partially offsets the suckdown created by the entrainment action of the wall jets For some cases, the fountain flow also induces higher suction pressures between the jets and the fountain, which tend to increase the suckdown The mechanisms involved will be discussed in another section.

In transition between hover and conventional flight out of ground effect, there are several

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flow mechanisms that induce forces and moments on the aircraft Flow into the inlets produces an inlet momentum drag and usually a nose-up pitching moment. The exiting jet flow is deflected rearward by the interaction with the free stream and rolls up into a pair of vortices These vortices combined with the blockage and entrainment action of the jets induce suction pressures behind and beside the jets and positive pressures ahead of the jets. The net effect for most jet-V/STOL configurations is usually a loss in lift and a nose-up pitching moment. However, if the jets are at or near the trailing edge of the wing (particularly if they have appreciable spanwise extent as in a jet flap configuration), they induce positive lift and a nose-down moment. The jet wake system also induces a significant increase in the downwash at the tail

In ground effect at transition speeds (STOL operation), all the flow phenomena just described are present, but modified by the presence of the ground. In addition, a ground vortex is formed by the action of the free stream opposing the wall jet that is flowing forward from the impingement point(s) of the front jet(s). This ground vortex creates and defines the dust cloud produced when operating over loose terrain It is also one of the hot-gas ingestion mechanisms and it induces an additional lift loss and associated moment.

Both the ground vortex and the fountain flow are involved in hot-gas ingestion. In hover, the fountain flow provides a direct path to bring hot exhaust gases into the vicinity of the inlet where they can be ingested. The severity of this part of the hot-gas ingestion problem can be controlled to some extent by the placement of the inlet, by the arrangement of the jets, and by the use of suitable flow deflectors At forward speeds, the ground vortex flow field provides an additional mechanism to bring the hot gases of the forward-flowing wall jet back to the vicinity of the inlet.

The following sections review each of these flow phenomena in more detail, present and compare the results of key investigations, and discuss the anomalies that exist

Single-Jet Suckdown

The first definitive work on jet-induced suckdown in ground effect was done by Wyatt.[6] He showed that the suckdown for plates of different diameters could be correlated on the basis of height and the diameters of the plate and jet, as shown in Fig. 2. He also showed that the suckdown for noncircular plates would follow the same curve when the effective, angular, mean diameter (D) of the planform is used.

A few years later, Hall used a J-85 engine in a full-scale investigation.[7] His results (Fig. 3) were in good agreement with the estimate based on Wyatt's work and appeared to indicate that any scale or real-jet effects were negligible However, the small-scale results of Ref 8 indicated somewhat more suckdown than either Wyatt's or Hall's work Other investigations have also shown departures from Wyatt's results and there have been several attempts at reconciling these differences (see Ref. 2, Section 2 2.1)

More recently Christiansen, Eshleman, and Mitchell at NASA Ames have also shown slightly different results in two large-scale investigations (Fig 4; Ref 9) There are now three sets of full-scale data and several sets of model-scale data that show slightly different results The differences are not large and do not contradict the basic framework of Wyatt's correlation However, there appear to be factors at work that affect the constant and exponent in Wyatt's expression. These factors may include the jet pressure ratio, the exit velocity distribution, and turbulence. The size of the groundboard, random crosswinds, and gusts in the test area may also be factors. Future work should be done to examine the basic mechanisms that generate the induced downloads.

Suckdown is created primarily by the entrainment action of the wall jet flowing radially outward from the impingement point as depicted in Fig. 5. The wall jet, and to a lesser extent the vertical jet, entrains air, lowers the pressure, and induces an inward flow between the ground and the lower surface of the configuration As the height is reduced, the gap between the wall jet and the planform is reduced, so the induced velocity must increase. If the height is reduced by half, the velocity will be doubled. The suction pressures and therefore the download should be a function of the square of the height. In practice, the exponent is slightly over 2.0 (2 3 in Wyatt's expression) because the gap is in reality the distance between the planform and the upper edge of the wall jet; it is not the distance to the ground as used in the expressions for estimating suckdown

Future work should focus on two areas
1) The wall jet and its ability to entrain air needs to be studied The effects of pressure ratio, temperature, turbulence, and exit velocity distribution of the vertical jet on the formation and entrainment ability of the wall jet needs further study. 2) The possible effects of slight crosswinds and random gusts in the test area need to be examined Estimates made by the method of Ref. 10 indicate that gusts or crosswind velocities of approximately 1% of the jet velocity can increase the suckdown by approximately the same amount as the differences between various investigations. There is need for carefully controlled investigations of the effects of test chamber size.

Multiple Jet Suckdown and Fountain Effects

When the wall jets from two jets meet, a fan-shaped upwash or "fountain" is formed between the jets (Fig 6). If there are more than two jets, a fan-shaped fountain is formed between each pair of jets and a fountain "core" is formed where the fountain fans meet. The impingement of the fountain flow on the configuration produces an upload which partially offsets the suckdown induced by the wall-jet entrainment action

However, the net induced load is not simply the sum of the vertical momentum of the fountain (or that part of the fountain that impinges on the configuration) and the suckdown estimated for an equivalent single jet. The net induced load is almost always less than that sum and, in some cases, the suckdown for multiple jet cases is actually greater than would be estimated for an equivalent single-jet configuration Lummus[11] measured more suckdown on a two-jet configuration (Fig 7) than on a single jet configuration having the same planform area to jet area ratio (and nearly the same planform aspect ratio) Other investigators have also shown increased suckdown for some multiple-jet configurations

The probable cause of the additional suckdown is shown in Fig. 8 (from Ref. 12). With a two-jet configuration, a vortex-like flow is formed between the upward flow of the fountain and the downward flow of each adjacent jet The impingement of the fountain on the plate produces the expected positive or lifting pressures at the center of the plate (right side of Fig 8). However, the vortex-like flows between the fountain and the jets can induce sufficiently strong suction pressures to offset the fountain lift. The estimated suckdown for a single-jet configuration with the same ratio of planform area to total jet area would correspond to an average suction pressure about equal to the outer contour line shown in Fig. 8 ($Cp = -0.004$) Thus, both the lifting pressures and the additional suckdown pressures are much greater than the pressures induced on a single-jet configuration The question of whether there is a net lift gain or loss depends on which predominates. Unfortunately, these are the only pressure distribution data of this type available.

Flow surveys and additional pressure distribution data of the type shown in Fig 8, covering a range of heights and jet spacings, are needed to obtain a better understanding of the total flow field and of the effects of multiple jet interactions. Such pressure distribution data appear at this time to provide the best hope of developing a reasonable method for estimating multiple-jet ground effects.

There are conflicting results on the effects of turbulence. Lummus[11] investigated the effect of jet turbulence by placing a grid of wires in the nozzle slightly upstream of the exit to change the turbulence of the jetstream His data for a two-jet configuration[9] show that both turbulence intensity (I) and jet pressure ratio (NPR) increased the suckdown However, it is not known whether this increase is due to the turbulence increasing the entrainment action of the wall jet, decreasing the fountain strength, or increasing the additional suckdown because of the vortex-like flows between the fountain and the jets On the other hand, Christiansen showed no effect of pressure ratio for his single-jet configuration using a J-97 engine.[13]

Foley investigated turbulence in the fountain between two jets and its sensitivity to "trips" on the stagnation line where the wall jets meet to form the fountain.[14] The study showed [10] that both the upward velocity at the centerline of the fountain and the turbulence in the fountain were very sensitive to obstructions at the stagnation line. Even a 1/8 in. "trip" (about the thickness of the boundary layer under the wall jet) had a noticeable effect.[10] Apparently there is an appreciable energy exchange between the wall jet flows across the "stagnation" line. Additional carefully conducted investigations of the effects of jet turbulence and pressure ratio for single- and twin-jet configurations are needed to determine the mechanisms and interactions by which pressure ratio and turbulence affect the suckdown.

These investigations relate to "laboratory" flat-plate configurations with round jets of equal thrust On an actual aircraft, the wing is seldom in the same plane as the fuselage lower surface which is contoured Also V/STOL configurations often incorporate "strakes" or "fences" in an attempt to "catch" the fountain flow and augment the lift. Future aircraft will probably use noncircular nozzles and have front and rear jets of different sizes There have been investigations of the effects of all these variables and, once a firm basis for estimating the suckdown and fountain effects on flat plate configurations is established, these data can be assessed to determine where additional work in these and related areas is required

Ground Vortex

In STOL operation, the wall jet that is flowing upstream of the configuration is opposed by the free stream and rolled back onto itself to form a horseshoe-shaped ground vortex (Fig. 11) This ground vortex creates and defines the dust cloud that is often seen during flight operations from unprepared sites. It is one of the primary mechanisms of hot-gas ingestion and can cause a lift loss and associated pitching moment.

A ground-vortex type of flow is also associated with the lift loss experienced on jet flap configurations. Williams et al [15] observed a trapped vortex under a high-aspect-ratio full-span, jet flap configuration in ground effect tests (Fig 12). The problems of ground-board, boundary-layer and jet-flap testing will be discussed in the next section

The ground-vortex type of flow is also encountered in the operation of thrust reversers in ground effect (Fig. 13) Thrust reversers direct some of the jet flow forward at an angle to the ground The wall jet is thereby thickened and the ground vortex moved forward and strengthened (relative to a vertical jet). Joshi[16] shows that large lift losses and pitching moments can be generated (Fig. 13) Joshi reported a severe rolling oscillation during conditions in which the ground vortex was present [16] The implications of these rolling oscillations on controllability during landings is unclear at this time

The ground vortex associated with vertical jet impingement has been studied in several investigations. Two of these measured the pressure distribution induced on the ground board by the ground vortex.[10,17-20] Figure 14 illustrates a typical distribution on the centerline through the impingement point The jet is swept aft by the free stream and produces high positive pressures in the impingement region The pressure decreases rapidly under the forward-flowing wall jet and reaches a maximum negative pressure under the vortex. Ahead of the vortex, the pressure rises and there should be a stagnation point where the wall jet and free stream are in balance However, the pressure coefficient does not reach a value of 1.0, probably because of unsteady mixing in this region.

Pressure distributions measured in the region of the ground vortex show a difference in both the location and the apparent strength of the ground vortex.[10,17] Stewart's and Kuhn's data[10] show a greater negative pressure indicating a greater vortex strength (Fig. 15) The reason for the difference is unclear but may be associated with the rather large difference in the jet pressure ratio in the two investigations.

The relative thickness of the boundary layer in the two investigations may be another factor Figure 16 presents the forward extent of the ground vortex flow as observed in five different investigations The variation in the results may be partially caused by the manner in which the forward edge of the flow field was defined (some investigators measured the leading edge from photographs of dust clouds and some (i e., Stewart and Kuhn) used the position of zero-pressure coefficient as shown in Fig 11 Also, the investigations were performed at different pressure ratios. However, the boundary layer on the ground board may be the biggest factor. With a boundary layer, the high velocities in the wall jet, which are very close to the ground, can penetrate further against the relatively lower velocities in the ground-board boundary layer than would be possible against the free stream velocity The investigation,[18] in which Schwantes set out to simulate the relatively thick boundary layer between the wind and the ground, indicates the most forward penetration (Fig 16) Abbott,[19] on the other hand, used the moving model technique and thus there was no boundary layer This technique shows the smallest penetration The information available on the other investigations showed only that they were made at the lowest Reynolds number and thus probably had a relatively thick boundary layer

Another factor may be the effect of the velocity of the model over the ground. With the moving-model technique (as in the actual situation of the aircraft moving over the ground), the velocity of the model (or aircraft) is added to the wall-jet velocity; additionally, the scrubbing drag on the wall jet thickens the boundary layer between the wall jet and the ground, reduces the momentum in the wall jet and reduces its ability to penetrate upstream With the model fixed, this reduction in wall-jet energy is not present.

Because of the importance of the ground vortex to STOL performance and to hot-gas ingestion (to be discussed in another section) a better understanding of the factors that determine the location and strength of the ground vortex is needed The primary need at this time is to determine the effects of jet-pressure ratio, the ground boundary layer, and motion over the ground

Jet Flap Ground Effects

Jet flap configurations can generate very high lift coefficients but when operating at these high coefficients, they suffer a large lift loss when entering ground effect. Williams et al [15] showed that when the jet sheet from the jet flap impinges on the ground, a ground-vortex-like flow is generated between the wing and the ground plane (Fig 12). Turner[21] showed, by using the moving model technique, that the lift loss measured in a wind tunnel with a boundary layer on the ground board was considerably larger than the lift loss when the boundary layer was absent (when the model was moving over the ground board). Furthermore, Werle,[22] using the ONERA water tunnel to show the flow, demonstrated (Fig 17) that the interaction of the wall jet flowing forward from the impingement region with the boundary layer caused a major alteration in the flow under and ahead of the model

These results led to the development of several moving-belt, ground-board installations, first in England and later in the United States and elsewhere The principle features are illustrated in Fig 18. A suction slot just ahead of the belt is used to remove the boundary layer, and the belt, running at the same speed as the free stream, prevents the regeneration of the boundary layer. Turner[23,24] showed that this technique gave the same result as the moving model technique (Fig 19).

Unfortunately, a moving-belt ground-board is impractical for large wind tunnels such as the NASA Ames National Full-Scale Aerodynamics Complex 40×80-ft tunnel and for testing when high jet-exhaust temperatures are involved The use of suction or blowing on the ground-board has been suggested as an alternative, but the problem is where and how much blowing or suction to apply

The boundary layer control must be placed ahead of the ground vortex, but not so far ahead that the ground-board boundary layer can regenerate before it meets the wall jet from the model. Hacket[25] has suggested a blowing system that can be traversed fore and aft to position the boundary layer control (BLC) slot (Fig. 20). The pressure distribution signature of the ground vortex (Fig. 21) may provide a logical guide for positioning the BLC slot for each operating condition. An experimental program would be required to verify the concept.

A jet placed at the trailing edge of a wing acts like a short-span jet flap in that when the wing is out of ground effect a favorable lift increment is induced In the Stewart and Kuhn study,[10] the ground effects on a configuration with two round jets at the wing trailing edge are compared with the ground effects of the same model with two slot jets at the trailing edge (Fig. 22) The round jet and the slot jet had different areas and pressure ratios, so a direct comparison was difficult, but the conditions chosen in Fig. 22 usually give about the same induced lift/thrust ratio when out of ground effect. The round jets showed a favorable ground effect whereas the slot jets showed the expected, adverse ground effect asosciated with jet flap configurations. The different behavior appears to be caused by the differences in the ground vortex position and probably the strength The ground vortex, as determined from the ground board pressures, was much further forward and had a greater spanwise extent for the slot jets than for the round jets

The large favorable ground effect for the round jets is not very helpful (the configuration still has to fly out of ground effect) but the adverse behavior shown by the slot jet configuration should be avoided A configuration between these two should provide a better compromise An investigation of the effects of jet-spanwise extent as well as size and shape should be undertaken.

Downwash at the Tail

Lift is produced by deflecting the flow around the aircraft downward. Slower flight speeds result in greater deflection of the flow. Powered lift systems are designed to achieve this high deflection on the flow and, as a consequence, produce high downwash angles behind the wing (Fig. 23).[26] Proximity to the ground interrupts this downward flow and therefore changes the downwash at the tail.

Data are available on the downwash behind jet flap configurations out of ground effect, but relatively little exits on the effects of ground proximity. Stewart[10] presented a curve for the ratio of the downwash in ground effect to the out-of-ground-effect downwash (Fig 24) Unfortunately the curve is based on only two sets of data. Additional data are needed to determine its range of validity.

There are even less data on the downwash behind direct jet-lift configurations either in or out of ground effect. Figure 25 presents the effect of ground proximity on the downwash for a Harrier-type model [27] The data indicate the surprising result that at low-speed, high-power conditions (Ve = 0 1), the downwash is negative, that is, an upwash is experienced close to the ground Stewart and Kuhn speculated that this upwash may be due to the fountain flow generated between the rear pair of jets on this configuration [10]

Additional data are needed to clarify these data and to provide a broader data base for estimating the effects of ground proximity General research programs can be visualized, but are unlikely in view of all the other ground effect work needed Instead it is recommended that whenever ground effect tests are planned using complete configurations, the program should be designed to include tail on/off tests in and out of ground effect to build up the data base

Hot Gas Ingestion

Three basic mechanisms are involved in the hot-gas ingestion problem. First, far-field ingestion (Fig 26) occurs when the outward flowing wall jet decreases in velocity to the point at which buoyancy causes it to separate from the ground and be entrained back to the vicinity of the inlet. The inlet-temperature rise associated with far-field ingestion is small because 1) there is considerable mixing before the flow reaches the inlet and 2) the time required for the flow field to develop is such that this mechanism is seldom a problem in normal operations

The fountain flow (Fig 6) is a more serious hot-gas-ingestion mechanism. When the wall jets, flowing radially outward from their impingement points, meet they are projected upward in a fountain flow. Because the path from the jet exit is short and the velocities are high, the inlet temperature rise can be large.

The ground-vortex flow field (Fig 11) is the third basic mechanism. In STOL-operation, the wall jet flowing upstream from the front jets is opposed by the free stream and rolled back on itself into a horseshoe-shaped ground vortex. This flow field transports hot gases back to the vicinity of the inlet. The level of the inlet temperature rise depends on the forward velocity and the operating height

The role that the sink effect of the inlet plays in determining the level of the inlet-temperature rise depends on the direction and energy of the hot flow that comes into the vicinity of the inlet. Hall[12] investigated the effect of inlet flow on the inlet-temperature rise for two isolated-lift engine simulators (Fig. 27). In this case, the fountain transported hot gases upward between the simulated engines, but the temperature at the inlet face was not changed by the amount of inlet flow The air above and between the inlets was heated by mixing with the fountain flow and brought back to the inlet by the induced downflow Apparently, the sink effect of the inlet is not strong enough or close enough to the fountain to draw fountain air directly into the inlet

Figure 28, on the other hand, shows a case in which the inlet flow is significant. In this case, the fountain flow impinges on the bottom of the configuration.[20] Some hot air flows upward around the body and is, in turn, stopped and redirected by the wing and/or canard. Boundary layers are generated on the various surfaces, leaving low-energy hot air in the vicinity of the inlet where the sink effect can draw it in In this case, the inlet flow is very important but the full mass flow does not have to be simulated.

Flow control devices can be used to minimize the amount of hot gas that can get into the vicinity of the inlet Hall[28] showed that if "shields" are located so as to redirect the fountain flow before it has lost significant energy, the inlet-temperature rise can be drastically reduced (Fig 29) By making the shields a lateral extension of the lower surface of the body, the laterally deflected fountain itself became an extension of the shield and prevented hot gas from getting directly into the vicinity of the inlet. On the other hand, shields placed near the inlet were ineffective because they allowed the fountain to flow up around the body, to lose energy and leave low-energy air near the inlet where it could be ingested

The type of flow control devices shown in Fig. 29 are not always feasible. Also, the types of flow control devices desired for decreasing the suckdown are usually not the best for reducing hot gas ingestion. The LIDs (Lift Improvement Devices) developed for the AV-8B[29] are shown in Fig 30 A spanwise fence incorporated between the gun pods minimized the forward projection of hot gas flow and significantly lowered the inlet temperature rise.

At this time, the flow control devices for minimization of inlet temperature rise have been developed through ad hoc efforts. The data base does not permit direct design and prediction of the resulting inlet-temperature rise However, the flow mechanisms involved are known. A research program is needed to provide the data base on which methods for design and prediction of flow control devices and their effectiveness can be based.

At forward speeds, the ground-vortex flow field becomes a major factor in hot gas ingestion. The free stream that opposes the forward-flowing wall jet and rolls it up into the ground vortex also carries hot gases from the top of the wall jet back to the inlet (Fig 31). As the speed increases, the distance from the impingement point back to the inlet and the time for mixing with the ambient air are both reduced and the inlet temperature rises Eventually a speed is reached where the ground vortex is blown behind or under the inlet and the inlet temperature rise goes to zero. These trends are clearly shown by the data for the four-jet in-line configuration of Ref. 30; shown in Fig. 32 (left side).

The maximum inlet temperature rise for this configuration has been correlated with the inlet height (Fig 32, right side). This four-jet model was tested with both top and side inlets and with the wing in high and low position The data from all four configurations show that the maximum inlet-temperature rise is inversely proportional to the square of the ratio of inlet height to the diameter of the front jet (For the side inlets, the height is measured from the lowest point of the inlet.) This finding applies only to single or in-line jet configurations With side-by-side configurations, a fountain flow is projected upward and forward between the jets and the inlet-temperature rise is greater

To avoid ingestion, the inlet must be ahead of or above the hot gas cloud created by the ground-vortex flow field. The available data on the forward projection of the cloud were presented in Fig 16 and repeated in Fig. 33 along with an indication of the depth of the cloud. Those investigations that attempted to determine the depth indicated it to be about half the forward extent. As with the forward projection, Abbott's moving-model data[19] with no ground-board boundary layer showed the least depth. The Schwantes study[18] which set out to simulate the boundary layer that would be present with atmospheric winds showed the greatest depth. Two boundaries then are feasible; one for hovering in a wind ($z/d = 0.45/V_e$) and one for STOL operation with no wind ($z/d = 0.27/V_e$). These boundaries are for single jet or in-line jet configurations.

The speed at which the inlet-temperature rise went to zero for the four-jet, in-line configuration[30] discussed in McLemore's and Smith's study[30] are compared with these boundaries in Fig 34 Because the data were taken in the wind tunnel with a ground-board boundary layer, they should approach the "wind" boundary. The estimated boundary appears about right, but the investigation was not carried to sufficiently high speeds or heights to be conclusive

With two jets placed side by side, a fountain flow will be projected forward and upward ahead of the configuration. This will increase the depth of the ground-vortex flow field. Abbott found that the depth was nearly doubled for the spacing he used[19] Unfortunately, there is no data on the effect of the spacing ratio For very closely spaced jets, one would expect the flow to approach that of a single jet of twice the area and the depth would only be increased by $\sqrt{2}$ Similarly, if the jets are very widely spaced, they will produce two isolated flow fields with no increase in depth. More study of the factors that determine the depth and forward extent of the hot gas cloud and the speed needed to avoid ingestion is needed.

The preceding discussion has considered primarily steady-state data In practice, it takes some time for the flow field to develop. McLemore presented a sequence of photographs (Fig 35) showing the development of the hot gas cloud in a 5 to 8 knot crosswind[31] The model used a J-85 engine with a top inlet and a single exit at a height of 2 jet diameters The concrete ground plane had a radius of 25 ft or about 25 exit diameters A deflector was attached to the exit enabling the engine to be brought up to speed with the exhaust deflected aft to avoid ingestion. At time zero, the deflector was removed to bring the exhaust to the vertical and a pulse of smoke was injected into the upwind side of the jet. Photographs were taken at 0.2 sec intervals to record the development of the hot gas cloud About 1 sec was required for the cloud to develop to the point where smoke is brought back to the vicinity of the inlet and at this point the inlet temperature was observed to begin to increase

The photographs of Fig. 35 indicate that at 1 sec the hot gas cloud had grown to a radius of about 25 diam The data of Fig. 33 would indicate that the fully developed hot gas cloud would have a radius of over 50 diam with the stated crosswind condition. Apparently hot gas ingestion begins before the hot gas cloud is fully developed.

Although the hot gas cloud has reached a radius of 25 diam by the time ingestion starts, the ingestion apparently does not arise from the hot gases flowing out to the ground vortex and then being transported back to the inlet by the free stream. At a free-stream velocity of about 13 ft/sec, it would take 2 sec for hot gases to reach the inlet even if they were transported to the ground vortex instantly. The time required for hot gas ingestion to start is probably related to the height of the inlet and the speed at which the air mixing with the top edge of the wall jet rises to the height at which it can be blown back to the inlet. This appears to be the area where our basic understanding of the flow mechanisms is the weakest and where additional work is most needed.

Concluding Remarks

The basic flow mechanisms that produce the ground effects experienced by jet- and fan-powered V/STOL and STOL aircraft are known, but there apparently are details of the mechanisms that are not adequately understood Even for the simplest case, the suckdown on a single, centrally located jet, there are differences in the data from various investigators that cannot be explained In other areas, such as the ground vortex and hot-gas cloud formation experienced in STOL operation, there is unsubstantiated evidence to indicate that parameters such as pressure ratio and the ground board boundary layer have a significant impact, but there is an insufficient data base to quantify their effects

Additional force tests or temperature measurements alone would be of little help in clarifying the picture in most areas Carefully structured investigations to isolate and document the effects of key parameters on the flow field under and around the configuration as well as on the forces, moments, and temperatures are required

References

[1] Kotansky, D. R., "Jet Flow Fields," Special Course on V/STOL Aerodynamics, AGARD Rpt No 710, June 1984, pp 7-1 to 7-48

[2] Henderson, C , Clark, J , and Walters, M., "V/STOL Aerodynamics and Control Manual," NADC-80017-60, Jan 1980

[3] Koenig, D G., "Wind Tunnel Testing," Special Course on V/STOL Aerodynamics, AGARD Rpt No. 710, June 1984, pp 9-1 to 9-71

[4] Bore, C. L , "Ground Based Testing Without Wind Tunnels," Special Course on V/STOL Aerodynamics, AGARD Rept. No. 710, June 1984, pp. 10-1 to 10-6

[5] "Proceedings of Workshop on Ground Effects," NASA Ames Research Center, Aug. 20-21, 1985, NASA SP, to be published

[6] Wyatt, L A., "Static Tests of Ground Effect on Planforms Fitted with a Centrally Located Round Lifting Jet," Ministry of Aviation CP749, June 1962.

[7] Hall, G. R , "Scaling of VTOL Aerodynamic Suckdown Forces," AIAA Journal of Aircraft, July-August 1967, pp 393-394.

[8] Spreeman, K. P. and Sherman, R J , "Effects of Ground Proximity on the Thrust of a Simple Downward-Directed Jet Beneath a Flat Surface," NACA TN 4407, Sept. 1958

[9] Christiansen, R. L., Eshleman, J. E., Mitchell, L. K., and Dudley, M. R., "Large Scale Test of a Subsonic Coannular Jet Impinging Normal to a Ground Plan," NASA TM 86787, Sept 1985

[10] Stewart, V. R. and Kuhn, E. R., "A Method for Estimating the Propulsion Induced Aerodynamic Characteristics of STOL Aircraft in Ground Effect," NADC-80226-60, Aug. 1983

[11] Lummus, J. R. and Smith E. W , "Flow-Field Characteristics and the Effect of Jet-Exhaust Simulation for V/STOL Vehicles Near the Ground," Proceedings of the NADC V/STOL Aircraft Symposium, Naval Postgraduate School, Monterey, Calif., May 1979, pp. 293-313.

[12] Hall, G R. and Rogers, K H , "Recirculation Effects Produced by a Pair of Heated Jets Impinging on a Ground Plane," NASA CR-1307, May 1969

[13] Christiansen, R. S , "A Large Scale Investigation of VSTOL Ground Effects," AIAA 84-0356, Jan 1984

[14] Foley, W. H. and Finley, D B., "Fountain Jet Turbulence," AIAA Paper 81-1293, June 1981.

[15] Williams, J., Butler, S. F J., and Wood, M N., "The Aerodynamics of Jet Flaps," Royal Aeronautical Establishment (RAE) R&M No 3304, Jan. 1961

[16] Joshi, P. B., "Generic Thrust Reverser Technology for Near Term Application," Northrop Study for USAF, to be published.

[17] Colin, P. E and Olivari, D. Y., "The Impingement of a Circular Jet Normal to a Flat Surface with and without Cross Flow," AD688953 European Research Office, United States Army, Jan 1969.

[18] Schwantes, E., "The Recirculation Flow Field of a VTOL Lifting Engine," NASA TT F-14912, June 1973.

[19] Abbott, W. A , "Studies of Flow Fields Created by Vertical and Inclined Jet When Stationary or Moving Over a Horizontal Surface," RAE CP No. 911, 1967.

[20] Weber, H A and Gay, A., "VTOL Reingestion Model Testing of Fountain Control and Wind Effects," Prediction Methods for V/STOL Propulsion Aerodynamics, Vol. 1, Naval Air Systems Command, pp. 358-380.

[21] Turner, T. R., "Ground Influence on a Model Airfoil with a Jet-Augmented Flap as Determined by Two Techniques," NASA TN D-658, Feb 1961.

[22] Werlé, Henri, "Simulation de L'Effet de Sol au Tunnel Hydrodynamique (Ground Effect Simulation at the Water-Tunnel)," La. Rech Ae'rospatiale No 95, July-Aug. 1963, pp. 7-15

[23] Turner, T. R., "A Moving-Belt Ground Plane for Wind-Tunnel Ground Simulation and Results for Two Jet-Flap Configurations," NASA TN D-4228, Nov 1967.

[24] Turner, T R , "Endless-Belt Technique for Ground Simulation," NASA SP-116, April 1966, pp 435-446

[25] Hacket, J. E and Boles, R. A., "High Lift Testing in Closed Wind Tunnels," Proceedings of the AIAA 8th Aerodynamic Testing Conference, Bethesda, Md., AIAA Paper 74-641, July 8-10, 1974

[26] Lowry, J G., Riebe, J M , and Campbell, J. P , "The Jet Augmented Flap," IAS Preprint 715, Jan. 1957.

[27] Margason, R. J. et al., "Wind-Tunnel Investigation at Low Speed of a Model of the Kestrel (XV-6A) Vectored-Thrust V/STOL Airplane," NASA TN D-6826, July 1972.

[28] Hall, G. R , "Model Tests of Concepts to Reduce Hot Gas Ingestion in VTOL Lift Engines," NASA CR-1863, July 1971.

[29] Clark, R S and Vasta, S. K., "Development of the AV-8B Propulsion System," AIAA Paper 84-2426, Oct. 1984

[30] McLemore, H C and Smith, C C Jr , "Hot-Gas Ingestion Investigation of Large-Scale Jet VTOL Fighter Models," NASA TN D-4609, 1969

[31] McLemore, H. C , "Considerations of Hot-Gas Ingestion of Jet V/STOL Aircraft," NASA SP-116, April 1966, pp. 191-204

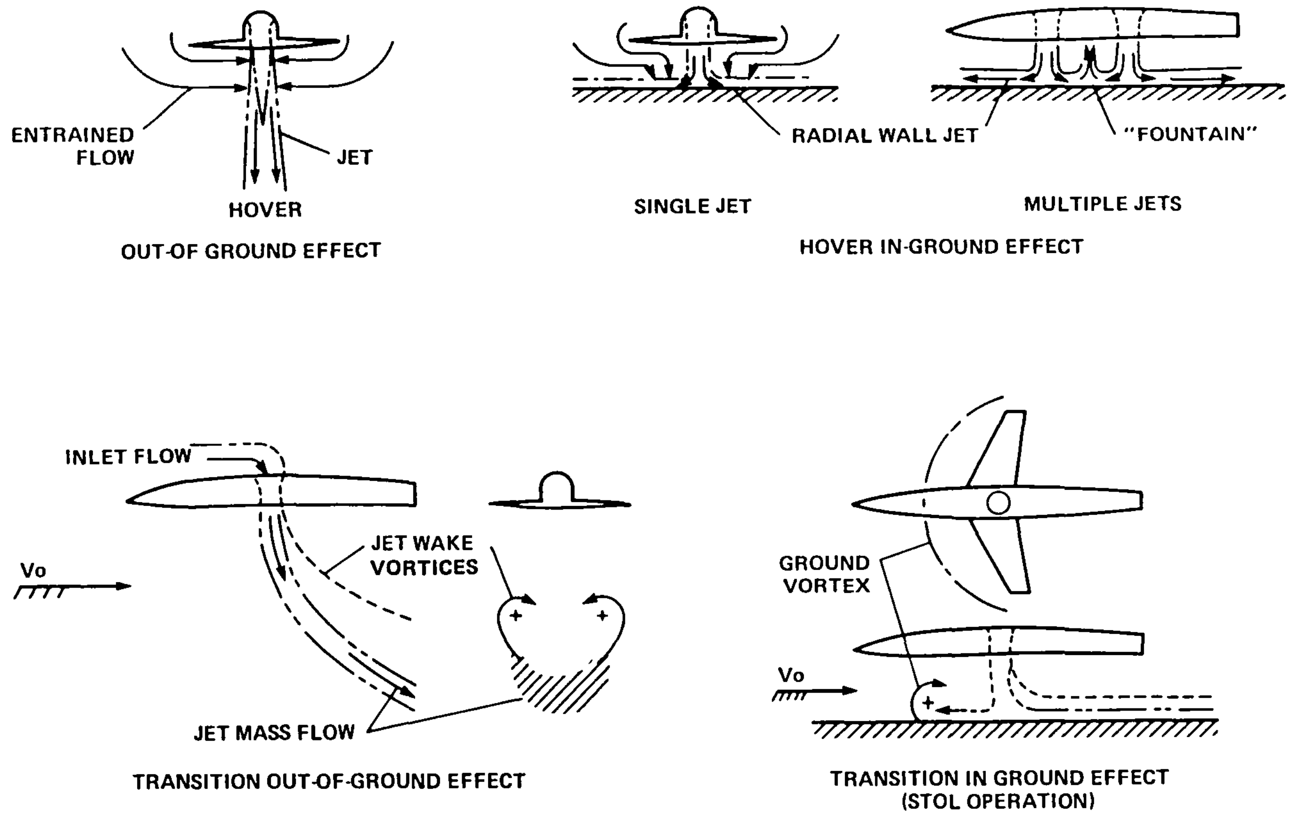


Fig. 1 Basic flow fields

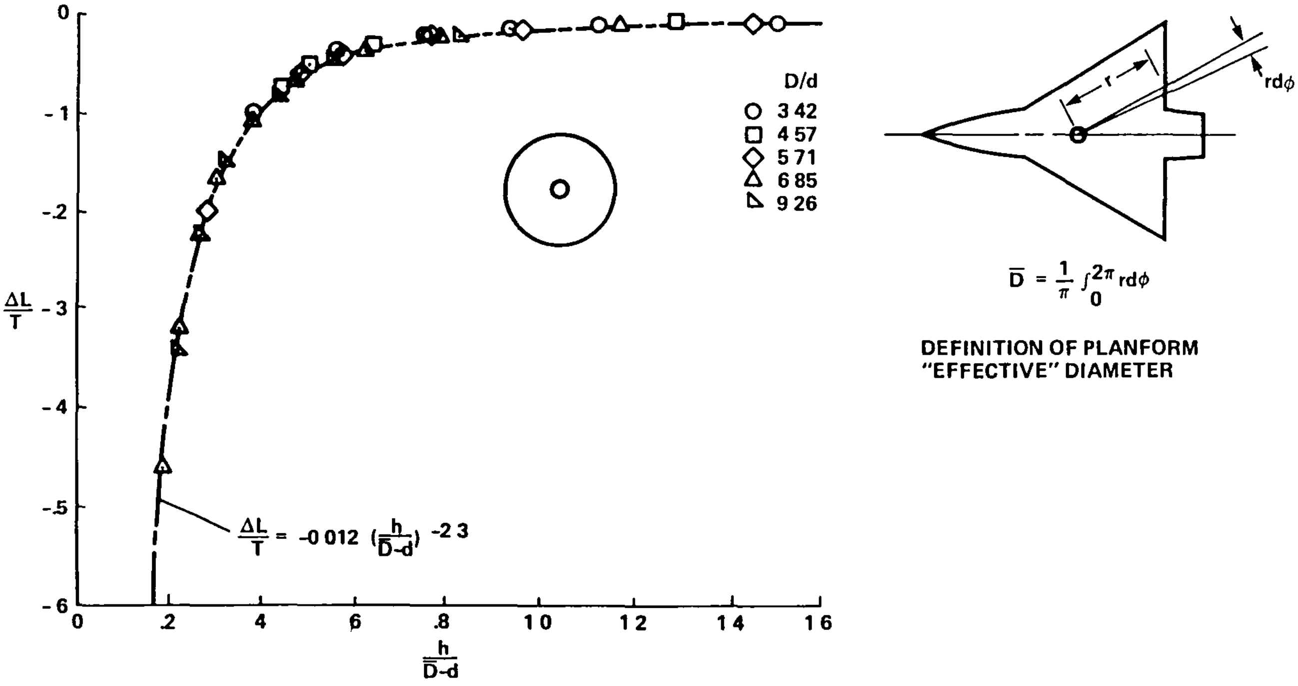


Fig. 2 Correlation of single jet suckdown by Wyatt.[6]

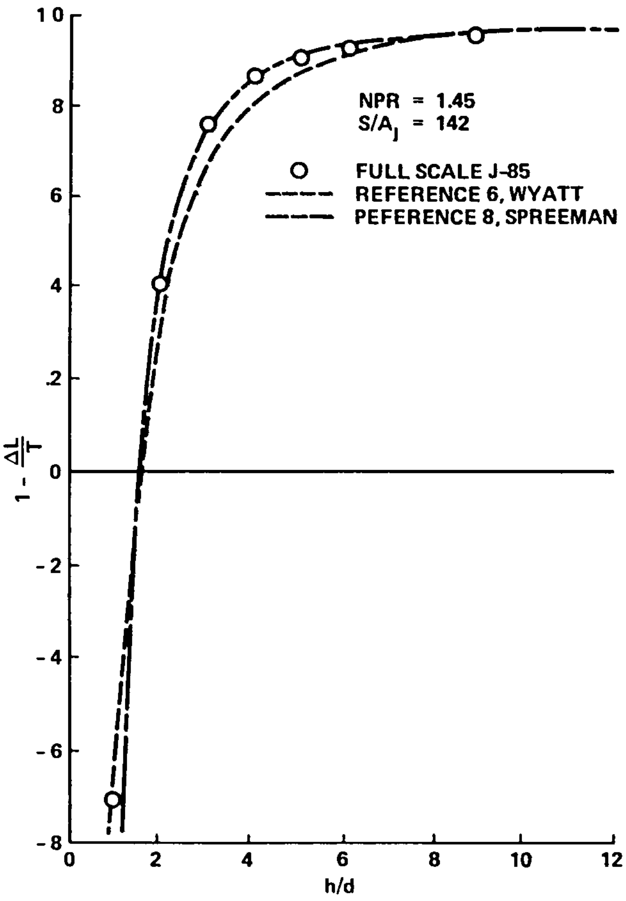


Fig. 3 Comparison of suckdown measured at large scale[7] with results from two small-scale tests.

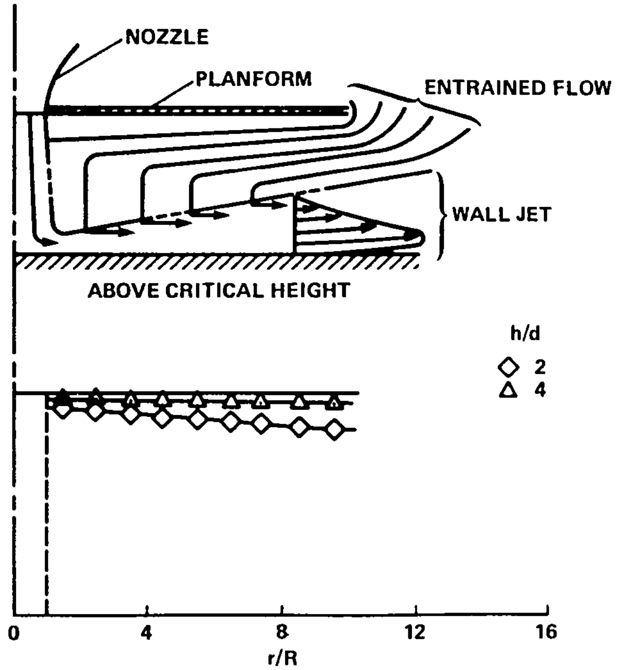


Fig. 5 Flow field and pressures induced by a single jet in hover.[8]

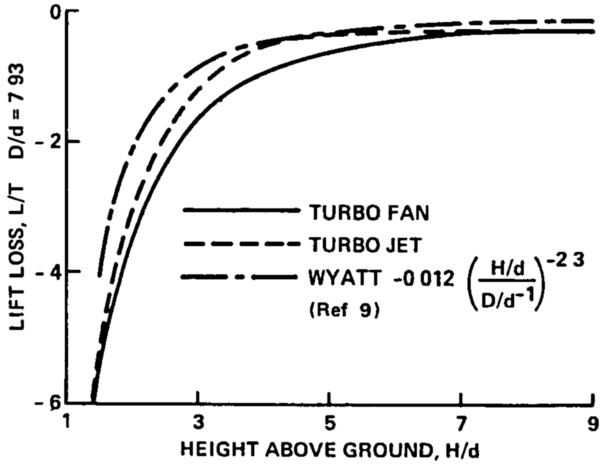


Fig. 4 Recent large scale results from NASA Ames Research Center.[9]

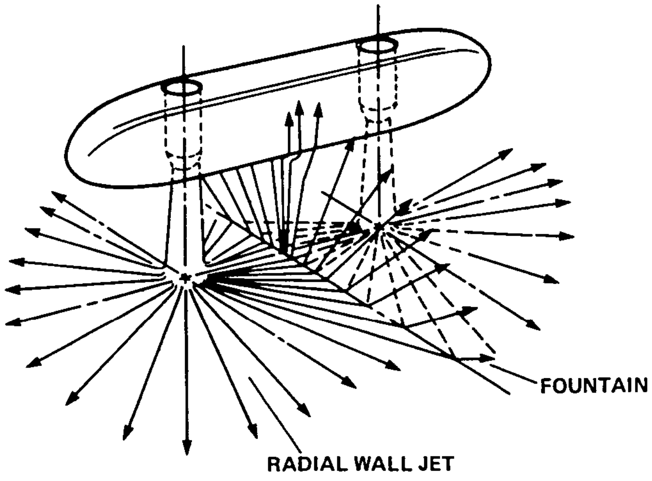


Fig. 6 Fountain flow generated between a pair of jets.

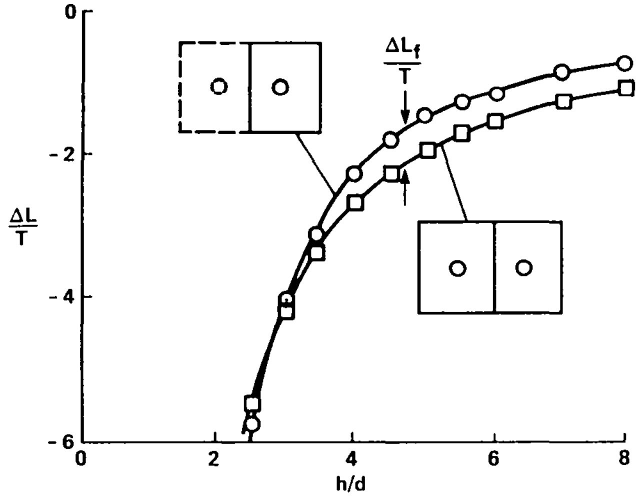


Fig. 7 Comparison of net suckdown for single and twin jet configurations [11]

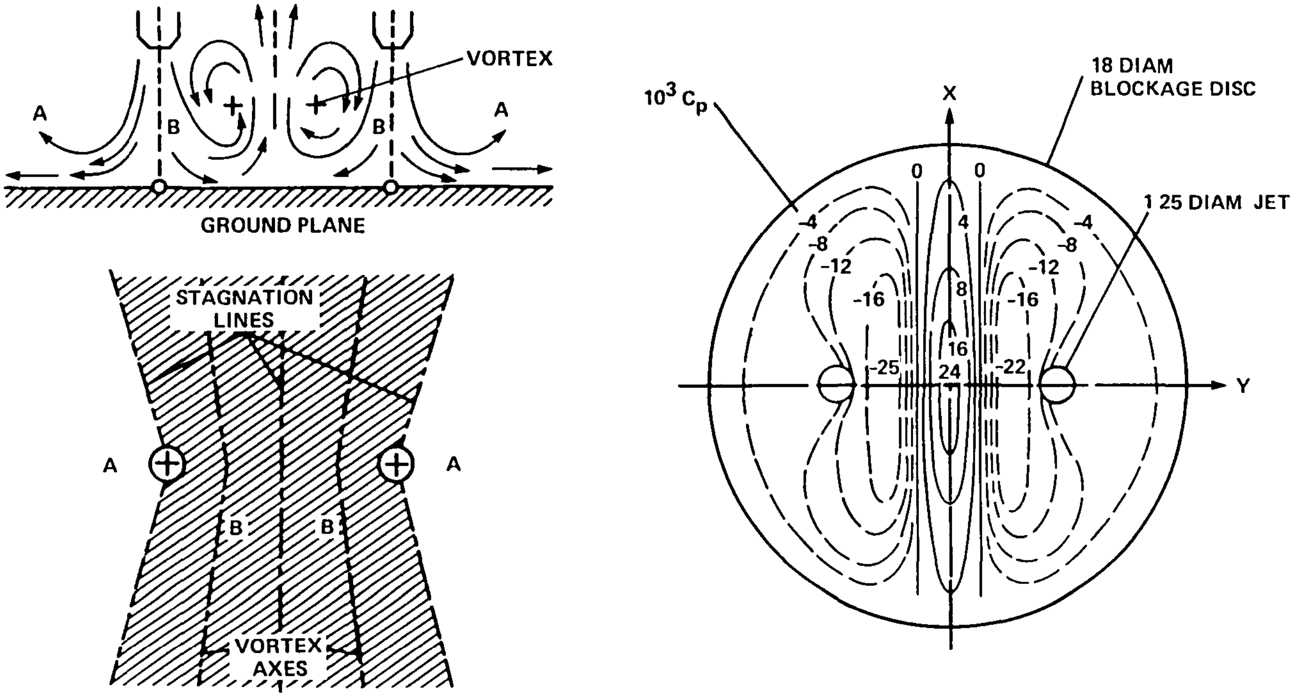


Fig 8 Flow field and pressure distributions between two jets hovering in ground effect.[12]

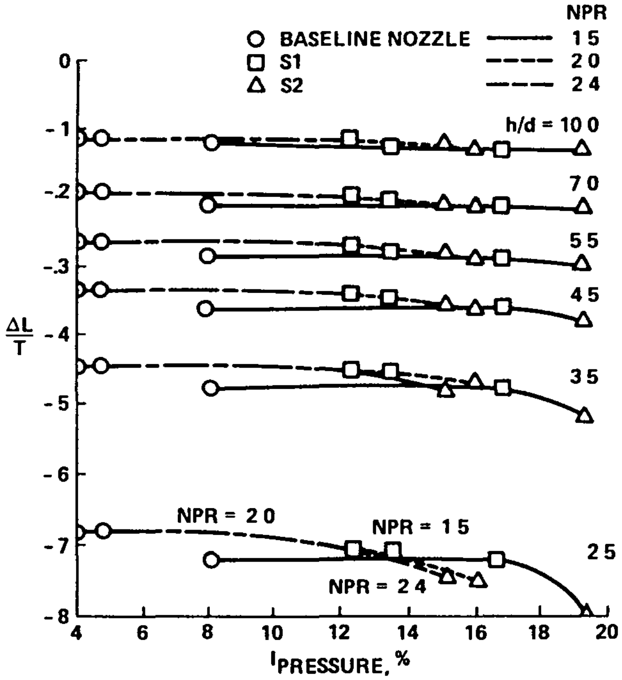


Fig. 9 Effect of turbulence, intensity, I, and pressure ratio, NPR, on suckdown for a two-jet configuration.[11]

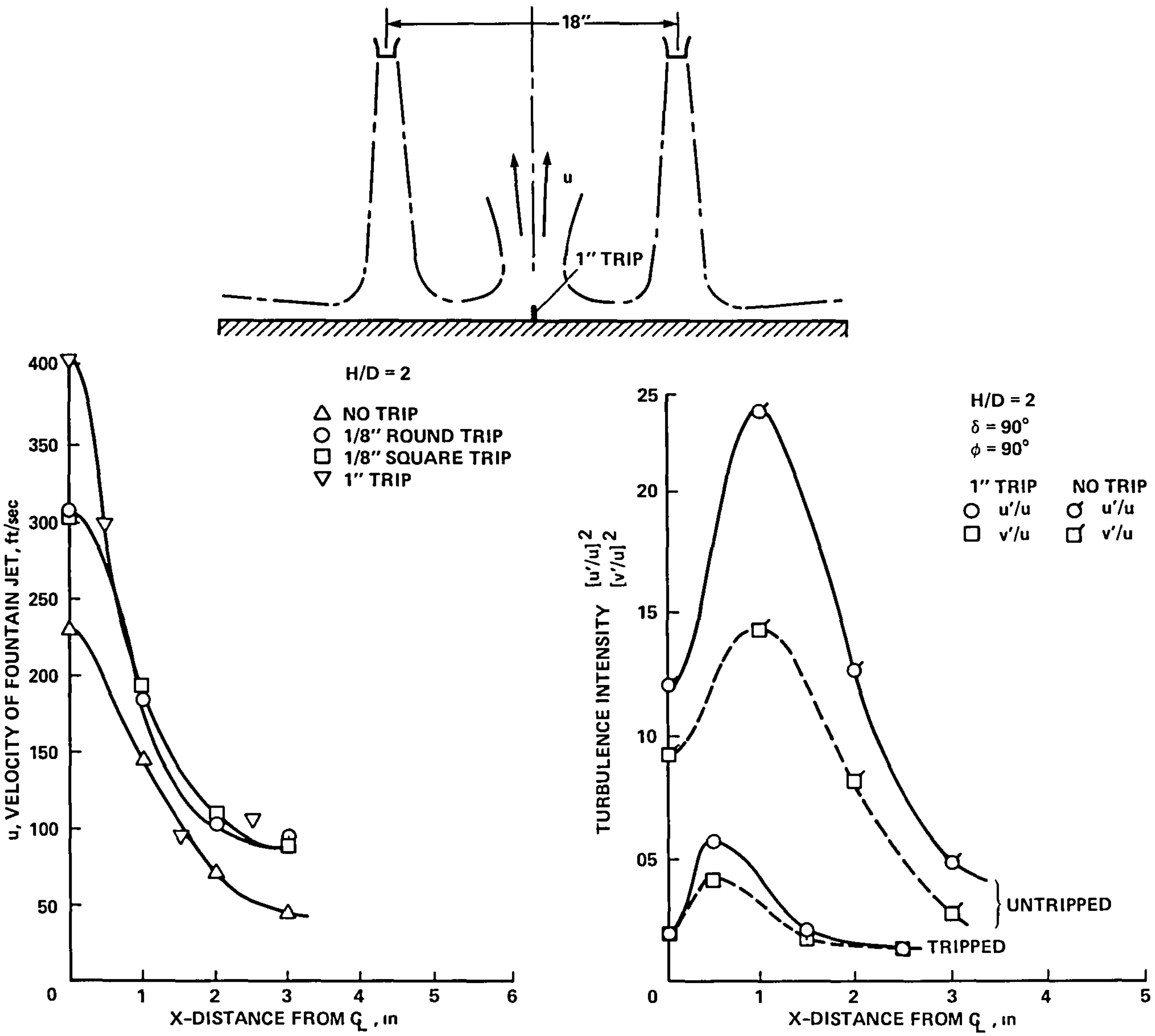


Figure 10.- Fountain turbulence.[14]

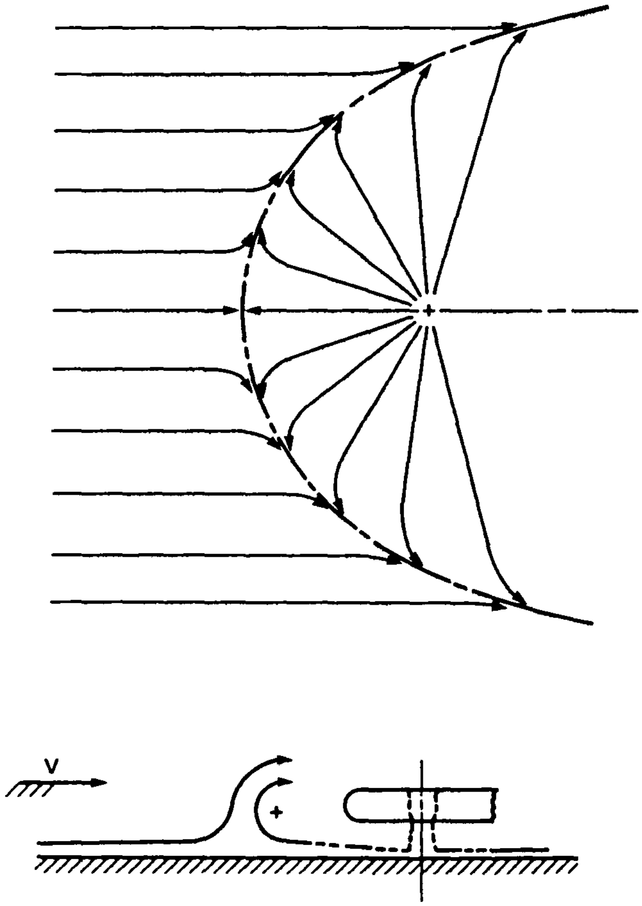


Fig. 11 Formation of ground vortex.

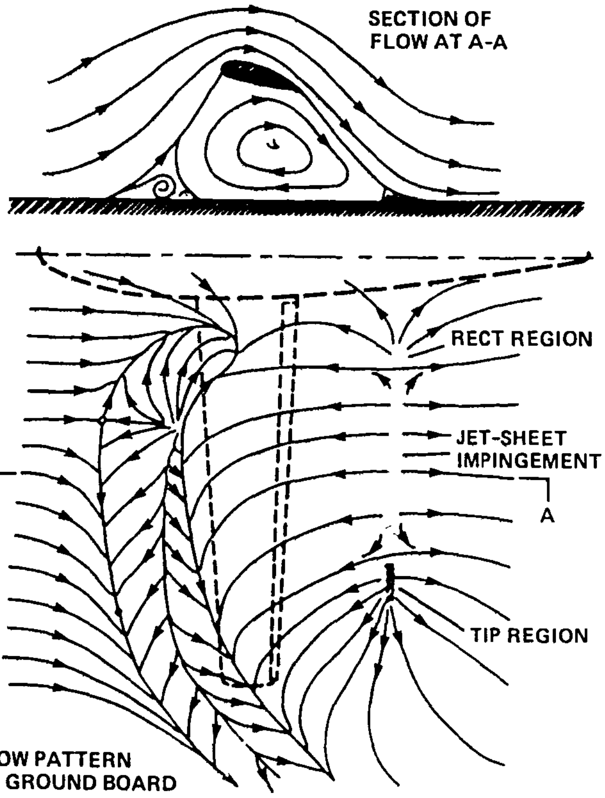


Fig. 12 Ground vortex under jet-flap configuration [15]

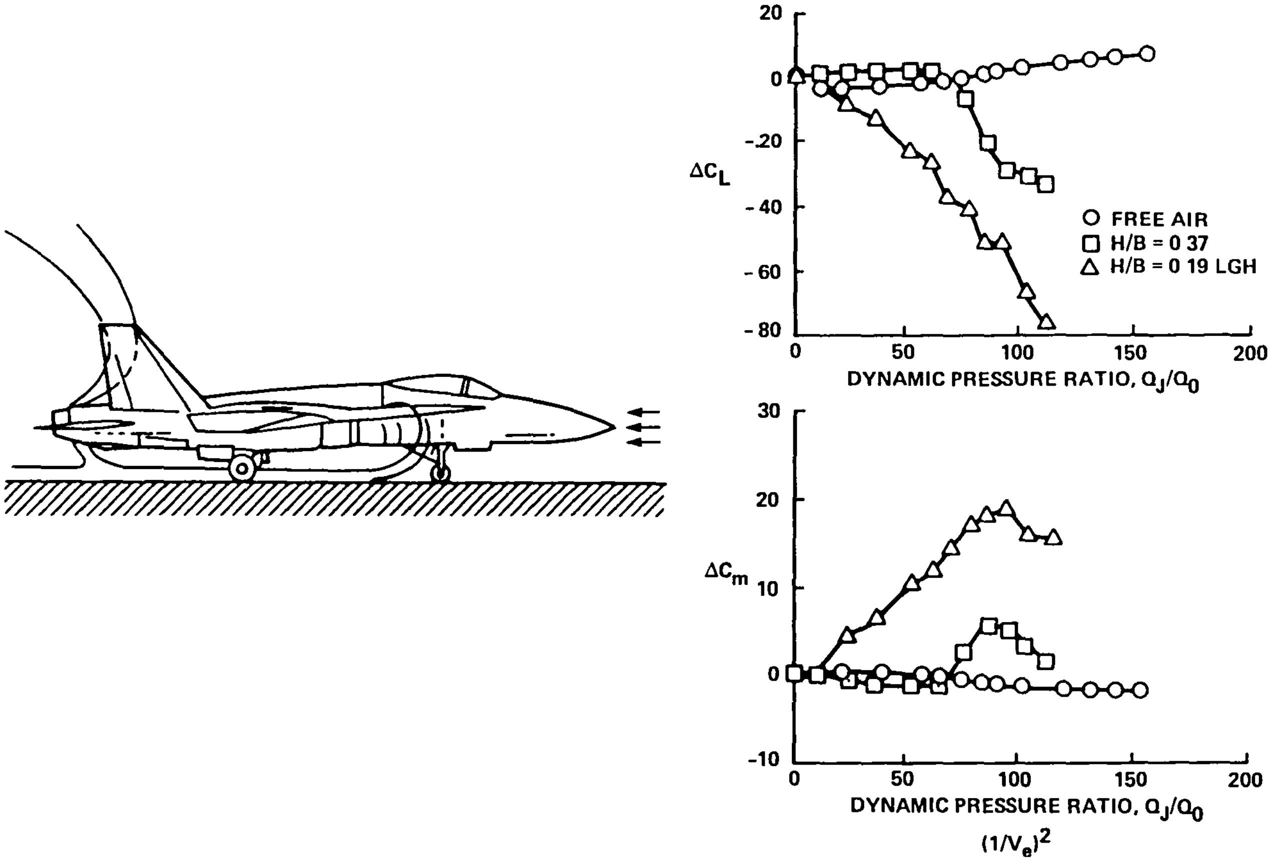


Fig. 13 Lift and moment induced by thrust-reverser-generated wall jet and ground vortex.[16]

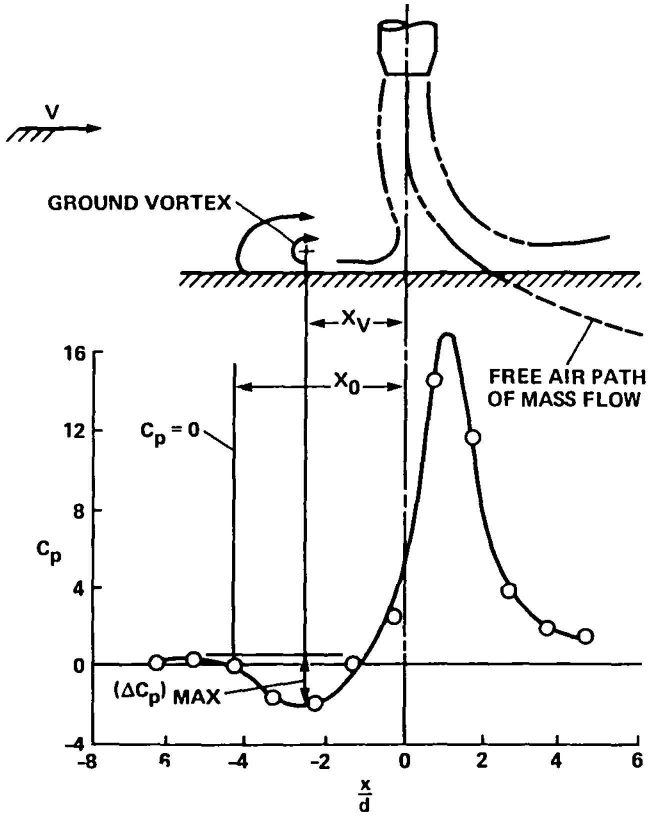


Fig 14 Typical pressure distribution on ground board.

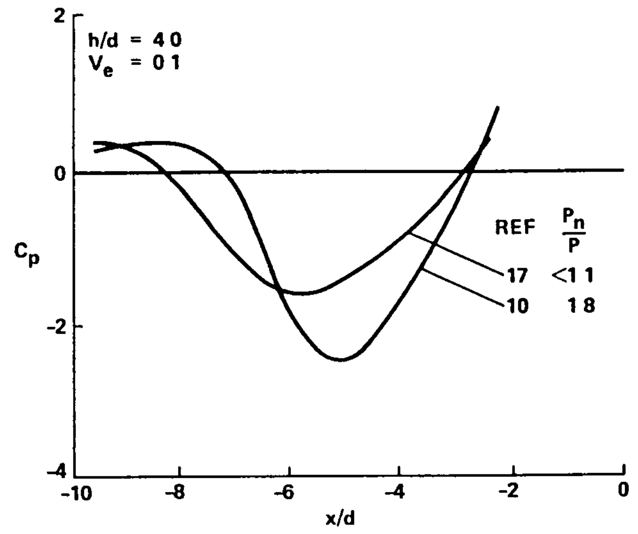


Fig. 15 Pressure distribution on ground board induced by ground vortex.

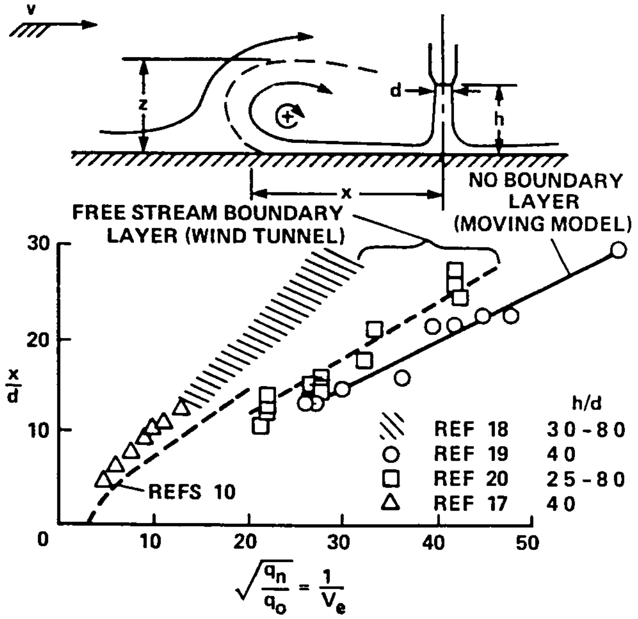


Fig. 16 Effect of ground boundary layer on forward extent of ground vortex.

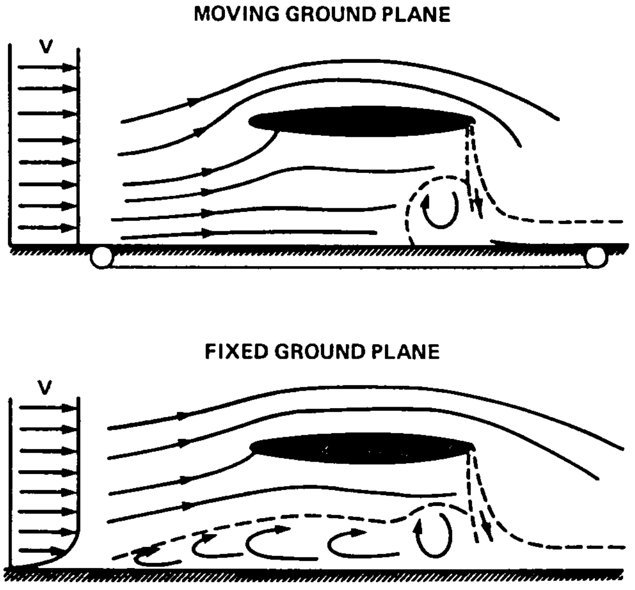


Fig. 17 Jet induced flow over fixed and moving ground planes.[22]

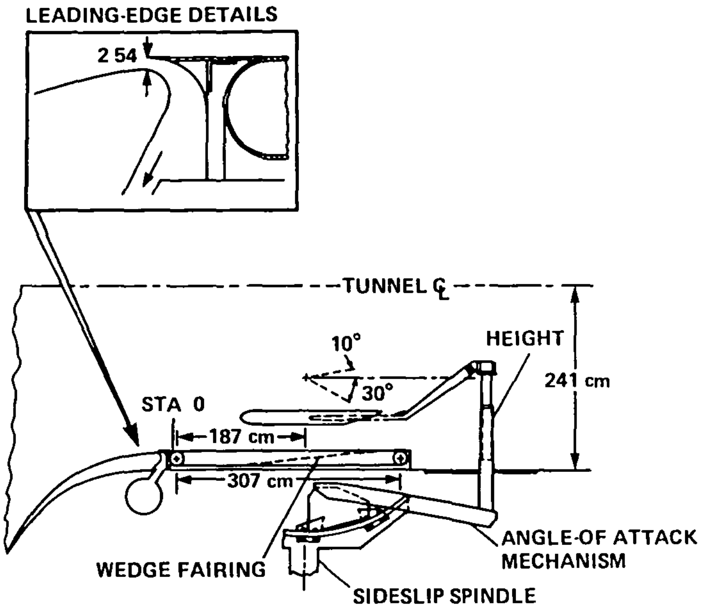


Fig. 18 Turner's moving-belt installation[23]

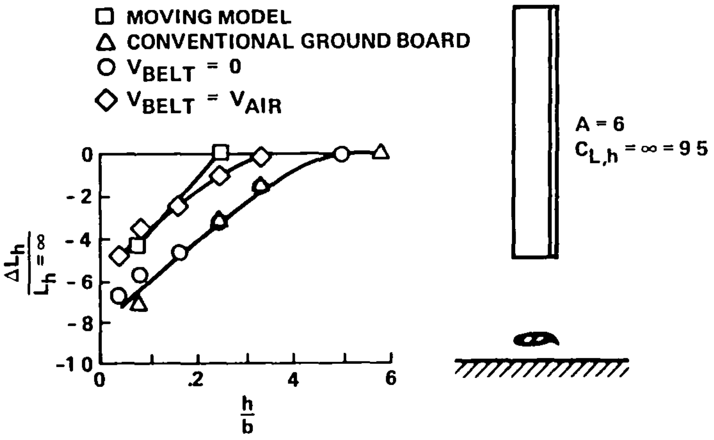


Fig 19 Lift loss for jet flap model as determined by several testing techniques.[23,24]

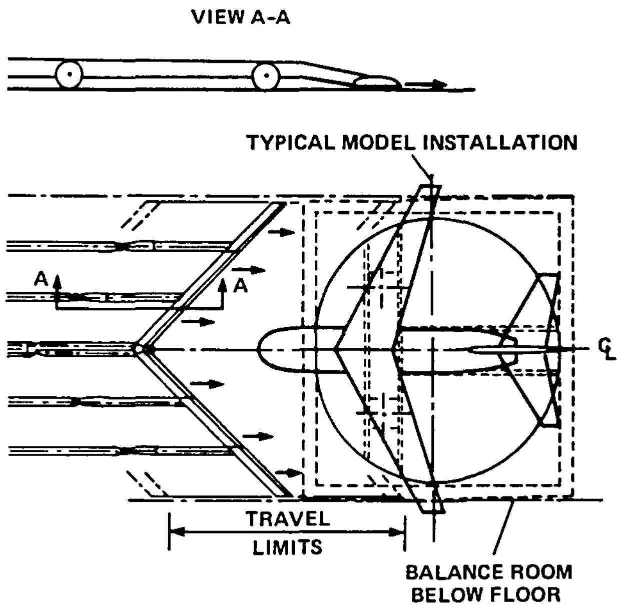


Fig. 20 Traversing, blowing BLC system proposed in Ref. 25.

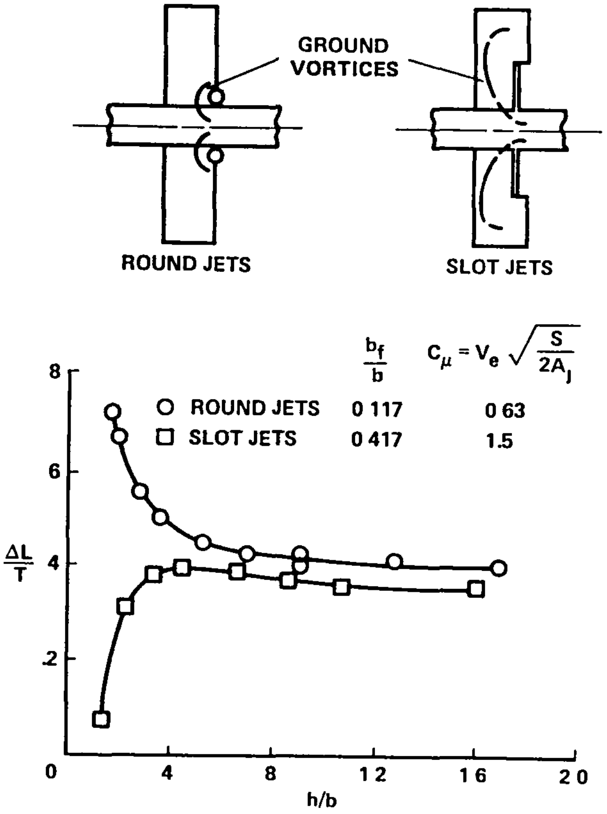


Fig. 22 Comparison of ground effects on circular (direct thrust) and slot jet (jet flap) configuration.[10]

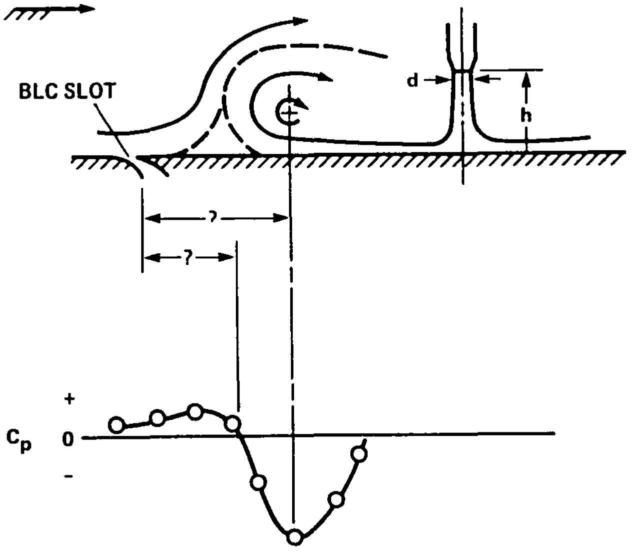


Fig. 21 The ground-vortex pressure signature could be used to position the BLC slot.

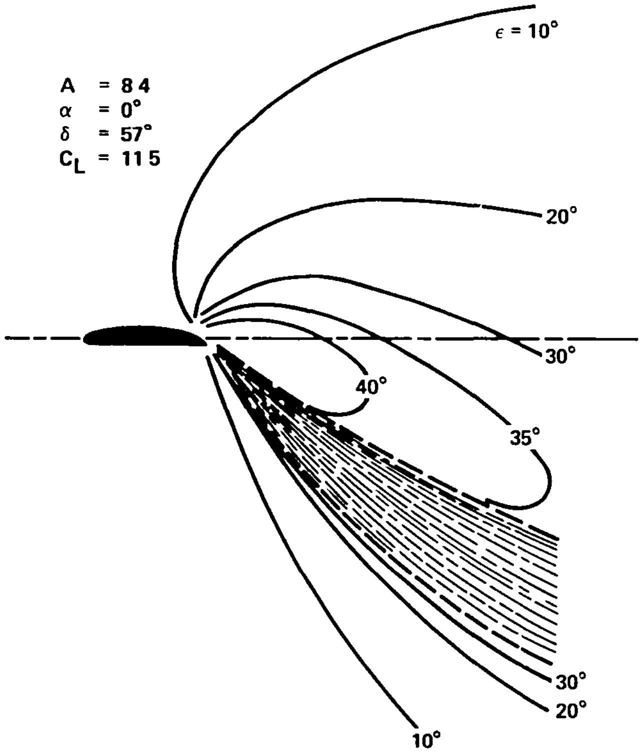


Fig. 23 Downwash field behind a jet-augmented flap at the midsemispan station.[10]

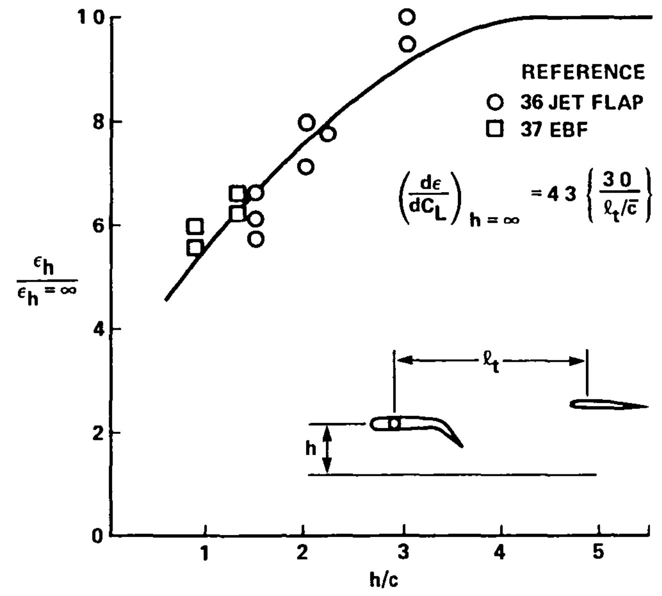


Fig. 24 Effect of ground proximity on downwash, jet flap configurations.[10]

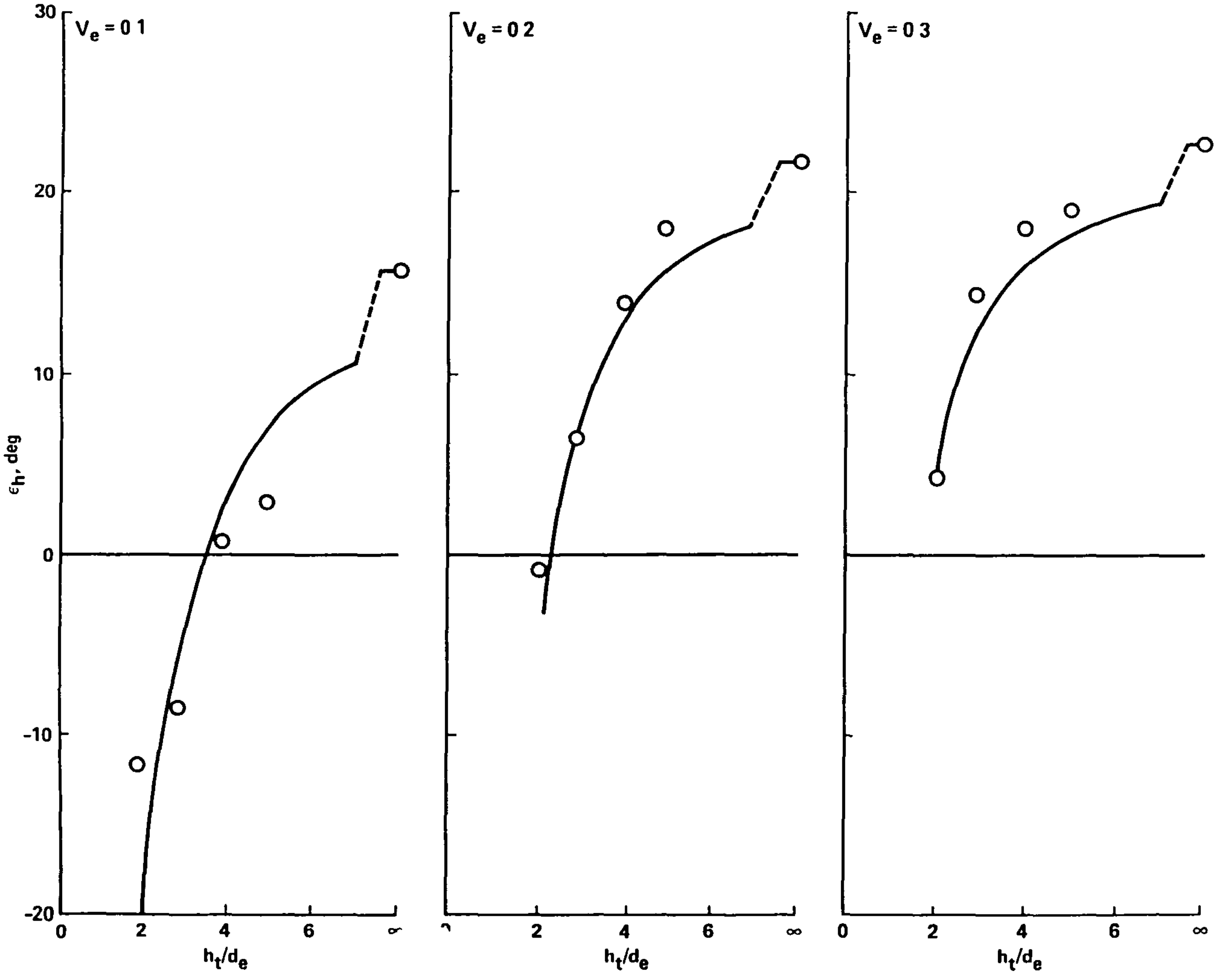


Fig. 25 Effect of ground on downwash behind Harrier type configuration[27]

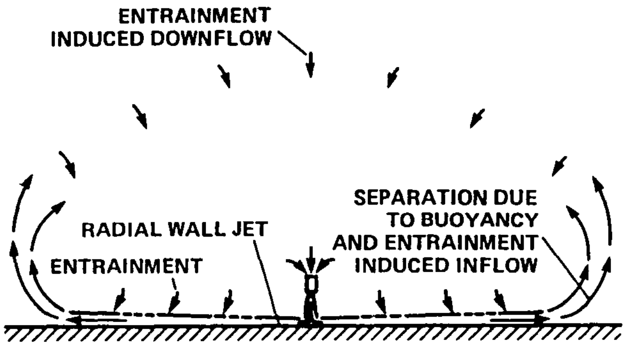


Fig. 26 Far field ingestion.

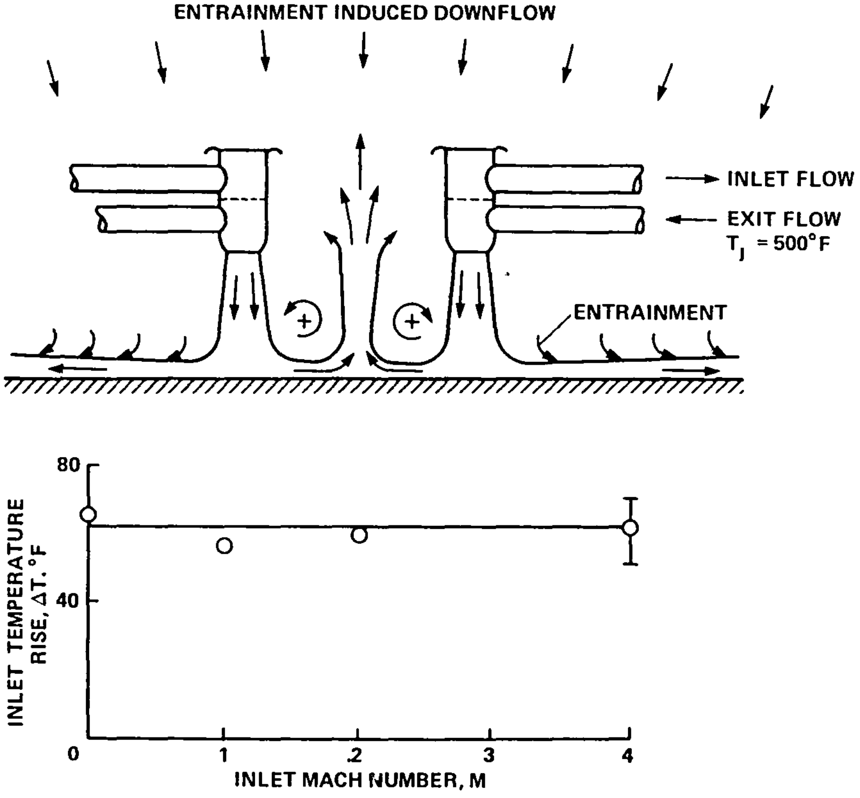


Fig. 27 Inlet temperature rise with two isolated jets.[12]

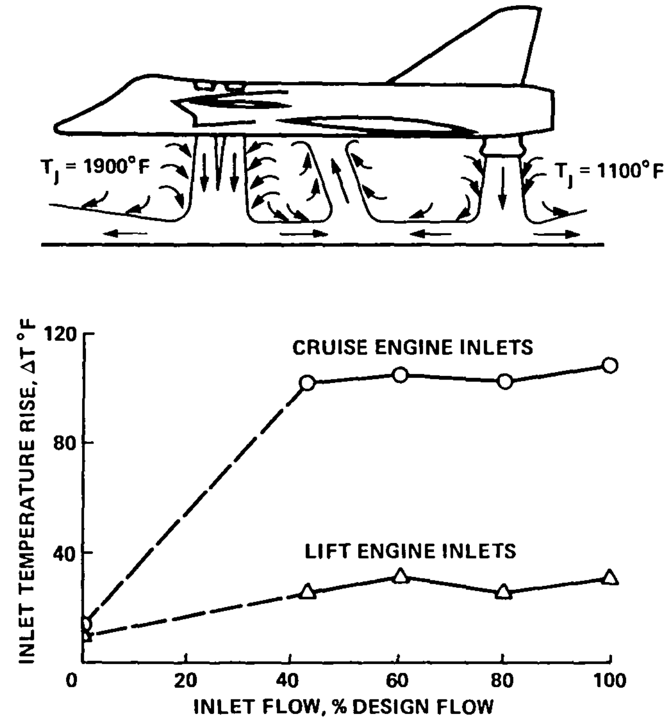


Fig. 28 Inlet temperature rise with fountain impingement.[20]

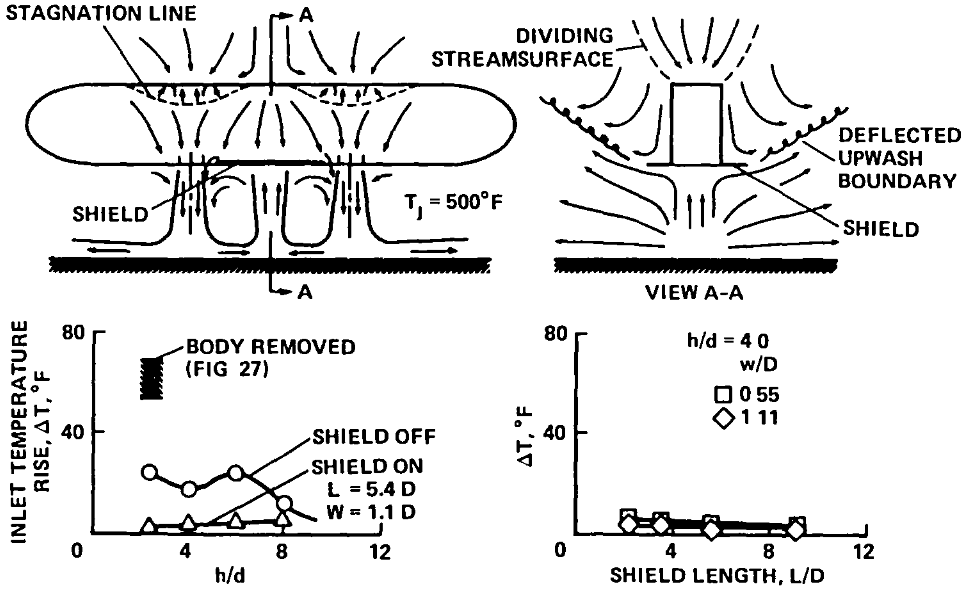


Fig. 29 Effect of exit plane shields.[28]

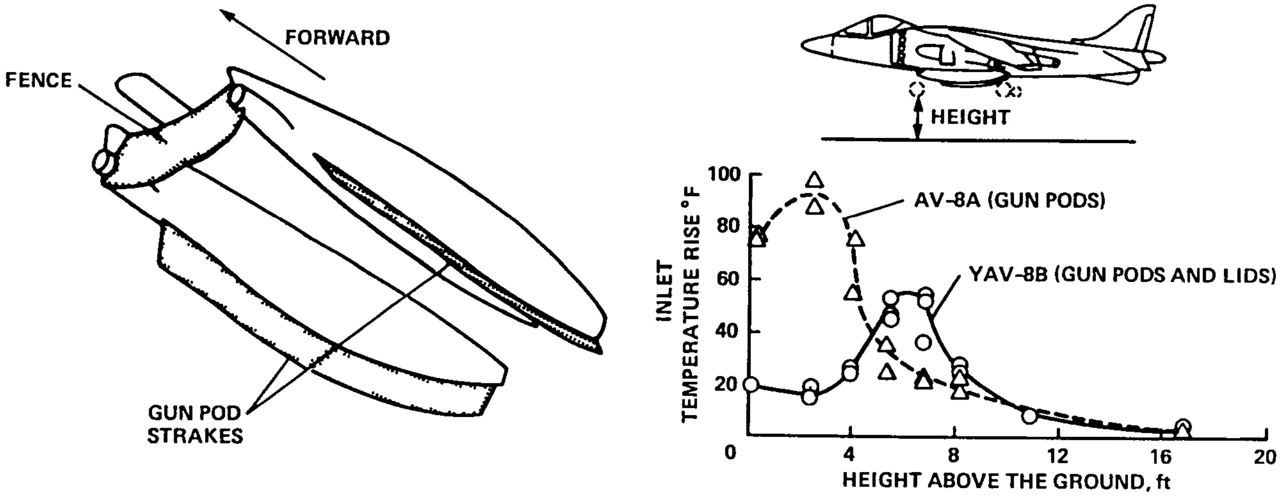


Fig 30 Flow control devices developed for the AV-8B.[29]

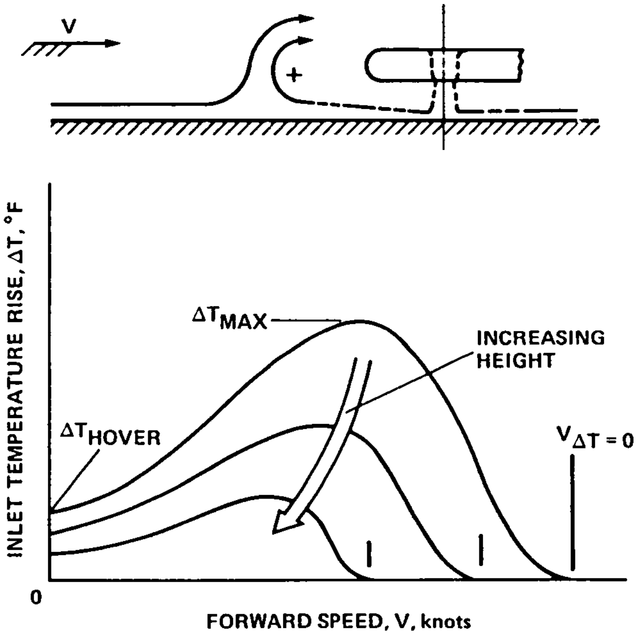


Fig 31 Typical variation of inlet temperature rise with forward speed.

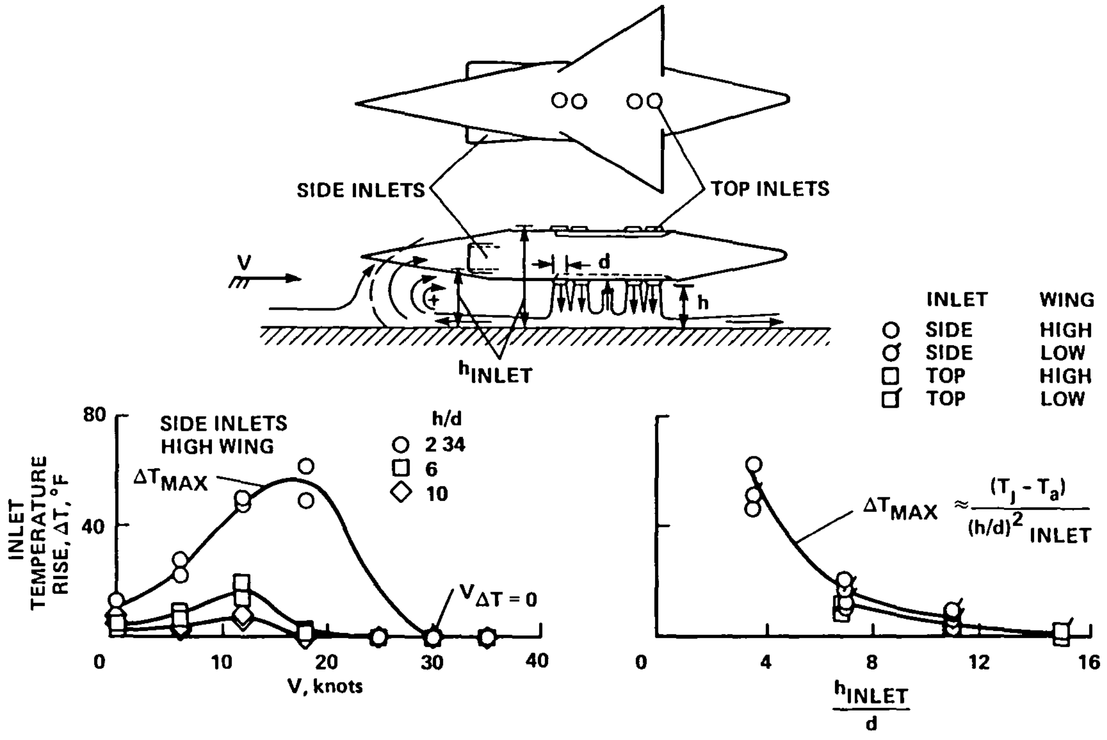


Fig. 32 Effect of height and velocity; four-jet in-line configuration.[30]

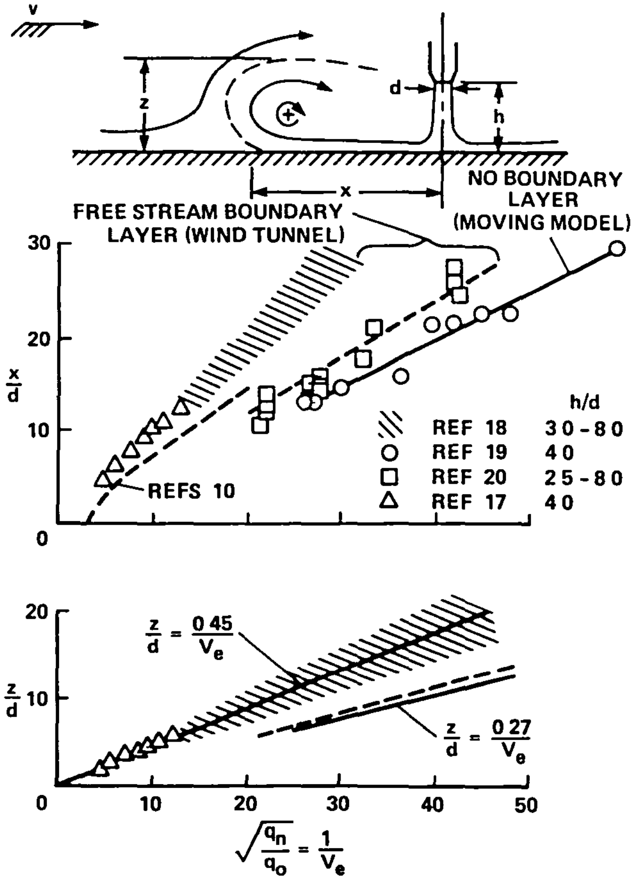


Fig. 33 Size of ground vortex recirculating flow region generated by a single jet.

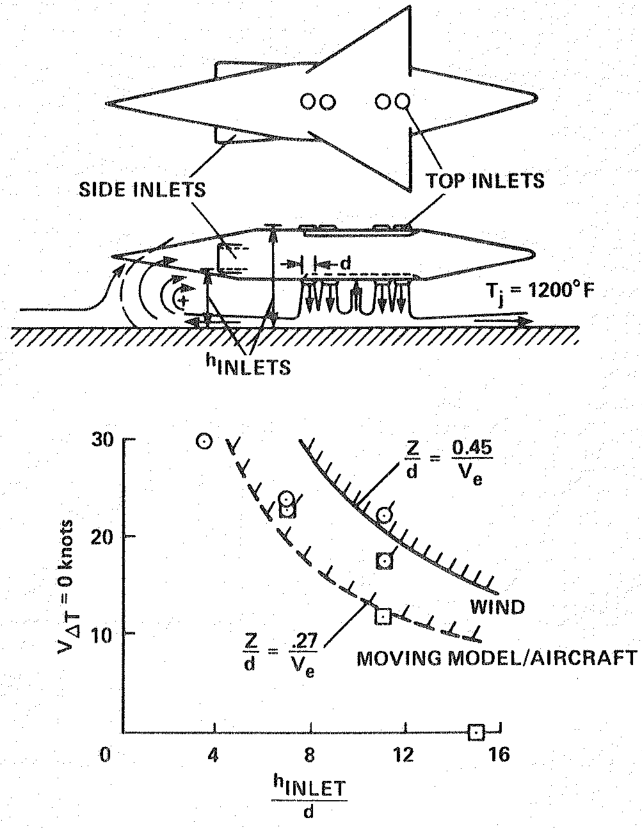
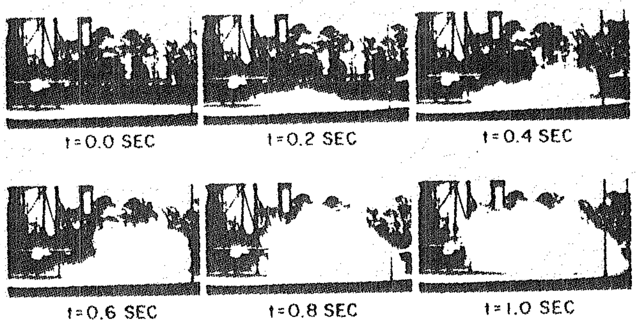


Fig. 34 Velocity required to avoid ingestion; in line jets.[30]


t = 0.0 SEC
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t = 0.4 SEC
t = 0.6 SEC
t = 0.8 SEC
t = 1.0 SEC

Fig. 35 Development of hot-gas cloud.[31]

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15 Supplementary Notes

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16 Abstract

The flow fields encountered by jet- and fan-powered Vertical/Short Takeoff and Landing (V/STOL) aircraft operating in ground effect are reviewed and their general effects on the aerodynamic characteristics are discussed. The ground effects considered include 1) the suckdown experienced by a single jet configuration in hover, 2) the fountain flow and additional suckdown experienced by multiple jet configurations in hover, 3) the ground vortex generated by jet and jet flap configurations in Short Takeoff and Landing (STOL) operation and the associated aerodynamic and hot-gas-ingestion effects, and 4) the change in the downwash at the tail due to ground proximity. After over 30 years of research on V/STOL aircraft, the general flow phenomena are well known and, in most areas, the effects of ground proximity can be estimated or can be determined experimentally. However, there are some anomalies in the current data base which are discussed.

17 Key Words (Suggested by Author(s)) Ground vortex, Fountain, Hot-gas ingestion, Suck down, Moving belt, Down wash	18 Distribution Statement Unlimited Subject Category - 02

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