Effects of a Central Fence on Upwash Flows

William G. Hill Jr.*
Grumman Corporation, Bethpage, New York

Flow properties in the upwash formed by the collision of two opposed radially spreading wall jets were found to be significantly affected by the presence of a small fence centrally located between the wall jet origins. Increasing fence height from zero to approximately twice the total wall jet thickness increased the total pressure in the upwash by more than a factor of 2. At the same time it decreased the upwash thickness by approximately the same factor. As a result of the combined increase in total pressure and decrease in thickness, the momentum in the upwash does not change significantly with fence height. These changes indicate that the presence of the fence affects the upwash formation region and the mixing process in a way that may be useful for improving V/STOL takeoff performance, however, their usefulness will depend on the aircraft width relative to the upwash width. The wall jet resulting from a single-jet/ground plane impingement can also be turned upward by a solid fence, and the resulting upwash behaves similar to the two-jet upwash with the exception that the single-jet upwash deviates from the vertical. This suggests that fences may prove useful in designing multijet upwash flows by controlling flow location and direction. The progressive change in upwash flow properties with fence height also suggests the usefulness of this technique for studying the upwash mixing mechanisms. A rudimentary theoretical model, developed in our earlier studies without a fence, was found to predict the momentum in the upwash with good engineering accuracy for both two- and single-jet upwashes.

Nomenclature

A = area
D = nozzle diameter
H = nozzle height above ground
K_T = thrust coefficient
M = momentum
P = pressure
q = dynamic pressure
R = radius from nozzle impingement center to point in upwash
U = velocity component in upward direction
V = velocity component in horizontal direction, normal to stagnation line and parallel to ground plane
X = direction along ground plane, normal to Y-Z plane shown in Fig. 1
Y = distance along ground plane, normal to stagnation line
Z = height above ground plane

Subscripts

J = jet
S = static
T = total
U = upwash
∞ = ambient

Introduction

VERTICAL takeoff and landing requirements are the most critical elements in the design of a V/STOL aircraft. The downward-directed thrust must be considerably greater than the aircraft weight to provide for the dynamics of takeoff and landing, attitude control, and safety margin. Therefore, this phase of operation determines the engine sizing; the higher the thrust required, the heavier the engine and the lower its efficiency in forward flight. During takeoff and landing the propulsive jets strike the ground and spread along the ground. The entrainment of ambient air into jet plumes and spreading wall jets results in a below atmospheric pressure on the aircraft underside and a resulting downward force that has become known as "suckdown." This is one element of "in ground effects" (IGE) or ground interference phenomena. As an example of the sensitivity of V/STOL aircraft performance to interference forces, Grumman design engineers have found that a 5% downward interference force would result in a 40% decrease in mission radius for a load delivery aircraft or a 40% decrease in time on station for a loiter aircraft.

Additional features of the ground interference flows hold the possibility of relieving the negative suckdown effect, but they also bring complications and possible new problems. When the spreading wall jets from two impinging propulsion jets meet, they turn upward, forming a relatively narrow sheet of flow (similar to a two-dimensional jet but spreading faster and having a three-dimensional structure). This flow is referred to as an upwash. When several jets are involved, the upwash sheets intersect, forming more concentrated areas of upward flow known as fountains. Capturing some of the upward momentum of the upwash or fountains can produce a force which more than offsets the suckdown. However, the upwash and fountain locations move with aircraft attitude and, therefore, become a large factor in stability and control. The upflow also carries heated exhaust gases that can cause heating problems on the aircraft stores or engine problems if reingested into the engine inlets. The complexity of these flows makes it very desirable to understand, predict, and control the IGE flows. The results of our extensive investigations of this problem,[1-4] together with the analytical results of the present paper, provide design engineers with a method of modeling IGE flows based on elementary considerations.

The purpose of the present investigation is twofold. A determination is sought for the benefits that a small obstacle on the ground might provide for improving the takeoff performance of a VTOL aircraft by controlling the upwash formation and development. An interrelated goal is to gain additional information on the role of the upwash formation conditions on the turbulent mixing processes within the upwash.

Turbulent mixing rates are considerably higher in upwash flows than in other free turbulent flows. One possible reason for this anomaly is an unsteady formation, where two turbulent wall jets supply a fluctuating direction and/or location of the origin for the upwash.[5] A central obstacle could suppress this fluctuation and change mixing rates. These considerations, combined with our own unpublished observations that a small flat obstacle on the ground plane could deflect a

Presented as Paper 84-0533 at the AIAA 22nd Aerospace Sciences Meeting, Reno, Nev., Jan. 9-12, 1984; received Aug. 23, 1984; revision received April 8, 1985.

*Staff Scientist, Corporation Research Center. Member AIAA.

wall jet upward, led to the series of experiments and analysis described in this paper. This is quite different from previous studies of ground plane modifications where the intention was to turn the jets upward from the ground similarly to ground plane turbine buckets[6] or to guide the wall jets away in ribbed mats to reduce upflow and hot-gas reingestion.[7]

In the past,[1] it has been found that small-scale, cold-flow, incompressible experiments can be used to accurately predict the upwash from full-scale, heated, compressible aircraft engine jets. The small-scale experiments capture the fundamental flow behavior and require only a small correction for temperature and/or compressibility as long as the nozzle flow is subsonic. Therefore, the present experiments follow that approach. To study the basic phenomenon, a single spacing between nozzles and a single nozzle height above ground were chosen with values large enough to avoid any jet plume/upwash interference.[4] This geometry also provides room for a series of upwash measurements at several heights above the ground. Thin sheet metal fences were held between two ground plane segments so that the fence/ground plane geometry was a simple sharp corner. Fence heights were varied from zero to approximately twice the overall wall jet height at the centerline location. Total and static pressure traverses in the upwash were taken in the plane of the two nozzle centerlines ($X=0$). We believe the results of this study will be qualitatively correct for other nozzle spacings and heights, and can be transformed to those conditions via our modeling in Refs. 1-3 and the present paper, as long as the jet plumes and upwash are far enough apart so that they do not interact. Closer nozzle spacings will require more study.[4]

Experimental Facility

This investigation was conducted in the Low-Speed Flow Laboratory of the Grumman Corporate Research Center. Figure 1 shows the flow geometry investigated and a definition of the geometry symbols used herein. Note that the X direction is normal to the plane of the figure, and that the usual linkage of X-Y-Z with U-V-W has been violated. The flow is supplied by a centrifugal compressor, diffused into a large settling chamber, smoothed by honeycomb and screens, and then accelerated through a pair of matching 5.08-cm (2-in.) i.d. nozzles. This results in a steady, controllable flow. In the present experiments, the spacings between the nozzle and the nozzle height above ground were both fixed at 5 nozzle diameters. This geometry was chosen to avoid nozzle plume/upwash interactions. Probe traverses were all made on lines connecting the nozzle centerlines (in the $X=0$ plane) at varying heights (Z) with a combination Kiel and static pressure probe. Further descriptions of this facility and background experiments can be found in Refs. 1-4.

Measurements of total pressure in the wall jet, at the fence location ($X=0$, $Y=0$) with one jet operating, were taken for reference conditions. The height at which the total pressure is one-half the maximum total pressure, $Z_{1/2}$, is 0.114 nozzle diameter and the total wall jet height is approximately 0.3 nozzle diameter. The half velocity height for this wall jet, which corresponds approximately to the one-quarter P_T height, is 0.16 nozzle diameter. The fences employed in the experiments extend the length of the ground plane (18 nozzle diameters square) and are very thin, but rigid. The fence heights range from 0.15 to 0.5 nozzle diameter, covering the range from 0.5 to 1.2 times the overall wall jet thickness.

Upwash Measurements with Two Impinging Jets

For convenience of presentation, the total and static pressure measurements presented herein are all referenced to atmospheric conditions, e.g., $P_T \equiv P_T - P_\infty$, and $P_S \equiv P_S - P_\infty$, where $P_T =$ total pressure, $P_S =$ static pressure, and $P_\infty =$ ambient static pressure. An example of the upwash flow properties without a fence is given in Fig. 2. The role of the static pressure is seen to be quite important and is included in

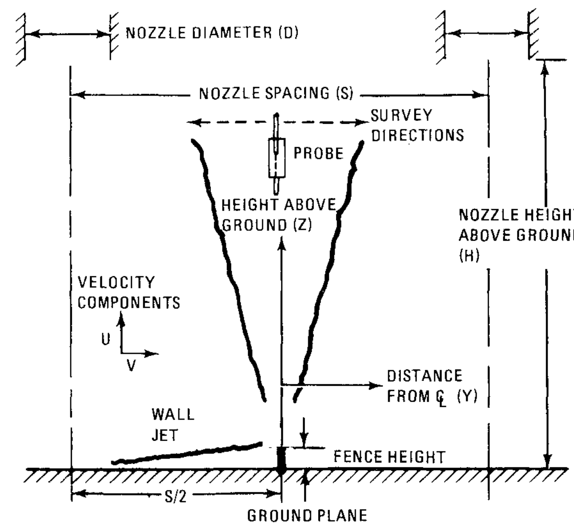


Fig. 1 Schematic of flow geometry and symbol definition.

the experimental results presented and in the analysis. Note that as the probe height above ground increases, the role of the static pressure becomes even more important, so that at $Z/D=5$ the total pressure is almost ambient while the dynamic pressure is still significant. This may explain why investigators who use only total pressure probes find that the upwash appears to vanish at low values of Z. Flow behavior was found to be qualitatively similar with and without the fence, but the thickness and maximum values differ. With the fence present, the static pressure at the edges of the upwash is closer to atmospheric ($P_S/P_{T\,\mathrm{jet}}=0.01$ vs 0.02).

To test similarity in the data analysis and comparisons, the profiles of $P_T - P_S$ were compared with Gaussian curves. All the data fit a Gaussian quite well and the maximum and half-values are used in following comparisons. Figure 3 demonstrates the effect of fence height on the upwash development. Fence heights range from less than the wall jet half-velocity thickness to over the total thickness of the wall jet. Figure 3a shows an increasing value of $P_T - P_S$ as the fence height is increased, while Fig. 3b reveals that this is accompanied by a reduction in upwash thickness. Further data reduction and analysis of these data will be presented after the upwash results for a single jet and fence geometry are presented.

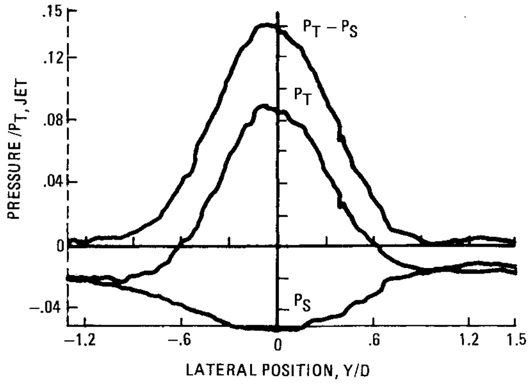
Upwash from Single Jet and Fence

Upwash flows were also formed by the use of fences from the wall jet spreading from a single-jet/ground impingement. The jet impingement and fence locations were the same as those used in the two-jet upwashes. These upwash flows behave qualitatively the same as the two-jet upwashes except they do not flow vertically upward, but instead follow upward curved paths dependent on fence height. Locations of the upwash peak values of $P_T - P_S$ are shown in Fig. 4 for the five fence heights investigated. A fence of 0.375D, approximately equal to the overall wall jet thickness, produces the closest path to a vertical line. Profiles for the single-jet-originated upwash surveys also matched the Gausian profiles but showed a greater scatter than found for the two-jet upwash.

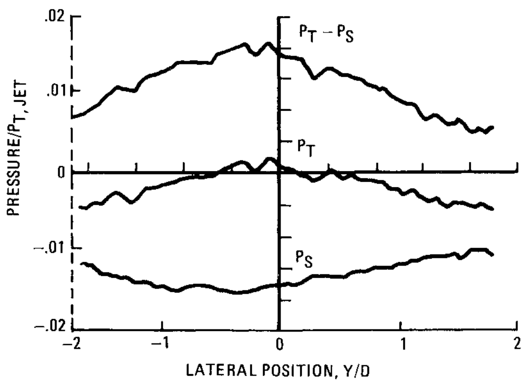
Figure 5 shows the effect of fence height on decay of maximum $P_T - P_S$ and growth of the upwash thickness with height above ground. Similar to the results for the two-jet upwash (Fig. 3), increasing fence height causes a higher $P_T - P_S$ and a thinner width.

Data Analysis and Predictions

Using the elementary assumptions of a radially spreading flow, starting from the center of the jet/ground plane im-

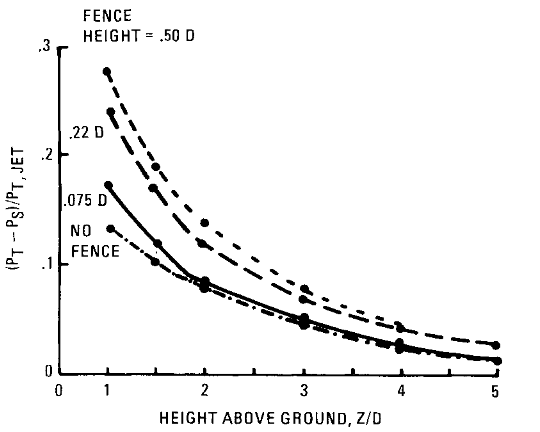


a) **Height above ground = 1 nozzle diameter.**

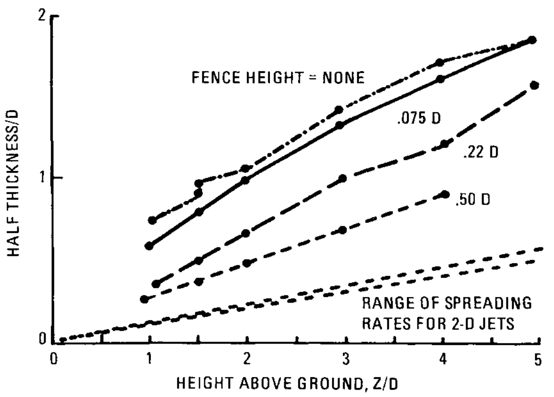


b) **Height above ground = 5 nozzle diameters.**

Fig. 2 Examples of two-jet upwash pressure profiles with no fence present.



a) **Decay of maximum $(P_T - P_S)$ with height above ground.**



b) **Spreading of half-thickness profiles with height above ground for several fence heights.**

Fig. 3 Effect of fence height on development of two-jet upwash.

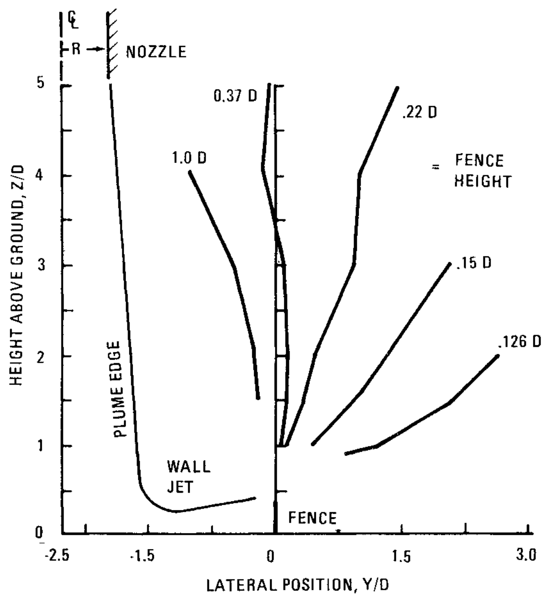


Fig. 4 Path of maximum value of $P_T - P_S$ for single wall jet deflected by several fence heights. Fence is located at $Y/D = 0$ for all cases.

pingement and continuing upward into the upwash, and assuming the conservation of the magnitude of the momentum within streamlines even though the flow directions are changed, a very elementary prediction and convenient normalization of the data are achieved.

The momentum per radian in an axisymmetric jet is given by

$$M_J \text{per rad} = (q_J D_J^2 K_T)/4 \tag{1}$$

The modeling of the jet impingement process herein assumes that the axial momentum in each segment of the flow is preserved in magnitude but turned in direction to produce a radially spreading wall jet. While there is no explicit reason this must be true, it has been found by experience that it does work very well.[1-4]

A very similar assumption is made for the upwash formation process. On the centerline between the two jets, where the wall jet streamlines meet head-on, the horizontal momentum is turned upward to become vertical momentum. For locations off of the centerline where the wall jet streamlines meet at an angle other than 180 deg, it is assumed that the component of momentum normal to the stagnation line is converted to a vertical component while the component along the stagnation line is preserved. This can be visualized (for the case of equal jets where the stagnation line is a straight line) as if the ground plane under a spreading wall jet were folded 90 deg at the stagnation line.[3,4] From this formation, the momentum per radian in the spreading upwash is given by

$$M_U \text{per rad} = 2\int q \mathrm{d}A \tag{2}$$

With the model described for the upwash streamline spreading,

$$\mathrm{d}A = R \mathrm{d}\theta \mathrm{d}Y \tag{3}$$

where

$$\mathrm{R} \equiv (S/2 + Z) \tag{4}$$

$$M_U \text{per rad} = 2\int Q R \mathrm{d}Y \tag{5}$$

The momentum equation evaluated at two locations in a free flow where the pressure along the outer boundaries is constant is

$$\int \rho U_2^2 dA - \int \rho U_1^2 dA = \int P_1 dA - \int P_2 dA \tag{6}$$

The pressure across the nozzle exit plane is within 2% q of ambient and has both positive and negative regions. Therefore, this term is dropped from the equation. The static pressure in the upwash is a significant term (see Fig. 2) and, thus, is kept. Applying the momentum equation to the flow at two locations, the nozzle exit and a general point in the upwash,

$$M_U - M_J = -\int dA \text{ per rad} \tag{7}$$

or

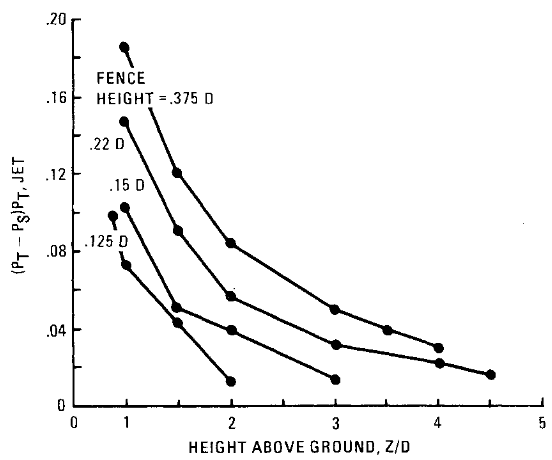
$$[M_U + \int P dA] = M_J \text{per rad} \tag{8}$$

Substituting Eqs. (7) and (10) into Eq. (13), and recognizing that the upwash arises from two jets,

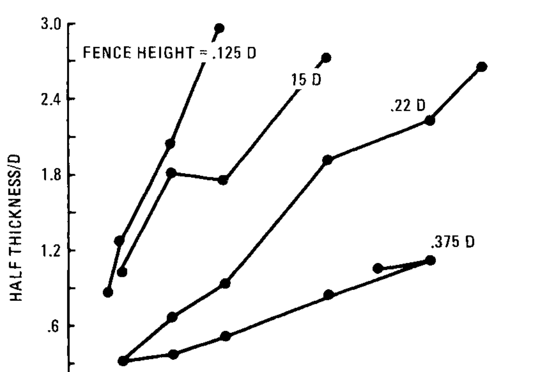
$$[2\int qR dY + \int PR dY]_{\text{upwash}} = \tfrac{1}{2} q_J D_J^2 K_T \tag{9}$$

Making the approximation that $q = P_T - P_S$, which is not completely true for the highly turbulent upwash flows but will be tolerated at this point, and dividing by 2

$$\int (P_T - P_S) R dY + \tfrac{1}{2} \int P_S R dY = \tfrac{1}{4} q_J D_J^2 K_T \tag{10}$$



a) Decay of maximum ($P_T - P_S$) with height above ground.



b) Spreading of half-thickness of $P_T - P_S$ profiles with height above ground.

Fig. 5 Effect of fence height on development of upwash from single wall jet.

Nondimensionalizing by $q_J D_J^2$,

$$\int \frac{P_T - \tfrac{1}{2} P_S}{q_J} \frac{R dY}{D_J D_J} = \tfrac{1}{4} K_T \tag{11}$$

The terms in the divisor are spread this way because we usually normalize each of the elements in the resulting fashion: pressures by q_J and distances by D_J.

Integral properties for the data were determined by use of Gaussian curve fits expressing properties in terms of maximum value of $(P_T - \tfrac{1}{2} P_S)/q_J$ and the Y distance where the function falls to half its maximum value by (Y_{half}). Equation (11) then becomes

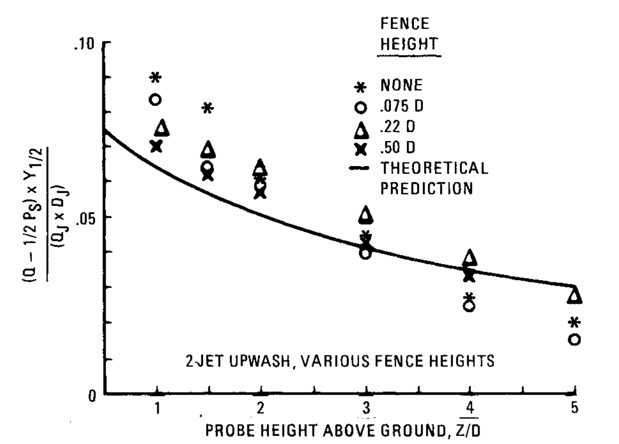
$$\left(\frac{P_T - \tfrac{1}{2} P_S}{q_J}\right)_{\max} \frac{4.24\ Y_{\text{half}} R}{D^2} = \tfrac{1}{4} K_T \tag{12}$$

Dividing by $2.12R/D_J$, and inserting the value of thrust coefficient, 0.95, results in

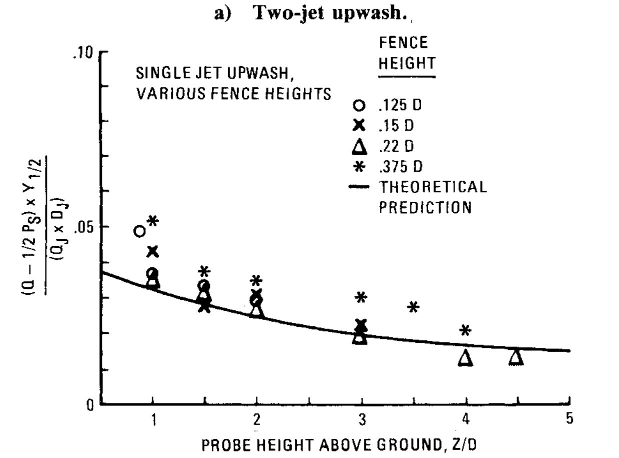
$$\left(\frac{P_T - \tfrac{1}{2} P_S}{q_J}\right)_{\max} \frac{2Y_{\text{half}}}{D_J} = 0.223 \frac{D_J}{R} \tag{13}$$

Note that if the term D_J/R were transposed to the left side of the equation, we would have a parameter that is constant. Since the equation is nondimensional in either form, we have chosen to present it as shown, considering this form intuitively more demonstrative of the flow behavior.

Figure 6 shows the predictions of this modeling compared with data from tests utilizing different fences. As was done in the modeling, q was assumed approximately equal to the



a) Two-jet upwash.



b) Single-jet upwash.

Fig. 6 Comparison of theory and experiment for momentum in upwash with various fence heights.

measured values of $P_T - P_S$ despite the fact that this is not exactly true for the presence of such high turbulence levels. Figure 6a is for the two-jet upwash, and Fig. 6b is for the upwash from a single-jet wall jet and fence. Predictions for the single jet have one-half the momentum of the previous equations. This comparison utilizing momentum conservation brings the data from all of the experiments into close agreement with the predictions, and it is the first success in predicting upwash properties from fundamental considerations rather than data correlations.

Implications of Results

At first sight, the increased total and total minus static pressures produced by the presence of a fence seem to promise improvement in the V/STOL interference forces by increasing the vehicle lower-surface pressures and thereby producing greater upward forces. On the other hand, showing that the fences do not affect the upward momentum flow might indicate that vehicle interference forces would be unchanged by the fences. A more thorough reflection indicates that either of these situations might occur depending on the upwash/vehicle interaction. If the vehicle body is narrow relative to the upwash width, the concentration of momentum caused by the fence should be beneficial. However, if the body is wide and captures all of the upward momentum anyway, the fences should produce little effect. In either case, the lower mass flow in the upwash means less entrained air and the possible detrimental effects of more hot exhaust gases impinging on the aircraft. A brief experimental program to test these hypotheses is intended.

The fact that a vertically flowing upwash can be generated from a single-jet impingement by the right choice of a fence may also be useful to the designer. The upwash location in a two-jet vehicle may be undesirable because hot gas could be ingested by the engines, and portions of the upwash from multiple jets could strike undesirable areas. By placing fences, or short sections of fences, in strategic locations, the upwash impingement of the aircraft can be controlled. While it appears that controlled location of the aircraft in relation to the fence(s) would limit their value to takeoff conditions, the maximum help is needed at the takeoff weight. The aircraft's weight on landing requires less thrust plus interference force (vis-à-vis the Harrier ski-jump and STOVAL in general).

Examination of the integrated momentum flow in the upwash, rather than individual aspects of flow behavior (e.g., maximum velocity or half-width), has shown for the first time that upwash properties can be successfully related to simple theoretical predictions. The experimental results also provide new information about the turbulent mixing process in the upwash flow. Mixing rates are higher in the upwash than in other flows, and one possible cause is the unsteadiness of the formation process. The results of this study indicate that the spreading rate (thickness growth) is affected by the fence, decreasing as the fence height is increased. Therefore, a change of the starting location and flow angle is very possibly the cause for the high mixing rates, and a series of ground plane fences will be a good tool to study the process.

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