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Recommendations for Ground Effects Research for V/STOL and STOL Aircraft and Associated Equipment for Large Scale Testing

R. E. Kuhn

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SYMBOLS

A	Aspect ratio
b	Span of blowing slots, ft
C_L	Lift coefficient
C_m	Pitching moment coefficient
C_p	Pressure coefficient
C_f	Skin friction drag coefficient
C_μ	Blowing momentum coefficient
D	Plate diameter, ft
$\overline{D}$	Planform angular mean diameter, ft
d	Jet diameter, ft
H, h	Height above ground board, ft
ℓ	Distance between blowing slots, ft
ℓ'	Distance downstream of blowing slot, ft
L	Lift, lb
$\dot{m}$	Mass flow from blowing BLC slots, slugs/sec
P_n	Jet total pressure, lb/ft
P_o	Ambient pressure, lb/ft
q_o	Free stream dynamic pressure, lb/ft
q_j	Jet stream dynamic pressure, lb/ft
s	BLC blowing slot thickness, ft
t	Time, sec
T	Thrust, lb
ΔT	Inlet temperature rise, deg, F
V, V_o	Free stream velocity, ft/sec
V_b	Belt speed, ft/sec
V_e	Effective velocity ratio, $V_e = \sqrt{q_o/q_j}$
V_j	Jet velocity, ft/sec
V_μ	BLC blowing slot velocity, ft/sec
$\dot{w}$	Weight flow from BLC blowing slots, lb/sec
x	Longitudinal distance or distance ahead of jet impingement point, ft
z	Vertical distance, ft
α	Angle of attack, deg
β	Downwash angle, deg
δ^*	Boundary layer displacement thickness, ft

SYMBOLS (Concluded)

θ	Boundary layer momentum thickness, ft
σ_o	Density of ambient air, lb sec^2/ft^4
σ_j	Density of jet flow, lb sec^2/ft^4

INTRODUCTION

The contract under which this report was prepared is part of the NASA Ames Research Center research effort on the ground effects associated with V/STOL and STOL operation. Primary emphasis is on future experimental programs in the 40- by 80-, 80- by 120-foot wind tunnel test sections, and the Outdoor Aerodynamic Research Facility (OARF) collectively referred to as the National Fullscale Aerodynamics Complex (NFAC).

Task I of the present contract covered a review of the then current understanding of the effects of ground proximity, an identification of the areas where additional research was needed and an outline of the experimental programs and test equipment needed. The Task I report is included as the leadoff paper in the published proceedings (ref. 1) of the International Workshop on V/STOL and STOL ground effects held at the NASA Ames Research Center at the conclusion of the Task I effort.

The Task II effort covered conceptual design of the equipment needed for the 80- by 120-foot test section and the associated outdoor static test stand for the large scale studies of ground proximity identified in Task I and at the workshop. This final report includes a summary of the results of the workshop and the Task I effort and presents the results of the Task II effort and associated recommendations.

BASIC FLOW FIELD

The development of equipment and testing techniques for investigating the ground effects of V/STOL aircraft must be based on the available understanding of the flow phenomena involved. Our current understanding of the flow mechanisms involved in hovering and in transition in and out of ground effect is discussed under several categories in the main body of this report and in more detail in reference 1. The paragraphs that follow give a brief overview in an attempt to put the flow mechanisms in broad perspective.

The basic flow fields associated with hovering, transition and STOL operation of jet powered V/STOL aircraft are depicted in figure 2. These flow fields induce forces and moments on the aircraft which must be known in order to make accurate predictions of the performance and stability and control characteristics of the aircraft.

When hovering out of ground effect (upper left hand corner of fig. 2) the jet streams that support the aircraft entrain air and induce suction pressures on the lower surfaces. These pressures produce a small download; usually about 1 to 2 percent or less of the jet thrust. These downloads are small and the available empirical methods for estimating them (ref. 2) are adequate.

As the hovering aircraft descends into ground effect, the jet stream impinges on the ground and forms a radial wall jet flowing outward from the impingement point. This wall jet also entrains air and significantly increases the induced suction pressures and the resulting down load as the configuration approaches the ground. There have been many investigations of the jet induced suckdown for single jet configurations, and while the basic phenomena is well understood, there are significant differences in the results obtained by various investigators. These discrepancies will be discussed in later sections.

With multiple jet configurations the radial wall jets flowing outward from their respective impingement points meet and form an up flow or "fountain". The impingement of the fountain on the aircraft produces an upload which usually partially offsets the suckdown created by the entrainment action of the wall jets. Unfortunately, the fountain flow also induces higher suction pressures between the jets and the fountains. The mechanisms involved are poorly understood and the present method for estimating the jet induced ground effects on multiple jet configurations are inadequate.

In the transition between hover and conventional flight there are several flow mechanisms that induce forces and moments on the aircraft. The flow into the inlet produces an inlet momentum drag force and usually a nose up pitching moment. The exiting jet flow is deflected rearward by the free stream and rolls up into a pair of vortices. These vortices plus 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 significant increases in the downwash at the tail.

In ground effect at transition speeds (STOL operation), all the above flow phenomena are present, but modified by the presence of the ground. In addition a ground vortex is formed by the action of the free stream in opposing the wall jet 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, is one of the mechanisms of hot gas ingestion, and induces an additional lift loss and an associated moment. Our knowledge of the factors that control the position and strength, and, therefore, the effects of the ground vortex are incomplete at this time.

Both the ground vortex and the fountain flow are involved in hot gas reingestion. In hover, the fountain flow provides a direct path to bring hot gasses into the vicinity of the inlet where they can be inhaled. The severity of this part of the hot gas 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 speed the ground vortex provides an additional path to bring the hot gas in the forward flowing wall jet back to the vicinity of the inlet. Our ability to design for minimum ingestion is compromised by our limited understanding of both the fountain flows and ground vortex.

The following sections will highlight the research needed in each of the above areas (the Task I effort) and briefly summarize the results of the Ground Effects Symposium. Later sections will present the conceptual design of the equipment recommended for ground effects research in the 80- by 120-foot test section and associated outdoor test stand.

RESEARCH NEEDS

Single Jet Suckdown

The first definitive work on jet induced suckdown in ground effect was done by Wyatt (ref. 3). He showed that the suckdown experienced on a wide range of sizes and shapes of plates by a single jet issuing through the plates could be estimated by the expression;

$$\frac{\Delta L}{T} = -0.012\left[\frac{h/d}{\overline{D}/d - 1}\right]^{-2.3}$$

A few years later Hall used a J-85 engine to measure the jet induced suckdown at large scale (ref. 4). His results are 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 reference 5 indicated somewhat more suckdown than either Wyatt's or Hall's work.

Other small scale data (refs. 5-7) also showed departures from Wyatt's and recent large scale tests by Christiansen and Eshleman (ref. 8) show more suckdown than that estimated by Wyatt's method (fig. 3).

There are several factors that could contribute to these differences. These include jet turbulence and temperature, exit velocity distribution, cross gusts in the room in which the tests were conducted or crosswinds in outdoor testing and the effects of ground board size. Few of the reports on jet suckdown give information on any of these factors. All of these and, perhaps others, need to be investigated.

It is doubtful that additional force tests could uncover the reasons for the differences in suckdown discussed above. What is needed are investigations to probe the fundamentals of the flow. Two investigations are recommended as follows:

1) The suckdown is caused by the lowered pressure under the planform due to the entrainment of ambient air into the wall jet flowing outward from the point where the jet impinges on the ground. Little is known about the effects of jet turbulence, pressure ratio, velocity distribution, etc. on the development of the wall jet and it's ability to entrain air. The investigation of these factors and their effects on the suckdown should have high priority.

2) There is limited evidence (ref. 9) that testing in a room of inadequate size can cause excessive suckdown. Estimates presented in the first paper of reference 1 indicate that cross gusts (or cross winds in outdoor testing) of only 1 to 2 percent of the jet velocity can produce increases in suckdown equal to the differences observed between various suckdown measurements (fig. 3, for example). An investigation of the effects of the size of test chamber on suckdown is needed.

Both of these investigations are justified and described in more detail in the first paper in reference 1.

Multiple Jet Suckdown and Fountain Effects

When the wall jets flowing outward from the impingement points of two adjacent jets meet, a fan shaped upwash or "fountain" is formed between the jets as shown in figure 4. If there are more than two jets a fan shaped fountain is formed between each pair and a fountain "core" is formed at the center where the fountain fans meet. The impingement of these fountain flows on the configuration produces an upload which acts to partially offset the suckdown induced by the outward flowing wall jets.

The result is usually, but not always, a reduction in suckdown. As shown in figure 5, Lummus (ref. 10), measured the suckdown for two configurations with equal planform to jet area ratio and found for the configuration shown in figure 5 that the suckdown for the twin jet configuration was greater than for the single jet configuration. Apparently there is an additional suckdown that more than equals the lift force produced by the fountain between the two jets.

The probable cause of this additional suckdown is shown in figures 6 and 7 (from ref. 11). A vortex-like flow is formed between the fountain flow and each of the adjacent jets and these vortex-like flows induce additional suction pressures between the jets and the positive pressure region produced by the fountain flow (fig. 7). Additional data and analysis of the multiple jet fountain flow and induced lift are presented in references 12 to 18.

Attempts to develop methods for predicting the multiple jet ground effects have been made in references 13 and 14 but these methods are limited to configurations similar to those on which these empirical methods are based. A better understanding of the vortex-like flows developed between the upward flowing fountain and the downward flowing jets along with the associated pressure distribution data is needed to provide the basis for a more widely applicable method for estimating multiple jet ground effects.

For "real" aircraft configurations the effects of body and lower surface contour and of strakes or "lift improvement devices" (LID's) installed to "capture" more of the fountain flow must also be considered. Also the fore and aft distribution of surface area on which the suction and lifting pressures act is not usually symmetrical about the aircraft center of gravity and usually produces a ground effect induced pitching moment.

All of these effects must be recognized and considered but it is recommended that the first priority with respect to multiple jet ground effects should be given to obtaining a better understanding of the flow field between the jets and their associated fountain flows and the pressures these flows induce.

Ground Vortex in STOL Operation

In STOL operation the wall jet flowing forward from the impingement point of the front jet is opposed by the free stream and rolled up into a horseshoe shaped ground vortex as depicted in figure 8. When operating over loose terrain this ground vortex creates and defines the dust cloud that can reduce visibility and damage engines. It is also one of the primary mechanisms of hot gas ingestion and can induce a lift loss and moments on the aircraft.

A ground vortex type of flow is also associated with jet flap configurations. Williams et al., in ref. 19, found a trapped vortex under a high aspect ratio full span blown flap configuration in ground effect (fig. 9).

The ground vortex is also a problem when thrust reversers are operated in ground effect. The forward deflection of the jet to produce a drag component of the thrust projects the ground vortex further forward and increases its strength. This aggravates the hot gas ingestion problem and can also lead to significant lift loss and moments as shown by Joshi in reference 20 (fig. 10).

The ground vortex associated with jet impingement has been studied in several investigations (refs. 9 and 21-24). These five studies show a wide variation in the forward projection of the ground vortex flow field (fig. 11). Some of this variation may be due to the manner in which the forward edge of the flow field was defined or it may be due to the effects of jet pressure ratio or flow quality. However, it is believed that the boundary layer between the free stream and the ground board ahead of the ground vortex may be the principal 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 free stream boundary layer than they would be able to penetrate against the full free stream velocity. The investigation of reference 21 set out to simulate the boundary layer of atmospheric winds and, thus, had a thick boundary layer. It is seen to have the most forward penetration (fig. 11). Reference 22, on the other hand, used the moving model technique and, thus, there was no boundary layer. It shows the smallest penetration. Little is known about the boundary layer in the other investigations other than that the investigation of reference 24 was made at relatively low 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 scrubbing drag of the wall jet on the ground thickens the boundary layer between the wall jet and the ground, reduces the momentum of the wall jet and reduces its ability to penetrate upstream. With the fixed model over a fixed ground this more rapid reduction in wall-jet energy is not experienced.

The strength of the ground vortex also appears to be different in different investigations. Figure 12 shows the pressure distributions measured on the ground board under the ground vortices of two studies. The data of reference 9 show a greater negative pressure than the data of reference 24 indicating a greater vortex strength. The reason for the difference is unclear but may be associated with the rather large difference in jet pressure ratio in the two investigations.

Because of the importance of the ground vortex to STOL operations and to hot-gas ingestion (discussed in a later 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 board boundary layer, and the movement relative to the ground.

Jet Flap Ground Effects

It has been recognized for a long time that the correct ground effects on jet flap models cannot be determined in tests over fixed ground board. Turner (ref. 25) showed that the lift losses measured over a fixed ground board were much larger than those measured with a moving model and that the use of a moving-belt ground gave the same results as the moving model tests (fig. 13). Flow visualization studies by Werle (ref. 26) show the large difference in the flow field under the model with fixed and moving ground (fig. 14).

The use of a moving-belt ground board in the 40- by 80- and 80- by 120-foot test sections appears impractical on two counts. First the development, installation, and maintenance of a large enough belt system would be excessively complex, time consuming, and costly. Second, the exhaust temperatures of the jet engines used in wind tunnel models would be difficult to accommodate. The use of blowing boundary layer control on the ground board to replace the belt has been suggested. In considering the design of such a ground board system the function that the moving belt serves must be fully considered.

It has usually been assumed that the belt did it's job just by eliminating the boundary layer between the free stream and the ground board ahead of the model position. Hackett (ref. 27) has pointed out that the belt has an additional direct effect on the vortex flow system under the model (fig. 15). Because the fluid in contact with the belt has to move with the belt a "negative" boundary layer is created in the region of the vortex system that acts directly on, and retards the vortex flow. Any attempt to develop a blowing BLC ground board to replace the belt must recognize and duplicate this effect of the belt.

Because most of the early work on the ground effects of jet flap configurations was done on configurations that developed very high lift coefficients out of ground effect and suffered a loss in lift in ground effect, it is sometimes assumed that all jet flap configurations will experience a lift loss in ground proximity. Stevens, in paper number 14 of reference 1, has presented flight test data on the QSRA that show a lift increase in ground proximity (fig. 16) and it is sometimes assumed that this indicates a disagreement between flight and wind tunnel data. However, Campbell (ref. 28) shows that the effect of ground proximity on jet flap configurations is highly configuration dependent. At moderate lift coefficients a lift gain similar to that experienced on the QSRA can be experienced on unswept partial-span jet-flap configurations (fig. 17).

There is no fundamental reason why wind tunnel tests should not be able to duplicate ground effects experienced in flight, provided the ground is properly simulated. The carefully derived QSRA flight data on ground effects provide a unique data base with which to evaluate wind tunnel technique. A carefully constructed model of the QSRA configuration should be built for use in evaluating and developing the ground simulation technique planned for the large tunnels.

Downwash at the Tail

Lift is produced by deflecting the flow around the aircraft downward. The high lifts produced by powered lift aircraft are associated with high deflections of the flow and, therefore, high downwash angles behind the aircraft in the region of the tail. The presence of the ground interrupts this downward flow of air and, therefore, the downwash at the tail would be expected to reduce as the ground is approached.

Unfortunately, there is little data available from which the effects of ground proximity on the downwash can be determined. Reference 9 attempted to correlate the effects of ground proximity for jet flap configurations (fig. 18) and jet lift configurations (fig. 19) and to develop expressions for estimating the observed effects.

Additional data on a wider variety of configurations is needed to determine the extent of applicability of the methods presented in reference 9 and it is recommended that additional data in this area be obtained by seizing every opportunity presented by tests of complete configuration to obtain additional downwash data in and out of ground effect.

Hot Gas Ingestion

The ingestion of hot gasses into the engine inlet depends on the flow field under and around the aircraft. Three basic mechanisms are involved. In far field ingestion (fig. 20), the wall jet flowing outward from the impingement point slows as it moves outward and eventually separates from the ground under the influence of buoyancy. The entrainment action of the wall jet induces a downward and inward flow that carries warm air back to the vicinity of the inlet. The inlet temperature rise is small because there is considerable mixing before the flow reaches the inlet and the time required for the flow field to develop is such that this mechanism is seldom a problem in normal operations.

The fountain (fig. 4) and ground vortex (fig. 8) flow fields are more serious problems because the flow paths can be short and there is little time for mixing to reduce the temperature of the air returning to the vicinity of the inlet.

The role that the sink effect of the inlet plays in determining the level of inlet-temperature rise depends on the direction and energy of the hot flow that comes into the vicinity of the inlet. If the hot flow is not directed at the inlet and has adequate energy, as in the case of the fountain flow between two isolated simulated lift engines investigated in reference 11, the flow into the inlet has no effect (fig. 21).

If, on the other hand, there is warm nearly stagnant air in the vicinity of the inlet, it can be drawn in by the sink effect as illustrated in figure 22 (ref. 23). In this case the fountain flow impinging on the lower surface of the body flows over the body and the wing and canard surfaces and looses energy as boundary layers are formed and this hot low-energy air is available to be drawn into the inlets.

Flow control devices can be used to minimize the amount of hot gas that gets into the vicinity of the inlet. Hall (ref. 32) 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. 23). In this case the flow control shield redirects the fountain flow laterally away from the configuration and the laterally deflected flow itself becomes an extension of the shield and prevents hot gas from getting 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 was ingested.

Unfortunately, the types of flow control devices needed to minimize hot gas ingestion and those needed to minimize lift loss in hovering are not the same and compromises must be made. The LIDS (Lift Improvement Devices) developed for the AV-8B (ref. 33) are shown in figure 24. A spanwise fence incorporated between the gun pods minimized the forward projection of the hot gas flow and significantly lowered the inlet temperature rise.

At this time, the flow control devices have to be developed on an ad hoc basis because the data base does not permit direct prediction of lift effectiveness and inlet temperature rise. A research program is needed to provide the data base on which rational design and effective prediction methods can be based.

At forward speed the ground vortex flow field becomes a major factor in hot gas ingestion (fig. 25). At hover and very low speeds the inlet temperature rise is determined by the fountain effects. 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 at which the ground vortex flow field is blown behind or under the inlet and the inlet temperature rise goes to zero.

The maximum inlet temperature rise for this configuration (ref. 34) has been found to be inversely proportional to the square of the ratio of inlet height (measured from the lowest point of the inlet) to the diameter of the front jet (right side of fig. 25). This finding applies only to single jet 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 much greater. Additional data on hot gas ingestion are presented in references 35 - 39.

To avoid ingestion the inlet must be ahead of or above the hot gas cloud created by the ground-vortex system. Unfortunately, there are wide variations in the data on the location of the ground vortex as was discussed above (fig. 11). Those investigations that attempted to determine the depth of the flow field indicated the depth to be about half of the forward projection. As with the forward projection, Abbott's data from the moving model tests showed the least depth and the Schwantes study, which attempted to simulate the deep boundary layers of atmospheric winds, showed the greatest depth (fig. 26). These anomalies in the data on the size of the ground vortex flow field need to be resolved before a satisfactory method for estimating the speed to avoid hot gas ingestion can be developed.

It is recommended that the investigation of the effects of jet pressure ratio and ground board boundary layer be designed to provide for extension to include the effects on hot gas ingestion of inlet position, single and side-by-side jets, and bodies or surfaces between the jets.

WORKSHOP RESULTS

A 2-day workshop was held at the NASA Ames Research Center on August 20 and 21, 1985, to review the findings and recommendations presented in the Phase I report (Paper no. 1 in ref. 1), summarized above, and to obtain industry views on the research needed on the effects of ground proximity. The papers presented at that workshop are published in reference 1.

The papers presented generally augmented the review presented in the Phase I report but also pointed out several areas which were not adequately covered. In particular the work of Kotansky and associates on the effects of jet pressure ratio and shape on the development of the wall jet as reviewed in reference 40 are of considerable significance in analyzing the suckdown and fountain effects in ground effect.

The work by Krothapalli and Saripalli (paper 2 in ref. 1) on the fountain flow between jets pointed out the high turbulence levels of the flow in the fountain which results in rapid mixing with the surrounding air and very rapid spreading.

The papers presented by Rizk and Childs (papers 3 and 4 in ref. 1) on numerical simulation of wall jets and jet induced interactions indicate that good progress is being made in developing these tools. In particular their work suggests that the interaction of the blowing from BLC slots on a blowing ground board with the free stream boundary layer and with the wall jet created by jet impingement can be calculated. These analytical tools should be of considerable help in understanding the development of the wall jet and ground vortex flow fields. They should also be of considerable help in developing the blowing BLC ground board proposed later in this report.

Billet in paper no. 5 of reference 1 reported on a unique program at Penn State to study the position and strength of the ground vortex for various operating conditions using LDV measurements. Although just starting, their initial finding that the wall jet flow and the free stream flow must both be seeded in order for a complete survey across the vortex location indicates that, for the single jet case, the two flows, the free stream and the ground vortex, do not mix rapidly and should be relatively easy to define.

The papers by Joshi and Glaze (nos. 6 and 7) both related to the flow fields and effects arising from thrust reverser operation. Joshi reported a rolling moment oscillation associated with thrust reverser operation in ground effect for a two-jet configuration. The unsteady rolling moments appear to be associated with a fore and aft oscillation of the ground vortices under the wings. Glaze reported some Concord data on hot gas ingestion that showed a 15 percent reduction in the speed when ingestion occurred when the model was tested over a moving belt ground board.

The papers by Penrose and Johns (nos. 8 and 9 in ref. 1) related to hot gas ingestion testing. Johns presented the hot gas ingestion investigation planned for a vectored thrust configuration in the 9- by 15-foot test section at the NASA Lewis Research Center.

Penrose (paper no. 8) reviewed the current work in the United Kingdom on hot gas ingestion research. He indicated that they are re-examining the scaling laws that have been used in the United Kingdom until recently and presented model/full-scale inlet temperature rise comparisons. In particlar he stressed the need for dynamic testing to properly reproduce the landing (or take off) maneuver and showed that inlet temperature rise measured in steady state tests can be up to twice the levels that would be experienced in an actual landing.

The paper by Murihead (no. 10 in ref. 1) also related to the need for dynamic testing but in this case the subject was the effect of ground proximity on the lift and moments induced on delta wings by leading edge vortices. He showed a significant lag in the development of the vortex lift.

Stevens (paper no. 11) presented well documented flight test data on the ground effects experienced on the QSRA upper surface blown flap configuration. These data showed the expected effect of ground proximity in reducing drag but also showed an increase in lift. Unfortunately, model data are not available for direct comparison.

Stewart and Kimmerly (paper no. 12) presented wind tunnel data on a low-aspect-ratio, partial-span, internal flow jet flap configuration taken over a fixed ground board. Pressure distributions taken on the ground board also showed the location of the ground vortex and these data show that when the ground vortex is aft of the wing, with the positive pressure field of the ground vortex under the wing, a favorable lift is induced. However, under conditions where the ground vortex moves under the wing a lift loss is experienced. The paper also reviewed some of the early criteria with respect to ground effect testing in the light of recent data and also stressed the need for dynamic ground effect studies.

The primary message from the workshop was that the effects of rate of climb in take-off and rate of descent in landing have large effects on the development of the flow fields and on the aerodynamic forces and hot gas ingestion experienced in ground proximity. Any serious program designed to investigate ground effects of powered lift aircraft must include the ability to investigate the effects of rate of descent and rate of climb.

RECOMMENDATIONS WITH RESPECT TO LARGE SCALE GROUND EFFECT STUDIES

Many of the research investigations recommended above can be undertaken at either large or small scale. However, investigations at large scale are desirable for most; in some cases to provide validation of small scale results, in some cases to provide flow fields that are large enough to insure adequate detail of measurement, and in some cases to adequately model the necessary details of the configuration. For some investigations, such as hot gas ingestion, inlet as well as exit flow is required suggesting the use of small jet engines for proper modeling. And, finally, investigations of the effects of rate of climb and rate of descent may be more accurately simulated at large scale because the starting and stopping accelerations are lower than are required at smaller scale.

The large scale ground effect facility for the 80- by 120-foot test section and associated outdoor static test stand should be designed to accommodate the following types of investigations:

1) Force tests and flow field studies around jet flap STOL and jet and fan powered V/STOL configurations.

2) Effects of thrust reverser operation.

3) Hot gas ingestion studies at jet V/STOL and thrust reverser configurations.

4) Fundamental studies of the position and strength of the ground vortex from single and multiple of vertical and inclined (thrust reverser angles) jets.

5) Fundamental studies of the fountain flow between dual and multiple jets and the forces and pressure distributions induced on flat plates and on representative body contours with and without LIDS.

6) Fundamental studies of the effects of inlet flow rate, inlet position, and flow control devices on hot gas ingestion from twin and multiple jet configurations.

Providing the ability to conduct these types of investigations will require developing special equipment in the following three areas:

1) Equipment to simulate the propulsion systems.

2) A model support system with the capability to simulate the climb and descent rates of typical operations.

3) A ground board that insures proper simulation of the flow under and around the model.

Discussion of the requirements for the equipment in each of these three areas and recommendations for their development are presented in the following sections.

PROPULSION SYSTEM SIMULATION

Small Jet Engines

For some investigations, tests of the full scale configuration with the proposed engines may be feasible, but more often suitable engines are not available. Either the proposed engines are not available in the early stages of the aircraft development or, for other reasons, tests of a subscale model of the proposed configuration are desired. In these cases alternative engines may be substituted but it is usually not possible to maintain the external aerodynamic lines (available engines are relatively larger than the proposed engines would be) or it is not possible to match the exit area, temperature, and pressure ratio.

Remotely Powered Models

In an attempt to circumvent the problems of matching the nozzle exit conditions and, at the same time maintaining the external aerodynamic lines of the configuration, the possibility of using externally mounted jet engines and ducting the hot exhaust flow into the model from one engine and ducting the inlet flow out of the model to another engine was examined. The problems of using this approach are illustrated in figure 27.

In this study it was assumed that the model of a Harrier-type configuration would be powered by two J-97 engines, one supplying the hot exhaust flow to the four nozzles and the other powering the inlet. On the Harrier the front and rear nozzles operate at different temperatures and pressure ratios. With one engine providing the flow to all four nozzles, it is not possible to match the pressure ratio and temperature of both the front and rear nozzles. Instead the total nozzle area was matched to that required by the J-97 engine. This resulted in an approximately one-third scale model.

The primary problem encountered with the remotely powered model approach is that most of the fuselage volume is taken up with the ducting required to get the exit flow to the nozzles. There is no space left for the inlet flow duct and this duct must be taken out the top of the model. The result is that the top of the model and the tail assembly is violated. The resulting model could be used for some ground effect and hot gas ingestion studies but only at zero sideslip. Investigations of lateral directional characteristics or downwash at the tail are impossible. A separate model powered by other means would be required for these tests. This approach, therefore, appears impractical for tests of specific models.

While the remotely powered model approach does not appear practical for specific models, it is attractive for some fundamental studies which will be discussed in a later section.

Hot Ejectors

Ejectors have been used to simulate jet engines in the past, particularly for small scale studies, but full representation of the jet engine has not been attained. In particular the jet temprature has not been reproduced and the inlet mass flow is not fully duplicated.

The possibility of adding a burner to provide the hot exhaust has been suggested and discussed with the two firms that have had extensive experience providing ejectors for jet engine simulation in wind tunnel tests. Both agree it is possible. Two approaches can be made: one using a remotely mounted burner with heated high pressure air piped to the primary nozzles, and the other using a burner with each ejector unit downstream of the mixing region (fig. 28).

The first approach minimizes the size of the simulator that must be installed in the model but presents the problem of ducting very hot high pressure air into the model. The second approach reduces the ducting problem to one that is routinely handled in powered model testing but increases the size of the unit that must be contained within the model lines. It is not obvious which approach is best and it is recommended that a two phase study of the development of hot ejectors suitable for use in powered model testing be undertaken.

For this approach it is assumed that the high pressure air (≈40 lb/sec at 3000 psi) available at the 40- by 80-foot test section will be available at the 80- by 120-foot test section also. The study should assume that four simulator units are to be used in a model of a PCB equipped Harrier-type configuration (similar to that shown in figures 27 and 28) with provision for separate control (thrust, pressure ratio, and temperature) of the front and rear jets. The study should be aimed at achieving the following characteristics in each of the four units:

Thrust	up to	1200 lb.
Jet exit diameter	nominal	6 in.
Jet exit pressure ratio ...	up to	3.5
Jet exit temperature	up to	1200°F
Drive air	less than ...	10 lb/sec at 3000 psi
Inlet flow	maximize	

It is recognized that the attainment of full inlet mass flow with an ejector based simulator is not possible. However, the limited hot gas ingestion data available indicates that full inlet mass flow is not required to determine the inlet temperature rise (fig. 22). The primary objective of the development program should be to obtain as much inlet flow as possible while attaining full simulation of the jet exit flow.

DYNAMIC RIG FOR THE 80- BY 120-FOOT TEST SECTION AND OUTDOOR STATIC TEST STAND

The Need

The Phase I report placed primary emphasis on ground effects in steady state operation. One of the main recommendations that came out of the workshop was that provision should be made for investigating the effects of rate of descent and rate of climb during landing and takeoff. There are a number of studies that show that there are time dependent aspects to the development of the flow fields in ground proximity that significantly affect the effects on the aircraft.

Turner, in ref. 25, showed that there is a lag in the development of the lift loss experienced by a full span jet flap configuration in ground effect (fig. 29). The tests were made using the moving model technique. The model was mounted from the carriage of a hydrodynamic towing tank (with the water removed) and moved the model over a fixed ground board. The leading edge of the ground board could be drooped to simulate a 10-degree landing approach. The data show that there is a lag in the development of the flow field that results in about a 3-chord length lag in the development of the lift loss.

Similarly, Stevens and Wingrove (ref. 41) present data from a landing approach and waveoff that shows a hysteresis in the lift increase due to ground effect on the augmenter wing aircraft (fig. 30). The lift increases as the ground is approached, but this increase is eroded during the waveoff.

A different type of time dependency is presented in figure 31. McLemore, in ref. 42, presents a series of photographs showing the development of a hot gas cloud. The model was powered by a J-85 engine with the inlet on the top of the model. The exit is at a height of two jet diameters above the 50-foot diameter (about 50 jet diameters) concrete pad. A deflector was attached to the exit so that the engine could be started and 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. Simultaneously, at time zero, a pulse of smoke was injected into the upwind side of the jet and photographs were taken at 0.2-second intervals to record the development of the cloud.

About 1 second was required for the cloud to develop to the point where the smoke is brought back to the vicinity of the inlet. This agrees with the temperature data which indicated that the temperature began to rise about 1 second after the deflector was removed.

Although these tests were run at fixed height, it is expected that a similar delay may be experienced in a landing descent. At a sink speed of 3 to 6 feet per second, the onset of hot gas ingestion would be delayed and initial ingestion may occur at a height 3 to 6 feet lower than would be indicated by steady state ingestion tests. The conjecture presented here needs to be verified by actual tests, but it does suggest the need for the ability to simulate the takeoff and landing climb and descent rates to obtain a reliable indication of the susceptability of a configuration to hot gas ingestion.

Penrose, in paper no. 11 of reference 1, presented a comparison of the inlet temperature rise as a function of headwind velocity from constant height--15-second hover tests and those measured in landing descents (fig. 32). The moving model tests show only about half the level of inlet temperature rise measured in the landing descents.

As a result of the favorable results obtained with moving model rigs in the United Kingdom, and in view of the high exit temperatures thought possible with the planned PCB versions of the engine used in the Harriers, Rolls Royce has developed a full scale dynamic rig (fig. 33) for hot gas ingestion investigations.

Also the probable problems associated with thrust reverser operation on fighter configurations in landing that have been pointed out by the work of Joshi (paper no. 9 in ref. 1) and Glaze (paper no. 10 in ref. 1) have led to a special test program as reported by both Joshi and Kimmerly (papers 9 and 15 in ref. 1). The program will use the Vortex Facility at the Langley Research Center (fig. 34) to move the model over a ground board with a sloping ramp to simulate the landing approach as Turner did in ref. 25.

The Concept

All of the above observations clearly indicate the need for a model support system for ground effect testing in the 80- by 120-foot tunnel and the associated outdoor static test facility that can simulate takeoff and landing rates of climb and descent as well as support the model at constant heights.

The type of model support system recommended is illustrated in figures 35 and 36. Figure 35 shows the general arrangement of the installation in the 80- by 120-foot test section. Two different carriages will be required. Figure 36 shows the carriage for tests of complete models supporting a jet flap configuration. Figure 37 shows the carriage and J-97 engine installation for fundamental studies of wall jet and ground vortex development studies as well as hot gas ingestion investigations. The carriages are supported and driven vertically by a hydraulic cylinder which can be controlled and programmed to provide various climb and descent profiles as illustrated in figures 38 to 40.

The complete dynamic rig is mounted on the "T" frame of the balance system in the 80- by 120-foot test section (which is rotated 180 degrees from its normal position) to provide support and ±30-degree yaw capability for the dynamic rig (fig. 36). Rather than modify the floor turntable to permit this installation, the entire floor turntable is removed. The 56-foot diameter hole opened when the floor turntable is removed is, of course, covered by the ground board which is used in conjunction with the dynamic rig.

Although the entire dynamic rig is mounted on the balance system (fig. 36), this balance system cannot be used to measure the model forces and moments because it does not have the response rates required and because all the air loads on the carriage and tack support structure will also be felt by this balance system. Instead the models will be mounted on internal strain gage balances.

The dynamic rig should be designed to duplicate the rates of sink and rates of climb likely in full scale V/STOL aircraft. Although normal landing sink rates are of the order of 3 to 6 feet per second, the ability to investigate higher sink rates--up to about 10 ft/sec.--should be available.

At a constant sink speed the inlet temperature rise experienced on the model will be the same as that experienced on the full scale airplane at the same nondimensional height if the model is operating at full scale nozzle exit pressure ratio and temperature and at the full scale sink speed. This occurs because although the path length from the nozzle to the inlet is shorter on the model, and, therefore, the time required for hot gasses to reach in inlet is reduced, the change in height during this time period is also reduced by the scale factor and the nondimensional height change (height/diameter) is the same.

A problem that arises when full scale sink rates are used with a scale model are the decelerations required at the end of the run. In an actual aircraft landing the stopping distance is the length of the landing gear stroke measured from the height at which the extended gear contacts the ground until it is fully compressed. On a scale model this distance is reduced by the scale factor (fig. 38(a)) and, because the model is descending at full scale sink speed the stopping deceleration must be increased by the inverse of the scale factor to stop in the scaled stroke. Figure 38(b) presents a comparison of the average "g′s" required for a one-third scale model to stop in the scaled stroke with the g′s experienced at full scale.

One way that could be used to alleviate this problem for some research investigations would be to fit the model landing gear with an artificially long long stroke and allow the bottom of the model to come closer to the ground at the end of the run than the scaled full scale height. Using this approach, applicable data would only extend down to the height of initial gear contact with the ground. This approach would permit reducing the stopping decelerations required of the rig to about 2 g′s.

A capability of 2 g′s will permit studies of landing sink rates of up to 5 ft./sec. second (normal sink speeds for operational aircraft) with scaled landing gear stroke and also permit research investigation up to sink speeds of about 12 ft./sec.

The rig should also be designed to permit investigations of decelerating sink rate landings and accelerating climbs as illustrated in figures 39 and 40. Because the time required for hot gas to go from the nozzle to the inlet is reduced by the scale factor the inlet temperature will change faster than they would at full scale if full scale accelerations and decelerations are used. To obtain the correct variation of inlet temperature rise with height/diameter ratio during accelerating or decelerating conditions, the accelerations and decelerations must be increased by the inverse of the scale factor.

At design gross weight, a V/STOL aircraft is usually required to have an excess thrust over weight of about 10 percent in hovering flight, which means it will have a vertical acceleration capability of 0.1 g. A one-third scale model will, therefore, need a 0.3-g capability to properly simulate a 0.1-g full-scale climb. At less than gross weight and a forward speed conditions where wing lift can augment the lift from the jets, higher vertical accelerations are possible.

It is suggested that the rig should be capable of producing up to 1.0 g upward acceleration.

Requirements

The general configuration and principal dimensions of the dynamic rig and its two carriages are shown in figures 35 - 37. The dynamic rig should be designed to have a vertical travel of about 20 feet and to position and hold the model at any desired height. Vertical travel rates of 0-15 ft/sec should be provided. A yaw capability of ±30 degrees should be provided by mounting the rig on the present balance system. And an angle of attack drive system capable of -10 to +30 degrees angle of attack should be designed into the complete model carriage. In order to minimize the loads on and deflection of the carriage, tracks, and support structure, special effort will be required to minimize the weight of the model and carriages.

The carriages, tracks, and support structure should be designed so that the deflection of the model center of gravity should not exceed 0.1 in. per 1000 lbs of loads in any direction. For the maximum thrust of the J-97 engine, this translates into a possible error in position of the nozzle center of only about 5 percent of the jet nozzle diameter.

Outdoor Static Test Stand

The dynamic rig should also be designed for use on the outdoor static test stand as depicted in figure 41. This will require that the hydraulic system that drives and controls the vertical motion will have to be portable or duplicated at the outdoor facility.

Alternate Concept

The alternate concept employing a "4-bar linkage" arrangement (fig. 42) was considered in the initial part of the present study. It had the advantage of avoiding the aerodynamic interference that may arise if the support structure behind the model in the recommended configuration becomes too large. However, it is more difficult to provide for yaw tests, some fore and aft movement of the model is associated with vertical motion causing a slight error in effective forward velocity and the supporting structure becomes excessively large, heavy, and difficult to install and remove from the tunnel when it is not being used.

Development

The problems to be solved in developing the proposed rig will include obtaining smooth and repeatable motion and positioning, minimizing the weight of the model and carriage to minimize loads on and deflections of the model, as well as minimizing drive power requirements resulting from the starting and stopping g's at the beginning and end of each run.

A two-step development process is recommended. The actual detail design and construction (step 2) should be preceded by a preliminary design and evaluation study to more clearly define the configuration. This preliminary design effort should include:

1) Preliminary design of representative models for test of the proposed rig. The design process should be carried far enough to determine the likely minimum weight (including the propulsion system and the internal balance) that can be attained without excessive cost while maintaining structural integrity. Three models are recommended:

   a) A model of the QSRA configuration. To provide wind tunnel data for comparison with the available flight data.

   b) A model of the YAV-8B configuration. To provide wind tunnel data for comparison with flight data.

   c) A J-97 powered nozzle/inlet rig for fundamental studies of flow fields and hot gas ingestion.

2) Preliminary design of two carriages. One for support of the specific models and one supporting the J-97 engines (fig. 37) for funamental studies. The designs should be carried far enough to determine the likely minimum weight while minimizing model deflection and extraneous motion.

3) Preliminary design of the vertical tracks and structure that support the carriage and model to insure sufficient stiffness and minimize unwanted motion of the model.

4) Choice of the hydraulic cylinder to drive the carriage and choice and design of the related power supply and control equipment.

5) Preliminary design of the umbilical chord that contains the instrumentation and control lines to the model and the fuel and control lines to the J-97 engines.

The output of this preliminary design effort should be a revised design concept and requirements and specifications for the final design and construction contract.

GROUND BOARD

The Need

It has been recognized for a long time that the correct ground effects on jet flap models cannot be determined in tests over fixed ground board. Turner (ref. 25) showed that the lift losses measured over a fixed ground board were much larger than those measured with a moving model and that the use of a moving-belt ground gave the same results as the moving model tests (fig. 13).

The use of a moving-belt ground board in the 40- by 80- and 80- by 120-foot test sections appears impractical on two counts. First the development, installation, and maintenance of a large enough belt system would be excessively complex, time consuming, and costly; and second, the exhaust temperatures of the jet engines used in wind tunnel models would be difficult to accommodate. The use of blowing boundary layer control on the ground board to replace the belt is suggested.

The Concept

The general arrangement of the proposed ground board is shown in figure 43. An inlet is provided at the leading edge of the board to remove the boundary layer on the tunnel floor and multiple blowing slots are provided to replace the energy lost in the boundary layer that builds up between slots on the board. Air is let in at the trailing edge of the board to fill the wake that would develop behind the raised ground board.

The boundary layer removal system at the leading edge of the board must replace the energy loss in the boundary layer on the tunnel floor and raise the static pressure from the test section pressure to atmospheric pressure. Preliminary analysis indicates that 12-200 hp, 140,000 cfm blowers will be required. Figure 44 presents the performance map of a commercially available blower that closely matches these requirements.

The volume of air flow required by the multi-slot BLC system on the surface of the ground board is considerably less than that involved at the leading edge but the pressure ratio required will be higher because the velocity from each slot will have to be two to four times the free stream velocity. Preliminary analysis indicates that 2-600 hp blowers will probably be required. A more complete discussion of the multi-slot BLC concept, rationale, and the development program required is presented in the following section.

No power will be needed to provide the flow required at the trailing edge of the ground board. The 80- by 120-foot test section operates at nearly atmospheric total pressure; therefore, the static pressure in the test section is below atmospheric and will draw air in to fill in the volume behind the ground board if a reasonably low loss flow path is provided.

The possibility of using blowing BLC on the ground board to substitute for the moving ground was investigated in reference 43. It was found that for jet flap configurations, a single blowing slot could be used to replace the moving ground if it were properly placed with respect to the pressure distribution induced on the ground by the model.

However, the results obtained with a lifting jet model were less encouraging. As shown in figure 45 there were no ground effects in region A (low jet velocities and high operating heights) and the single slot blowing system was adequate in region B. However, in region C (low heights and high jet velocities), the single blowing slot was not adequate. This is the region where strong ground vortex flows are encountered and where much of the hot gas ingestion research will be concentrated (fig. 26). If a blowing BLC ground board can be made to work it will have to have multiple and probably very closely spaced blowing slots.

Analysis of Requirements

In order to produce the correct aerodynamic effects on the ground vortex system and for hot gas ingestion research, it will be necessary to correctly reproduce the ground vortex flow field that is found in actual flight (and over a belt in wind tunnel tests, fig. 46). The moving ground (belt) has two effects:

1) It eliminates the boundary layer between the free stream and the ground board that would allow the wall jet from the model to penetrate further ahead than it would if it were opposed by the full free stream velocity.

2) The air at the belt surface must move with it. This causes a scrubbing action that reduces the momentum of the wall jet in the same way the wall jet from a moving aircraft is eroded by the ground surface.

Both of these effects act to reduce the forward penetration of the wall jet and move the ground vortex closer to the impingement point (fig. 46). A multiple slot BLC ground boad must reproduce both effects.

Momentum Replacement

In order to achieve an effective "zero boundary layer" situation ahead of the model the blowing slots must provide the momentum to replace the free stream momentum (friction drag loss). A uniform velocity distribution is not achieved as illustrated for a single slot case in fig. 47 (ref. 44) but if multiple slots are used the deficiencies and overages in velocity can be kept very close to the surface.

A rough estimate of the slot thickness (s) and mass flow (m) required can be made by the simplified analysis given below:

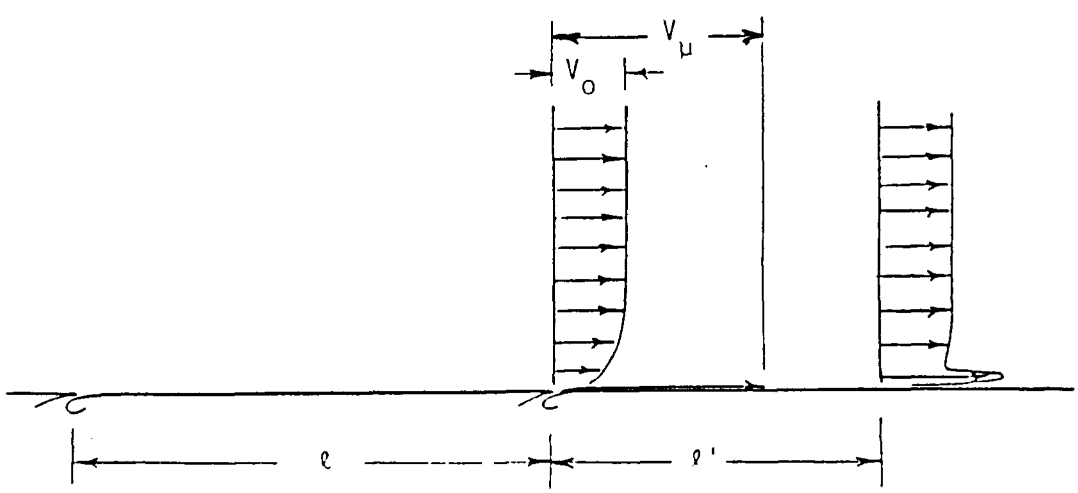

Figure 1.- Boundary Layer Replacement Requirements

The blowing momentum must replace the free stream momentum lost (friction drag, C_f) over the distance ℓ.

$$C_\mu = C_f$$

where C_f is the skin friction coefficient (from ref. 45 for example).
C_μ is the blowing momentum coefficient given by:

$$C_\mu = \frac{\rho s b V_\mu^2}{\frac{\rho}{2} V_o^2 b \ell}$$

and b is the span of the blowing slot.

Therefore, the thickness of the blowing slot required is,

$$s = \frac{\ell C_f}{2 \left(\frac{V_\mu}{V_o}\right)^2}$$

and the mass flow required per foot of blowing span is,

$$\frac{\dot{m}}{b} = \rho s V_\mu$$

These estimates are for a net momentum loss of zero at the blowing slot. There are additional losses downstream of the slot and if the average loss over the board is to be zero the blowing required will be somewhat greater. Figure 48 presents a comparison of estimates by the above expressions with the data from reference 44. In order to replace the momentum loss in the boundary layer at a distance of 200 slot thicknesses downstream of the slot the slot thickness and mass flow used were about twice those estimated by the above simplified analysis.

Single Slot Blowing for Ground Simulation

The slot thickness and mass flow required for the single slot blowing system for ground simulation proposed in reference 46 are compared in figure 49 with estimates by the above method for estimating the blowing required for momentum replacement. The order-of-magnitude difference in the results, and the dependence of the blowing required for ground simulation on jet pressure ratio, suggest that, for a single slot system, the blowing required to simulate the effect of the belt on the wall jet flowing forward from the model may be considerably different than that required for momentum replacement in the free stream boundary layer.

The conditions in the wall jet, at zero free stream velocity, with the belt running are illustrated at the top of figure 50. The air at the surface of the belt moves with the belt. This alters the boundary layer under the wall jet (between the wall jet and the ground) and reduces the peak velocity in the wall jet. These same effects will be felt by the wall jet between the impingement point and the ground vortex (where the free stream cannot have a direct effect).

The question is, what blowing configuration and rate will have the same effect on the wall jet as the moving ground? In order for the blowing BLC to have the same effect as the moving ground it must retard the flow in the boundary layer under the wall jet. This indicates that the sheet of air from the blowing slots (which simulates the layer of air moving with the moving ground) must be thin with respect to the boundary layer under the wall jet (fig. 51). This suggests that in order to keep this blowing sheet thin many closely spaced and thin blowing BLC slots will be needed.

The thickness of the wall jet in the vicinity of the impingement point is only about a quarter of the jet in the diameter and the thickness of the boundary layer under the wall jet is about 4 percent of the jet diameter. The jet sheet developed by the blowing BLC slots should probably be an order of magnitude thinner than the boundary layer, or only about .4 percent of the jet diameter (about .05 inches for a 1 foot diameter jet). Because the jet sheet grows in thickness with distance downstream from the slot, the slots themselves may have to be even thinner.

The development of multislot blowing BLC ground board will require several steps, including experimental verification, as outlined below.

Development Program

The development of a multislot blowing BLC ground board will require several steps including:

1) Analytical studies of the BLC slot design for:

   a) Control of the free stream boundary layer.

   b) Control of the wall jet development.

2) Experimental verification and development in the 7 by 10 foot tunnel including LDV surveys of the flow field around two models:

   a) A single circular jet model.

   b) A jet flap model.

3) Design studies to work out mechanical and structural design details and determine cost.

4) Rig tests of a mockup of part of the full scale board to insure adequate flow distribution.

Each of these development steps are discussed in more detail in the following paragraphs.

Analytical Studies. Analytical codes hav been developed that can predict the boundary layer development and interactions between boundary layers. And the work presented by Rizk and Childs (paper nos. 6 and 7 in ref. 1) at the workshop indicate that the interaction of the wall jet (at least a two dimensional wall jet representing the centerline of the wall jet flowing forward from the jet impingement point) and the counter flowing jet sheets from the multiple blowing slots can also be calculated.

The first step in the development of a multislot blowing BLC ground board should be to use these codes to analyse the slot spacing, slot thickness, pressure ratio and blowing rates required for both control of the free stream boundary layer and for control of the wall jet development. It is likely that the design suitable for control of the wall jet will be different than that needed for free stream boundary layer control. These same codes should also be used to investigate the sensitivity of the flows to the blowing rates and slot designs in an attempt to arrive at an acceptable compromise.

Design Studies. Steps 2 and 3 above can be undertaken (probably simultaneously) using the results of the above analytical studies. The structure of the blowing ground board assembly must span the 56 foot diameter opening for the floor turntable which will be removed when the dynamic rig and ground board are installed. The weight of the structure will be the primary design loads (because the balance chamber below the ground board is vented to test section static pressure) and the structure will have to be designed to minimize or compensate for the delection under these loads.

The 3 foot thickness of the ground board assembly suggested is based on removing most of the floor boundary layer that develops ahead of the ground board. The boundary layer on which the 3 foot thickness is based (fig. 52) was taken at the center of the floor turntable and indicates that most of the boundary velocity deficiency occurs below a height of about 36 inches (however the curve appears to asymptote a velocity ratio of about 0.95 rather than 1.0). A similar profile taken at the proposed leading edge of the ground board would show a slightly thinner boundary layer and permit reducing the depth of the structure. This would reduce the power required in the boundary layer removal blowers but would aggravate the structural problems.

The design of the blowers that supply the air to the BLC slots must await the completion of the above analytical studies which will determine the pressure ratio and mass flow required. The 2-600 HP blowers noted on figure 43 are based on very preliminary estimates and intended to give only a general idea of the requirements.

Other items such as the design of the slots themselves, their spacing, the slot adjusting system, honeycomb installation to insure uniform flow direction into the slots and the general air distribution system may need to be modified in light of the results of the analytical studies.

Experimental Verification. The multislot blowing BLC ground board design arrived at from the analytical studies will have to be verified experimentally. These tests can be made in the Ames 7- by 10-foot tunnel. The LDV system available in the 7- by 10-foot tunnel will be used to survey and establish the flow field around, under and ahead of the models; first with a moving belt ground installation and then with the blowing BLC board. The type of experimental setup envisioned is illustrated in figures 53 and 54.

A moving belt ground board will be built for the 7- by 10-foot tunnel and installed as close to the floor as the LDV system survey field will allow (fig. 53). The installation will include a system to remove the boundary layer ahead of the belt as is customary in such installations.

Tests over the belt ground board will be followed by similar tests over a multislot BLC board as shown in figure 54. This installation will use the same suction boundary layer removal system as used with the belt to insure that the BLC board starts with minimum boundary layer.

The verification and development tests should include both jet and jet flap configurations. The two models recommended are shown in figures 55 and 56. The jet flap model (fig. 55) recommended is the model used in the previous blowing slot ground board investigation (ref. 43) and will provide for direct comparisons with that investigation. The 2-inch diameter jet model shown in figure 56 will be constructed specifically for these investigations and will also be used to obtain some of the much needed fundamental data on the effects of pressure ratio and ground board boundary layer on the ground vortex as was indicated in the section on Research Needs above.

Both models will be supported from behind the ground board on a strut system that will provide for changing the height of the model in 2-inch increments as indicated in figures 53 and 54.

The multi-slot blowing BLC ground board will be arranged so that the effects of the spanwise extent of boundary layer control can be investigated in figure 54. In addition the centerline of the ground board will be fitted with pressure taps on 1/2-inch intervals to be used to correlate the ground vortex position determined by the LDV surveys with the position determined from pressure distributions in earlier investigations (refs. 9 and 24).

<u>The Test Program</u>. The verification test program is presented in Table I. The test program for the 2-inch jet model has a two-fold purpose. First to verify and develop the blowing BLC ground board concept, and second to provide fundamental data on the effects of jet pressure ratio, ground boundary layer and ground simulation technique on the location and strength of the ground vortex and related flow field.

The test matrix that can be convered by the 2-inch jet model is shown in figure 57. The actual free stream velocities required to achieve a desired effective velocity ratio V_e may be slightly different than those of figure 57 because of differences in the temperature and, therefore, the density of the jet and free stream air at the time the tests are run.

Experience has shown that belt speeds of more than about 100 feet per second are difficult to achieve. Therefore, the fundamental investigation of the effects of pressure ratio and ground board boundary layer on the ground vortex flow field that can be run over the belt will probably be limited to those combinations of pressure ratio and effective velocity ratio shown by the small circles on figure 57. This fundamental investigation will be extended to other combinations (those shown by the x's) after the blowing BLC system has been chosen.

The test program (Table I) can be discussed in several phases. The first group of tests (A, B, and C in Table I) will be static tests made in a large room (not in the test section so as to avoid flow recirculation problems). After the basic calibrations of the nozzle (Group A), surveys of the wall jet generated by the 2-inch nozzle (Group B) will be made over the belt to determine the effect of belt speed on the wall jet development with distance forward of the impingement point. These tests will cover a range of jet pressure ratios and heights.

The next group of tests will be made over the blowing BLC ground board and will cover the same range of pressure ratios and heights. BLC blowing rates bracketing the rate predicted by the analytical predictions of that required to match the belt effect will be investigated. The results of the Group B and C tests will be compared with the analytical predictions of the blowing rates needed to control the free stream boundary layer to determine the range of blowing rates that will be investigated in wind on tests in the 7- by 10-foot tunnel.

The first series of tests in the 7- by 10-foot tunnel will be over the belt and at belt speeds equal to the free stream velocity (Group D in Table I). This series of tests will provide the fundamental data needed on the effects of jet pressure ratio on the position and strength of the ground vortex for the case of zero boundary layer. The test series will cover the complete range of jet pressure ratios and effective velocity ratios possible with the belt (fig. 57) for jet deflections of 60, 90, and 120 degrees through a range of heights.

The second series over the belt (Group E) will investigate the sensitivity of the ground vortex flow field to ground boundary layer for a more limited range of operating conditions. The combination of the results of the series D and E tests should answer most of the open questions with regard to the ground vortex in STOL operations discussed in the Research Needs Section.

The flow fields defined by the LDV surveys in the Group D tests will also provide the baseline data for evaluating the effectiveness of the blowing BLC ground board which will be investigated in the Group G and H test series. Prior to these tests a few runs will be required with the model out to measure the build-up of the free stream boundary layer on the ground board and to determine the blowing required to eliminate it. These results, along with the blowing required to simulate the belt under static conditions (Group C tests), will help to determine the range of blowing to be used in the Group G and H tests to evaluate the effectiveness of the blowing BLC ground board. The abbreviated range of operating conditions is identified in figure 57 for belt evaluation purposes. The initial series of tests will be made at a height of one jet diameter and at one operating condition, but will cover a range of blowing rates and will include spans of blowing on the ground board of 2, 4, and 6 feet. A recommended blowing rate and span will be chosen on the basis of these tests. The adequacy of the chosen blowing BLC system will be evaluated for a wider range of operating conditions in the Group H test series and additional tests as needed will be run in the Group I series.

The final part of the program will be to install a mockup of the dynamic model support system planned for the 80- by 120-foot test section to evaluate the flow field around it and determine any interference at the model station.

A similar test program will be conducted with the jet flap model (fig. 55). The test range will be similar to that used in reference 43 and, as in reference 43, the principal data will be wing pressure distributions and flow field surveys (Table I).

Flow Distribution Rig Tests. The ground board concept proposed (fig. 43) assumes that the air flow for the blowing BLC slots will be provided by two specially developed blowers installed at either side of the ground board near the leading edge. The flow from these blowers will be ducted down each side of the board so that it can find its way into the passages feeding each individual blowing slot. Care will have to be taken to insure uniform and equal flow from all the slots.

Preliminary analysis indicates that the mass flow required will be small and the velocities in the passages will be very low (probably less than about 50 feet per second) which should ease the problem. Nevertheless, a mockup of one front corner of the ground board will probably be required to investigate the flow distribution problem and develop any turning vanes and/or flow metering devices to insure equal and uniform flow from all the slots.

Development Schedule. The development, construction, and installation of the blowing BLC ground board will require considerable time. An approximate schedule, as now envisioned, is presented in figure 58.

Moving Belt Ground Boards

It is recommended that the initial steps toward development of a blowing BLC ground board for the 80- by 120-foot tunnel be undertaken. However, it is recognized that there are difficult and conflicting requirements to be met. If at some point in the development of the blowing BLC ground board it appears such a ground board is impractical, a second look at the use of a moving belt ground board may be necessary.

The problems of building and operating a moving belt ground board increase with size. At present there is only one large operational belt in the United States. This belt is used in the Boeing Vertol wind tunnel near Philadelphia.

The Vertol belt is 18 feet wide, 26.5 feet long (between roller centers) and has an operational speed range of 8 to 170 feet per second. The personnel that operate it indicated that belts need to be replaced frequently. Typical comments were, "It takes a lot of tender care and feeding..." to keep it running and "it ate two and one half belts on the last job."

The Lockheed Georgia tunnel used a dual belt installation, one on each side of a centerline model support strut. However, they have been scrapped. Lockheed uses blowing for the automobile tests they frequently run.

The belt for the Langley 4- by 7-meter tunnel is inactive, but could be made operational. It is 14 feet wide and 20 feet long and was supposed to operate at speeds up to 330 feet per second; however, the material of the first belt failed at a speed of only 150 feet per second and the speed has subsequently been limited to 120 feet per second.

As far as is known no one has operated a hot jet over a belt. Such operation may be possible if the hot jet is only allowed to impinge on the belt while it is running and then only for a very brief period of time.

If consideration must be given to the use of the large belt in the 80- by 120-foot test section, the type of installation shown in figure 58 (three copies of the Vertol belt side-by-side) should be considered. The boundary layer removal system proposed for the blowing BLC ground board will still be needed as will the return flow at the downstream end of the board assembly. In addition an auxiliary boundary layer removal system will probably be needed just ahead of the belt unless the belt is made long enough to reach forward to the main boundary layer removal system.

If a moving belt ground board is to be considered, it is recommended that a workshop of personnel who have experience with the design and operation of moving belt ground boards be convened to discuss and present their experience and recommendations.

INITIAL RESEARCH INVESTIGATIONS

Five research investigations that should be undertaken early in the use of the ground effect equipment discussed above can be identified. These include tests of models of the QSRA and YAV-8B aircraft which provide unique opportunities for small-/full-scale comparisons and full scale surveys and measurements of the wall jet development (and associated suckdown), and surveys of the ground vortex flow field and hot gas ingestion using the J-97 powered rig.

Complete Model Programs

The well documented flight test data on the ground effects experienced by the QSRA Upper Surface Blowing configuration presented at the workshop by Stevens provide a unique opportunity for wind tunnel flight test correlation. Many model/flight data correlation problems can be traced to differences between the model configuration and configuration of the airplane that was eventually flown. Construction and test of a model of the QSRA configuration that accurately duplicates the geometry of the aircraft should eliminate these problems for this configuration and provide the data for a high quality wind tunnel/ flight correlation study. The flight test data should be reviewed to develop a test program and run schedule that will obtain the necessary wind tunnel data.

Similarly, the YAV-8B aircraft is in flight test status at Ames and provides a similar opportunity for wind tunnel/flight comparison on a jet V/STOL configuration. The flight test personnel and the wind tunnel personnel should get together and develop coordinated flight test and wind tunnel test programs to provide the data needed. Test programs for both the 80- by 120-foot test section and the outdoor static test stand should be developed.

Fundamental Investigations

In addition to tests of specific models, the investigation of some of the fundamental flow fields associated with operation in ground proximity should be undertaken using the J-97 rig. The first of these (Table II) should be an investigation on the outdoor static test stand of the effects of jet turbulence on the wall jet generated by a single jet nozzle, at fixed height, and on the associated suckdown on a circular blocking plate (fig. 60).

These investigations should be followed by an investigation in the 80- by 120-foot test section of the development of the ground vortex generated by a single jet (Table III). These tests should include measurements to define the distribution of both velocity and temperature in the flow field, their rate of change, and the rate of change of the entire flow field with rate of climb and descent. This investigation should be followed by and correlated with a third investigation (Table IV)--an investigation of the hot gas ingestion for various inlet locations.

The basic apparatus for these investigations is presented in figure 37. Two J-97 engines will be mounted in the second carriage of the dynamic support system. Only the lower engine will be needed for the first and second investigations to provide the hot gas to the nozzle. The top engine will be added for the last investigation to power the inlet. An auxiliary nozzle and two butterfly valves will be needed in the supply line to the research nozzle so that the engine can be started and brought up to the desired operating condition before the flow is directed at the ground board. At time zero the butterfly valves will be actuated to redirect the flow from the auxiliary nozzle to the research nozzle and the take-off or landing maneuver that is to be studied will be started.

The development of the flow field will be documented by four sets of measurements. High speed photographs (fig. 61) of the developing hot gas cloud (defined by smoke or steam injected into the nozzle) will be taken from several angles. Simultaneously, pressures on the ground board along the centerline of the tunnel will be recorded by high speed pressure transducers.

The velocity distribution within the flow field can be measured using the large scale Laser Velocimeter System developed for the 40- by 80- and 80- by 120-foot test sections (ref. 47). A separate rake of high response thermocouples will be required to measure the temperature distribution. These rakes will probably have to be bidirectional as depicted in figure 62 because a significant part of the flow in the wall jet is flowing forward, in the opposite direction to the free stream flow.

In order to survey the entire flow field, several duplicate runs will be required for each simulated operation (for each descent rate, for example). In order to minimize the number of runs, the constant height runs should be completed first and analyzed to try to predict the most important stations at which the measurements should be made during the climb and landing descent simulations.

Tests should be made for both vertical jets (V/STOL aircraft operations) and with the jet directed 30 degrees or more forward of the vertical to simulate thrust reverser operation.

The hot gas ingestion investigation should be made for the four inlet locations shown in figure 63. The operations simulated and the operating conditions used in the jet flow field investigation discussed above should be duplicated so that the actual ingestion experienced can be correlated with the temperature distribution obtained from the flow field investigation. In addition some runs should be made at reduced inlet flow to determine the sensitivity of the ingestion to the inlet flow rate. This information will be useful in evaluating the need for full inlet flow simulation in propulsion system simulation.

SUMMARY OF RECOMMENDATIONS

This study and the workshop that accompanied it has led to the following recommendations:

Equipment for the 80- by 120-Foot Test Section and the associated Outdoor Static Test Stand

1) A program to develop a multiple-slot blowing BLC ground board (as an alternative to a moving belt ground board) for the 80- by 120-foot test section should be undertaken.

2) The model support system should include the capability to produce rapid vertical motion so that the effects of rate of climb and descent can be studied.

3) Models of specific configurations should be powered with ejector based engine simulators with burners added to provide hot exhaust flows. For fundamental research investigations such as flow field studies, remotely mounted engines such as the J-97 should be used.

Blowing BLC Ground Board Development

4) The development of the multi-slot blowing BLC ground board should start with analytical studies of the interaction of the BLC flow with the wall jet flow from the model to determine the blowing requirements.

5) An experimental program will be required to develop and verify the design of the ground board. This program will include survey of the flow fields generated by a 2-inch nozzle and a small jet flap model tested over a small moving belt ground board to provide a base for comparison with surveys over a multiple slot ground board for verification of the design.

Research Investigations

6) Five research investigations should be planned as the initial ground effect studies in the 80- by 120-foot tunnel and the outdoor static test stand. They are:

   a) Tests of a model of the QSRA USB jet flap airplane for correlation with flight test results.

b) Tests of a model of the YAV-8B V/STOL airplane for correlation with flight test results.

c) Measurements of the effects of jet turbulence on the wall jet and associated suckdown using the J-97 powered rig.

d) Surveys of the development of the ground vortex flow field from a J-97 engine during simulated take-off and landing.

e) Related surveys of the hot gas ingestiuon for selected inlet locations.

7) Increased emphasis should be placed on the development of analytical codes to predict the effect of the ground on the flow fields around the configuration and the resulting effects on the aerodynamic characteristics.

8) Other areas of ground effect research that should be studied include:

a) Single jet suckdown in hover.- The effects of jet turbulence on the development of the wall jet and, in turn, on the suckdown will be studied in the program recommended above. These tests need to be extended to investigate other jet characteristics such as exit distribution and temperature. Also the effects of the size of the room in which tests are made should be investigated.

b) Multiple jet fountain effects and additional suckdown.- The flow field between the jets and the fountain and its effect on the induced pressure distribution and net suckdown need to be studied. Also the effects of body contour and flow control devices need more systematic study.

c) Ground vortex flow field and effects.- The effects of jet pressure ratio and of the boundary layer on the ground board will be investigated in the development program for the multi-slot blowing BLC ground board and in the large scale (J-97 powered) tests in the 80- by 120-foot test section. These tests should be extended to include studies of the effects of jet characteristics such as turbulence, exit flow distribution, etc.

d) Downwash at the tail.- The ground effect studies of the QSRA and YAV-8B configurations should include investigations of the effects of ground proximity on the downwash.

e) Hot gas ingestion.- Future programs in the 80- by 120-foot test section using the J-97 powered rig should include dual nozzles and the effects of body and other surfaces and shapes betweer the nozzles and inlets on the hot gas ingestion.

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TABLE I.- DEVELOPMENT OF BLOWING BLC GROUND BOARD

7- by 10-Foot Tunnel Test Program
(2-Inch Jet Model)

Static Tests Before Tunnel Entry:

A - Calibration of Nozzle, $h = \infty$

- P_n/P_o = 1.05, 1.2, 2, 4
- Velocity Profile

B - Effect of Belt Speed on Wall Jet

• Belt Speed = 0, 20, 49, 83 fps	6 surveys
• P_n/P_o = 1.05, 1.2, 2, 4	
• h/d = 1, 4, 12	× 3
	= 18 surveys

C - Effect of Ground Board Blowing

• P_n/P_o = 1.05, 1.2, 2, 4	4 surveys
• BLC blowing range	× 5
• h/d = 1, 4, 12	× 3
	= 60 surveys

Compare B and C to determine BLC system required to match belt for static conditions; compare with analytical estimates and with BLC required to eliminate free stream boundary laser.

Tests in 7- × 10-foot Tunnel - Over Belt:

D - LDV Surveys of Wall Jet and Ground Vortex Flow Fields (Baseline and Fundamental Studies)

• V_b/V_o = 1.0	
• V_e = 0.03 to 0.2	
• P_n/P_o = 1.05, 1.2, 1.4, 2	11 surveys
• h/d = 1, 2, 4, 8, 12, 20	× 6
• δ = 60, 90, 120	× 3
	= 198 surveys

E - Sensitivity of Flow Field to Boundary Layer

• Boundary Layer Profile - Jet Off	
• Survey Flow Field - Jet On	
- δ = 90	
- V_e = 0.03 to 0.2	5 surveys
- P_nP_o = 1.05, 1.2, 2	
- h/d = 1, 4, 12	× 3
• V_b/V_o = 0, 0.3, 0.6, 1.0	× 3
	= 45 surveys

Table I.- Continued.

(2-Inch Jet Model, Concluded)

Tests Over the BLC Ground Board:

F - Determine BLC Required to Replace Momentum Loss in Boundary Layer (Clean Tunnel), Compare with Analytical Estimates and with B and C Comparison Above.

G - Determine BLC Configuration Required to Match Belt

• Initial Tests @ h/d - 1.0, V_e = 0.1, δ = 90, and P_n/P_o = 1.2	
• Cu range	5 surveys
• Slot Span = 2, 4, 6 ft.	× 3
	= 15 surveys

H - Check Tests with Chosen BLC Configuration and Criteria For Setting Blowing Rate

• V_e = 0.03 to 0.2	5 surveys
• P_n/P_o = 1.05, 1.2, 2	
• h/d = 1, 4, 12	× 3
• δ = 60, 90, 120	× 3
	= 45 surveys

I - Additional Tests as Required

J - Install Mock-up of Dynamic Rig and Check for Interference

• V_e = 0.03 to 0.2	5 surveys
• P_n/P_o = 1.05, 1.2, 3	
• h/d = 1, 4, 12	× 3
	= 15 surveys

Table I.- Concluded.

(Jet-Flap Model)

Tests in 7- × 10-foot Tunnel - Over Belt:

K - LDV Surveys of Ground Vortex and Flow Under Model and Pressure Distributions on Wing

• Cu = 0.3, 0.7, 1.0, 2.0, 3.0 wing	5 surveys
• h = 3, 4, 5, 10, 20 inches	× 5
• V_b/V_o = 0, 1.0	× 2
	= 50 surveys

L - Determine Floor BLC Required to Match Belt

• Cu = 1.0, 3.0 wing	2 surveys
• h = 3, 5	× 2
• Slot Span = 2, 4, 6 ft	× 3
• Cu = Range floor	× 5
	= 60 surveys

M - Check Tests with Chosen BLC Configuration and Criteria for Setting Blowing Rate

• Cu = 0.3, 0.7, 1.0, 2.0, 3.0 wing	5 surveys
• h = 3, 4, 5, 10, 20	× 5
	= 25 surveys

TABLE II.- EFFECTS OF TURBULENCE ON WALL JETS AND SUCKDOWN

Tests on the Outdoor Static Test Stand

Configuration

- Single vertical nozzle
- Three circular planforms, D/d = 3, 6, 9
- Nozzle inserts to produce three levels of turbulence

Types of Measurements

- Suckdown force on planforms
- Pressure distributions
  - Four radial rows of orifices on planform
  - Four radial rows of orifices on ground board
  - High response static pressures at impingement point and selected radial stations on ground board
- Wall jet surveys, at five radial stations
  - Vertical rake of total and static probes
  - Turbulence surveys through wall jet
- Temperature distributions, at same stations as wall jet surveys

Operating Conditions, at constant height

- P_n/p = 1.2, 2, and maximum for J-97
- h/d = 1, 2, 3, 5, 9
- Turbulence: minimum, intermediate, maximum

Table III.- DEFINITION OF GROUND VORTEX FLOW FIELD AND HOT GAS CLOUD

Test Program In 80- × 120-foot Tunnel

Configuration

- Single nozzle, no inlet

Types of Measurements

- Flow visualization, high speed photos as cloud (smoke or steam) develops
- Pressure distribution on ground board center line, fast response pressure gages
- Flow velocity and angle, two rakes (one forward facing for free stream and one aft facing for wall jet) of fast response pitot and angle heads supported from overhead; five survey stations
- Temperature distributions, fast response thermocouples on above rakes.

Operating Conditions

- V_e = 0.03, 0.05, 0.1, 0.15, 0.2
- P_n/P_a = 1.2, 2, 4
- h/d = 1, 4, 12 (for fixed height tests)
- δ = 90, 120

Operations Simulated

- Fixed heights, determine rate of build-up of flow field. Close auxiliary nozzle at time zero and measure time history of flow field development until steady state is reached. Compare steady state with small scale steady state data
- Climb, climb accelerations = 0.02, 0.05, 0.1, 0.2 g's. Close trap door and start climb acceleration at time zero and measure time history of flow field development.
- Descent, sink speed = 3, 6, 12, 20 fps. Measure time history of flow field development

TABLE IV.- HOT GAS INGESTION STUDIES

Test Program in 80- × 120-foot Tunnel

Configuration

- Four inlet locations, single nozzle

Instrumentation

- Fast response thermocouples across inlet face

Operation Conditions

- Same as for flow field definition studies, additional runs at partial inlet flow to determine sensitivity at 0, 10, 20, 40, 60, and 100% flow.

Operations Simulated

- Same as for flow field definition studies

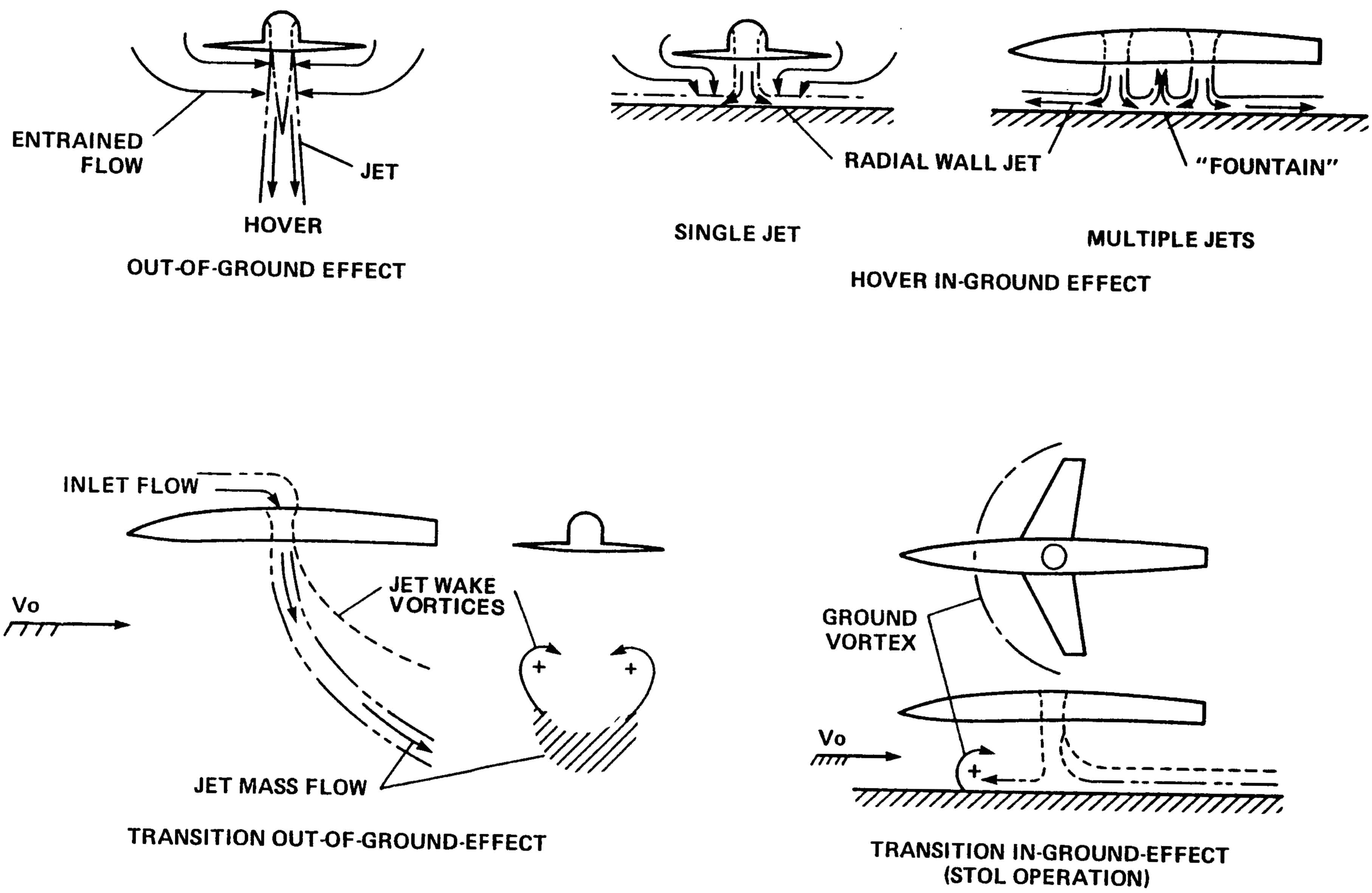


Figure 2.- Basic Flow Field.

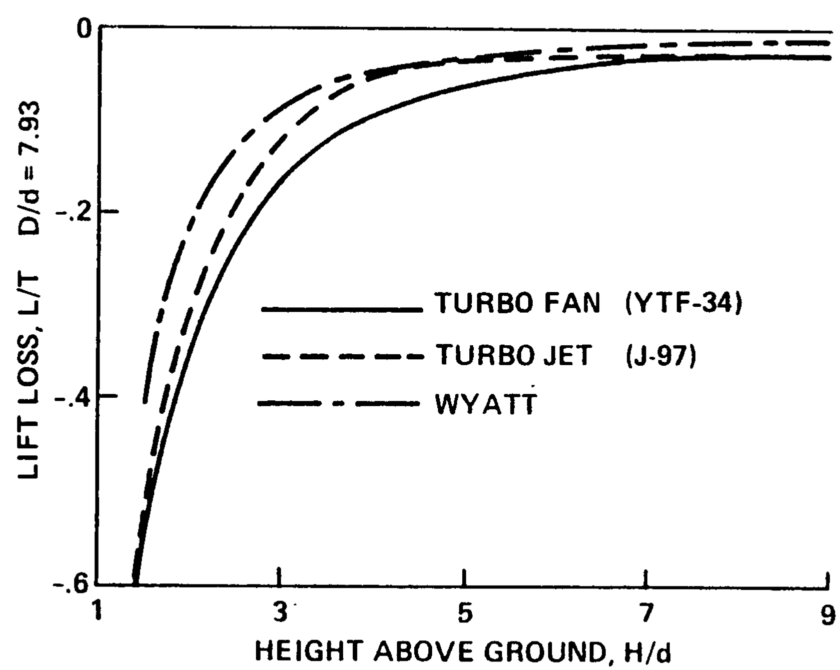


Figure 3.- Recent large scale results from NASA Ames Research Center. (Ref. 8)

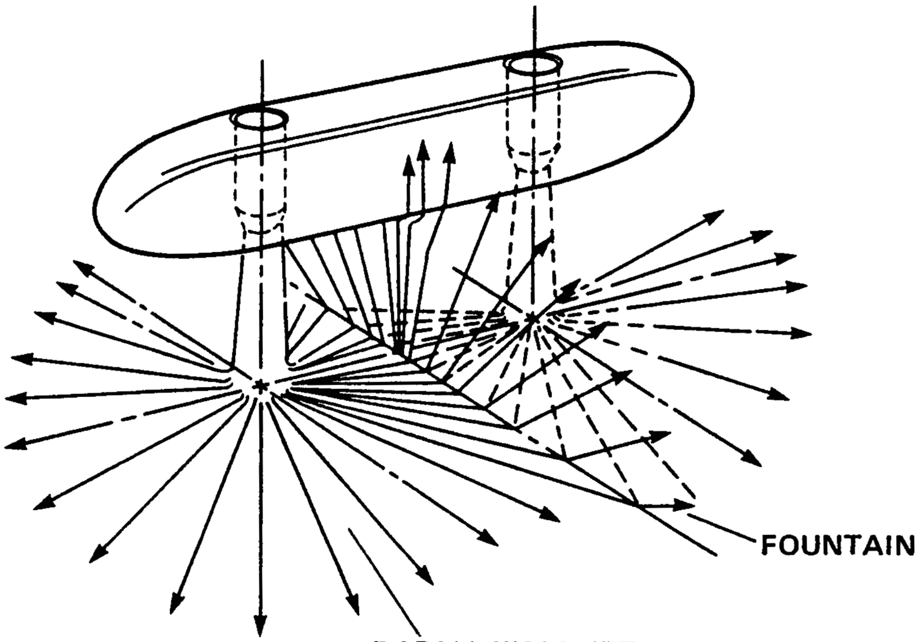


Figure 4.- Fountain flow generated between a pair of jets.

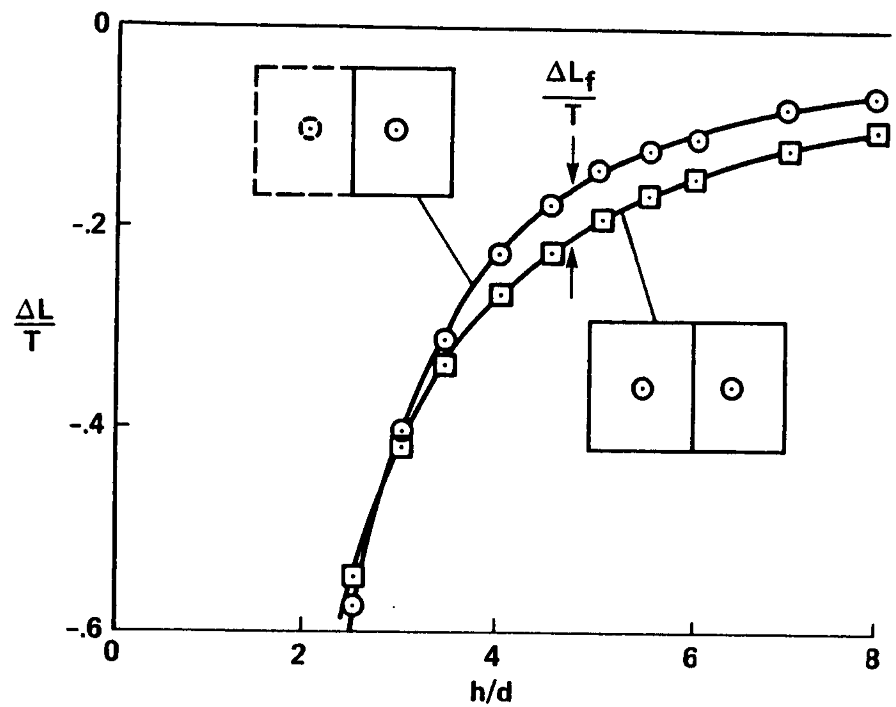


Figure 5.- Comparison of suckdown for single and twin jet configurations. (Ref. 11)

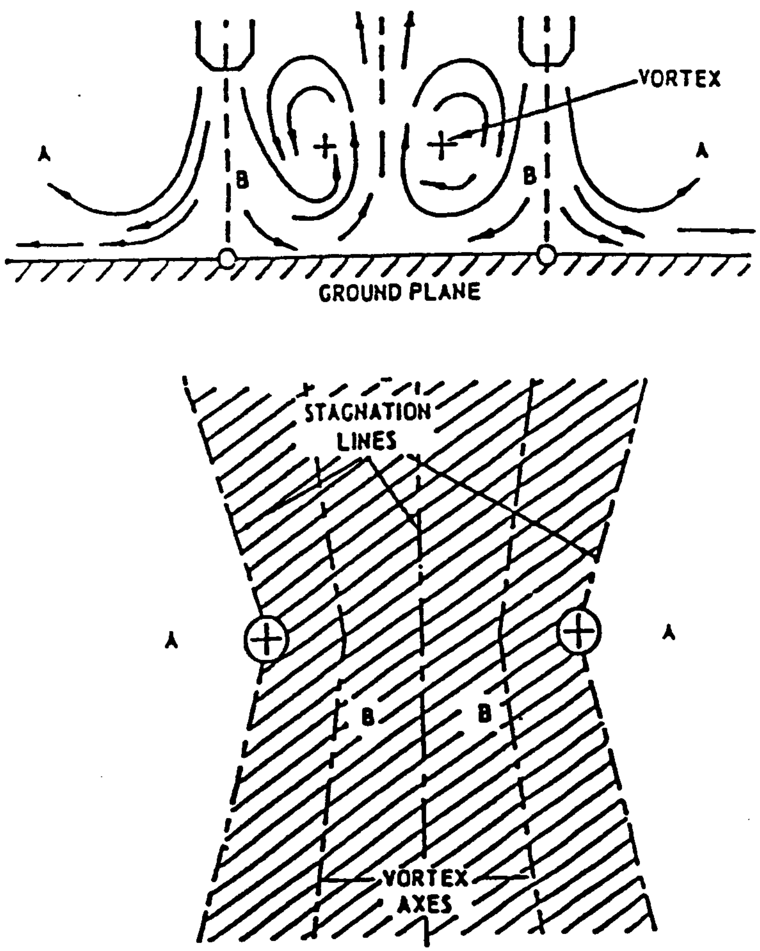


Figure 6.- Flow field between two jets hovering in ground effect. (Ref. 11)

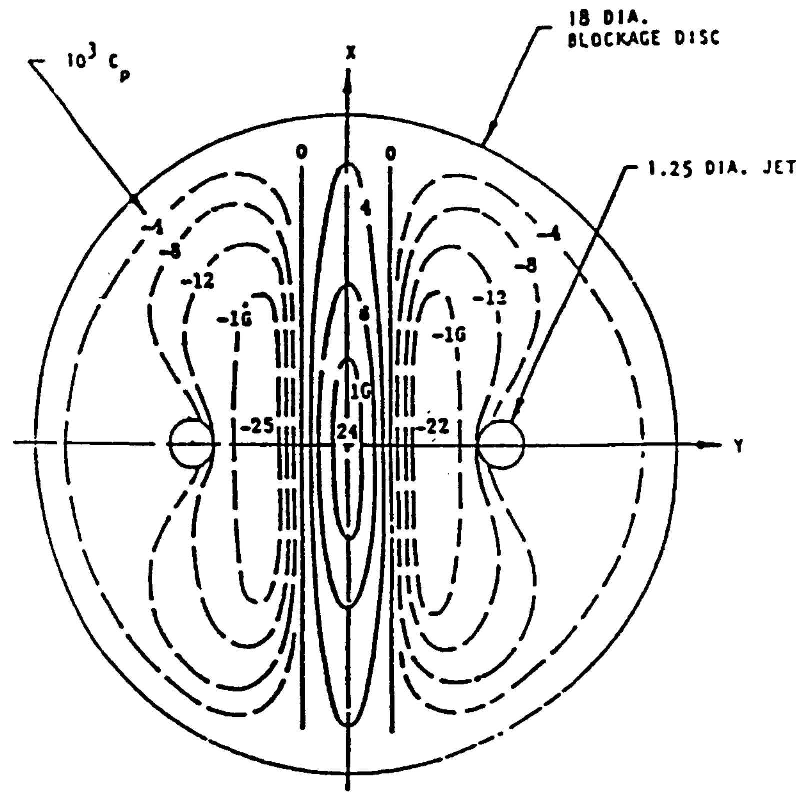


Figure 7.- Pressure distribution due to fountain flow from two jets in ground effect. (Ref. 11)

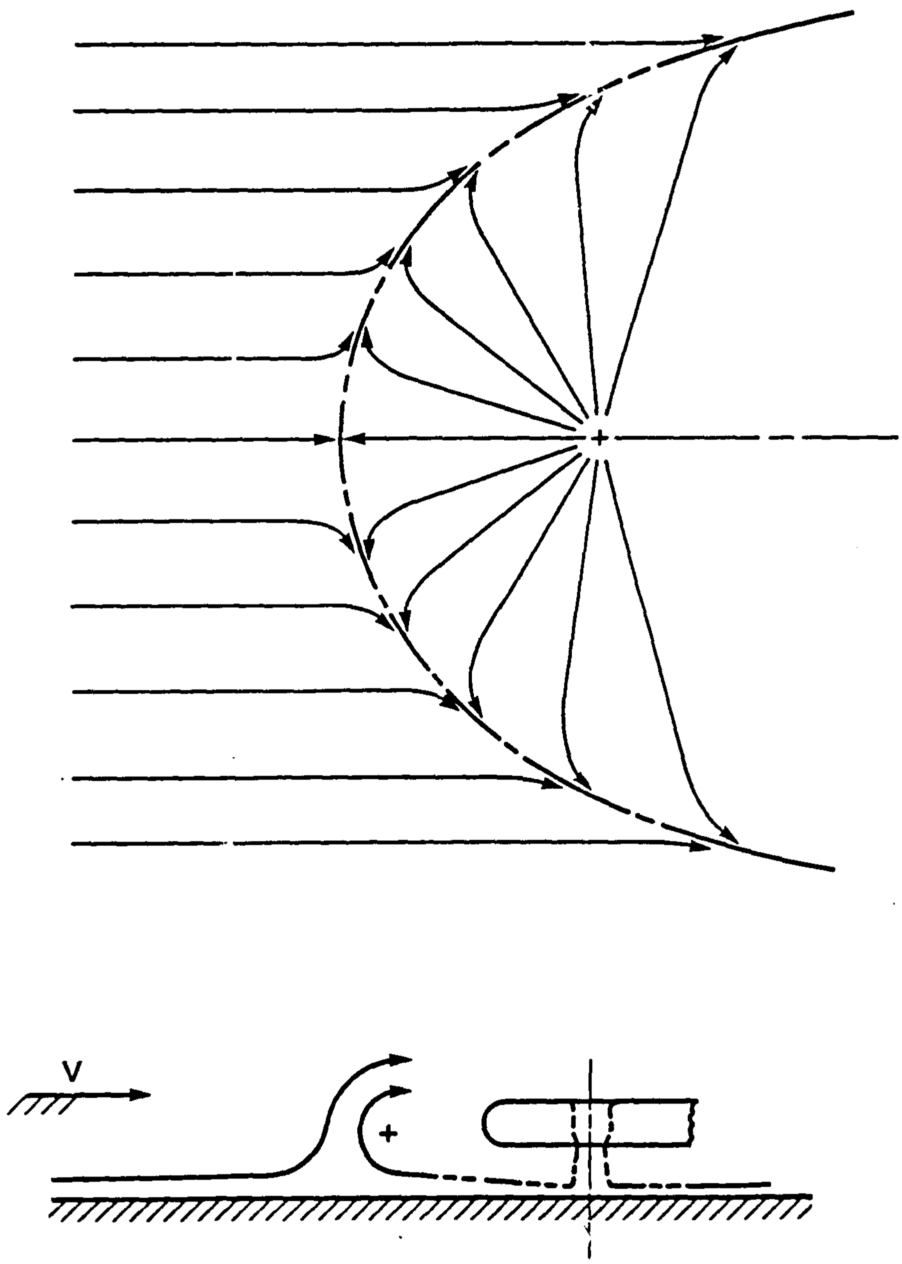


Figure 8.- Formation of ground vortex.

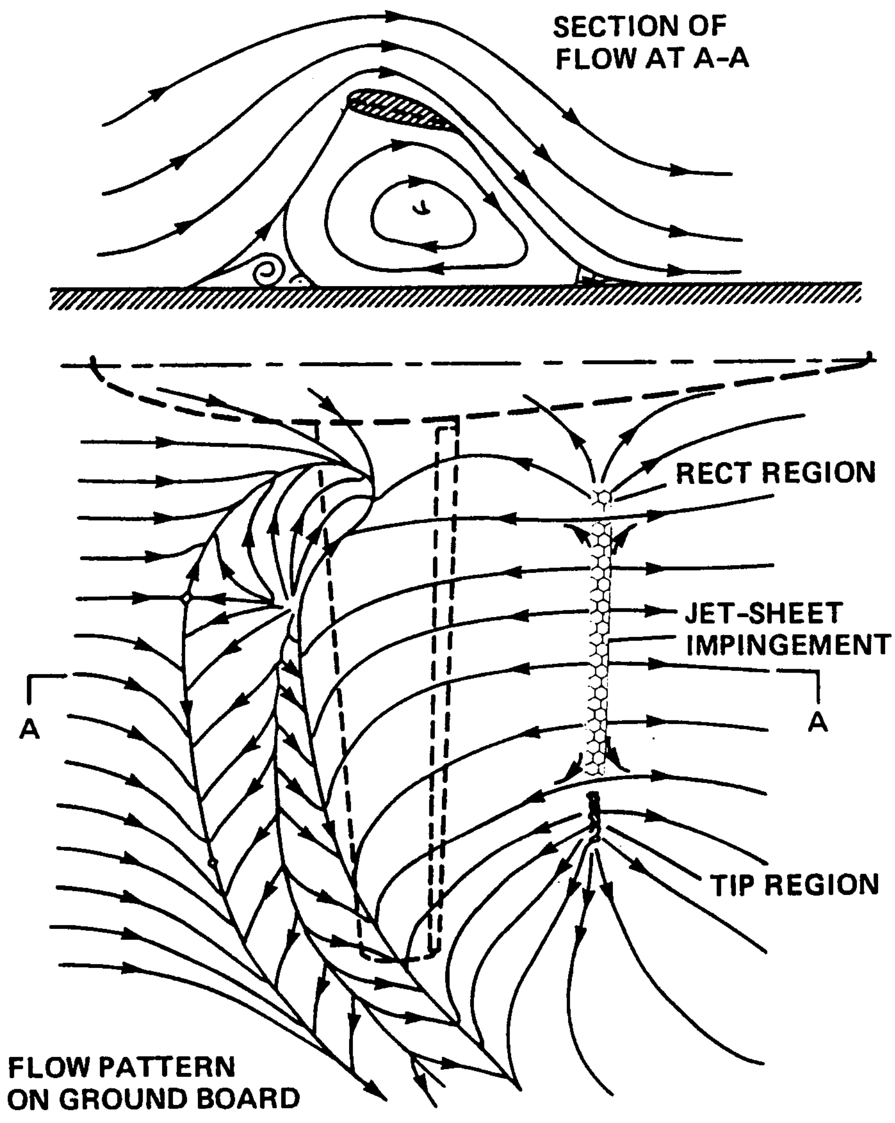


Figure 9.- Flow field under jet flap model with jet impingement on ground. (Ref. 19)
$\alpha = 15°$, $C_\mu = 2.1$, $H/\bar{c} = 1.5$, $\delta \sim 50°$

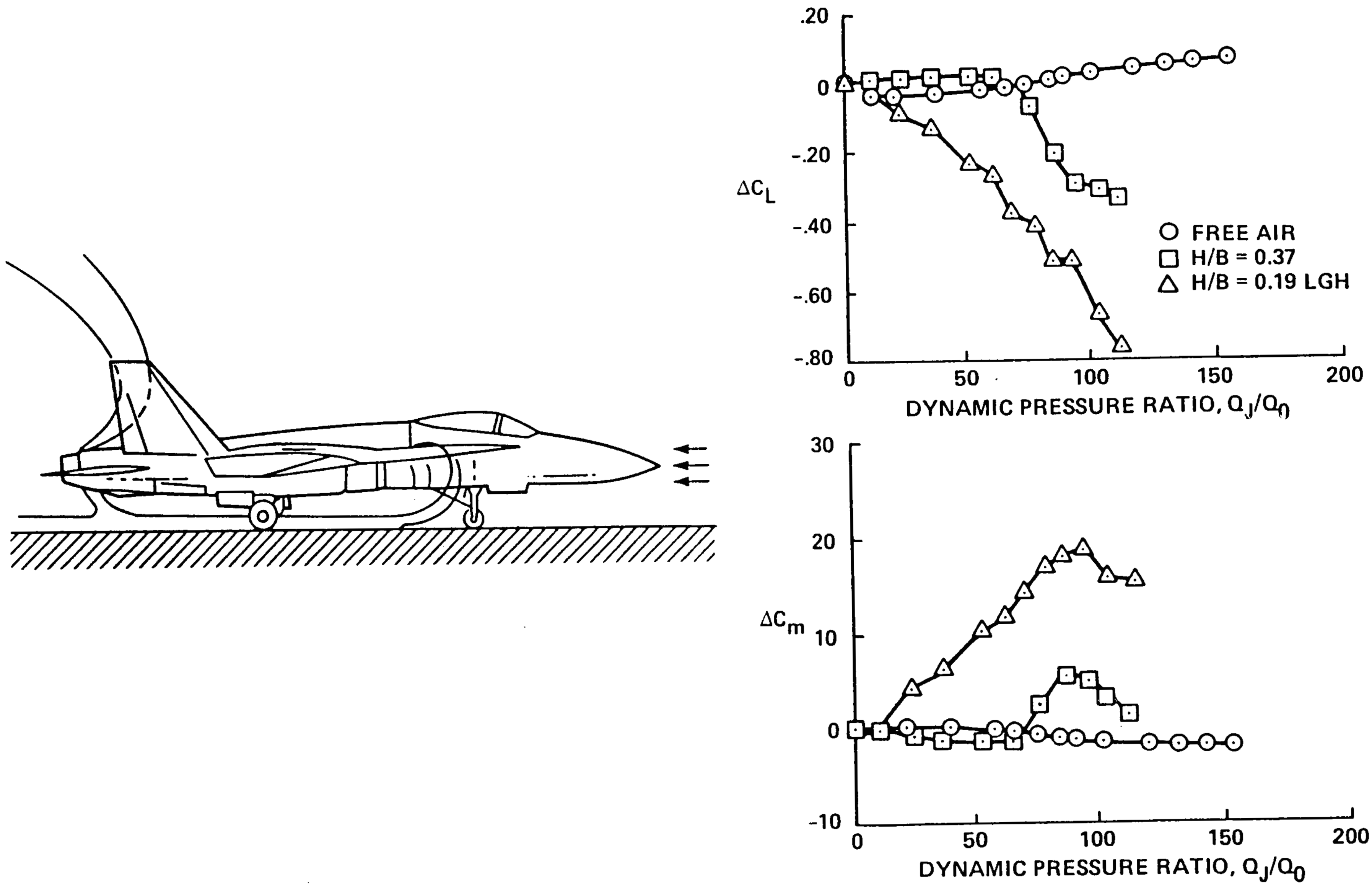


Figure 10.- Lift and moment induced by thrust reverser generated wall jet and ground vortex. (Ref. 20)

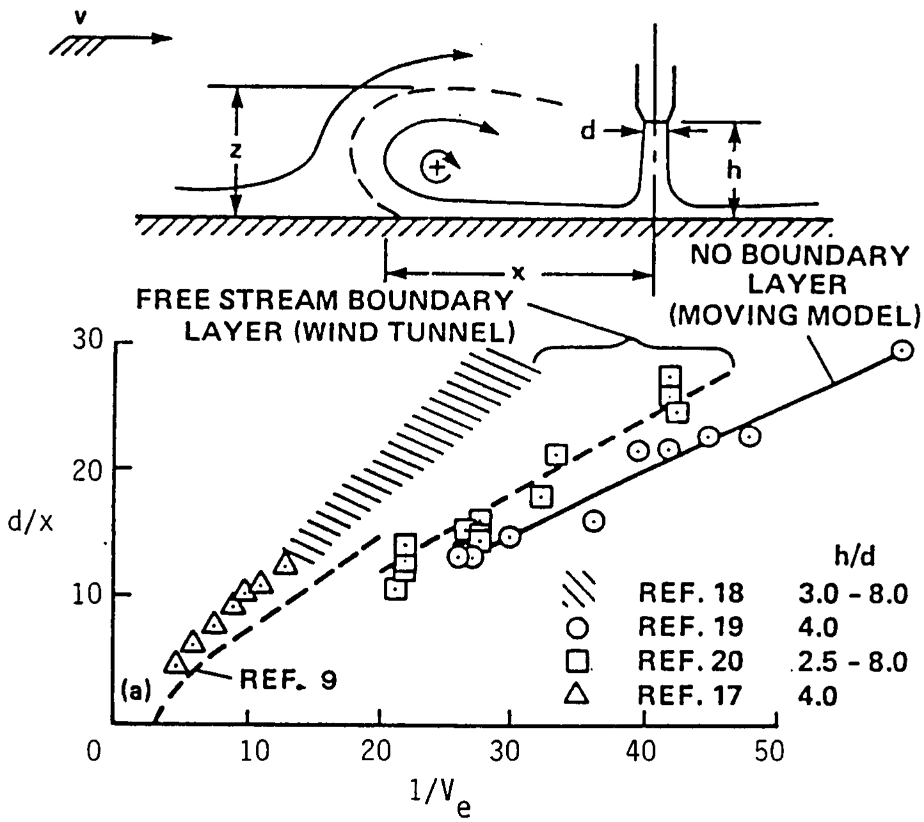


Figure 11.- Effect of ground boundary layer on forward extent of ground vortex.

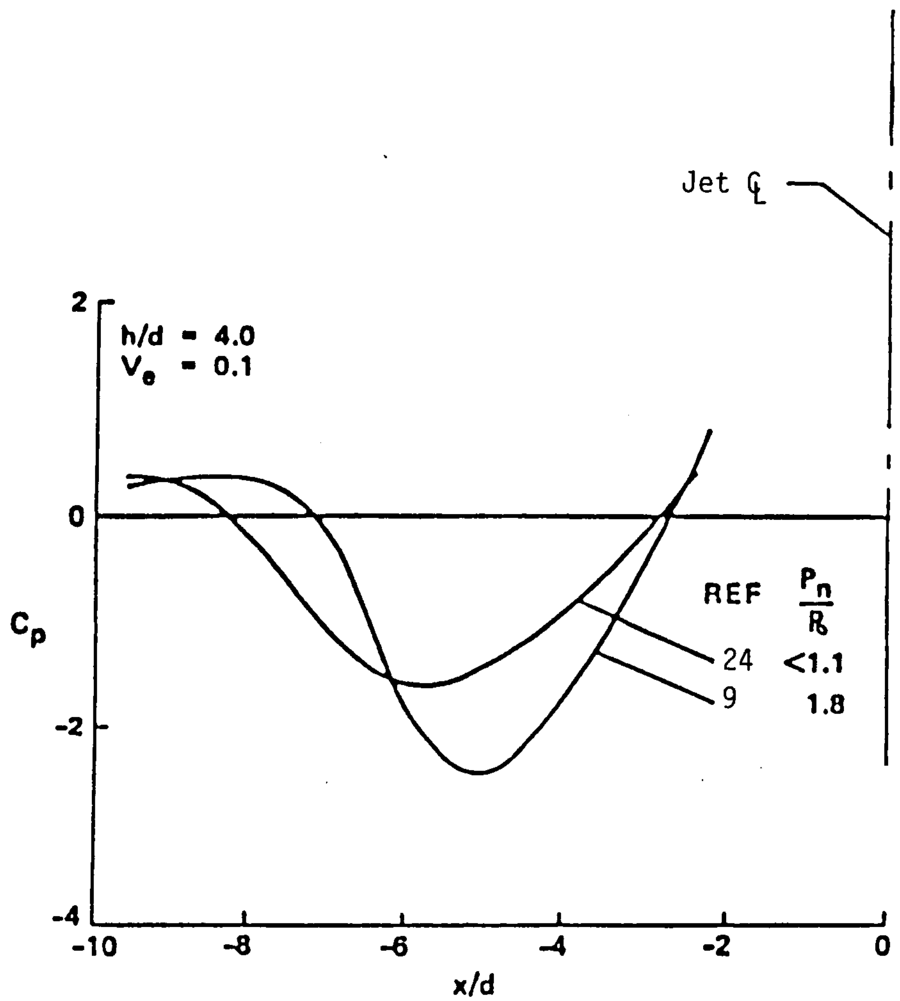


Figure 12.- Pressure distribution induced on ground by ground vortex.

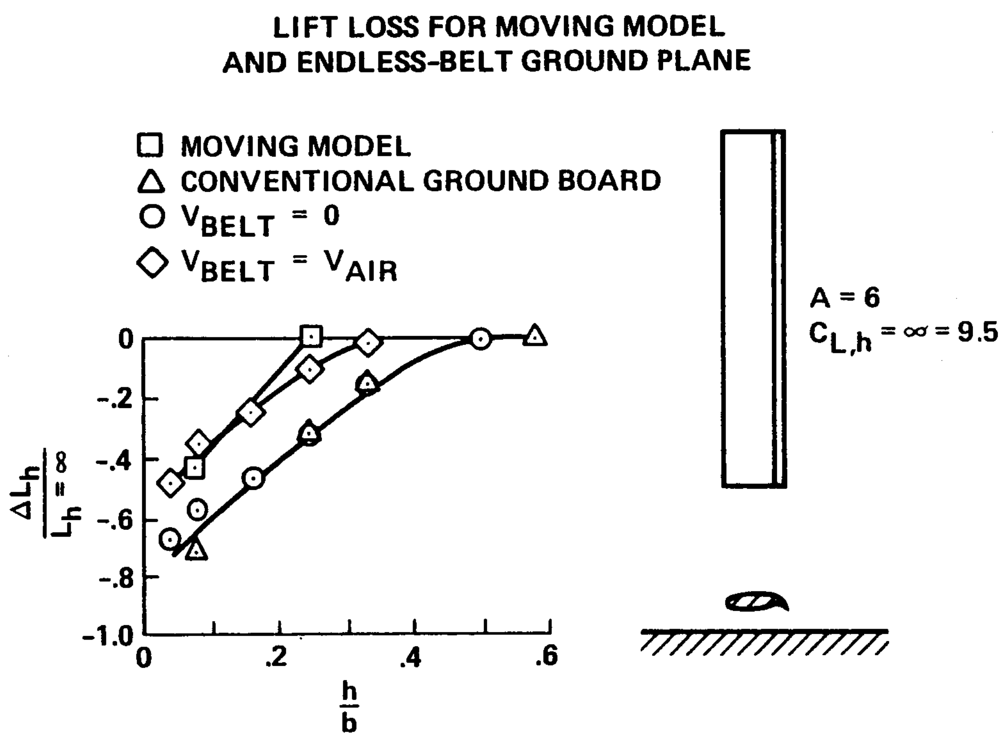


Figure 13.- Lift loss for jet flap model as determined by several testing techniques. (Ref. 25)

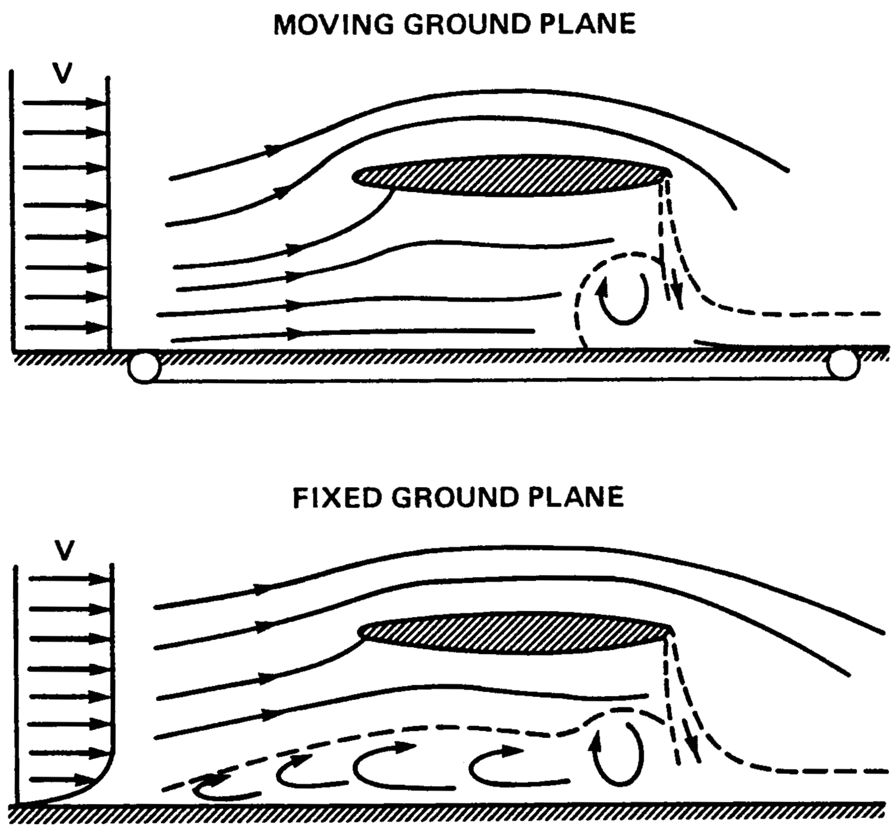


Figure 14.- Jet induced flow over fixed and moving ground planes. (Ref. 26)

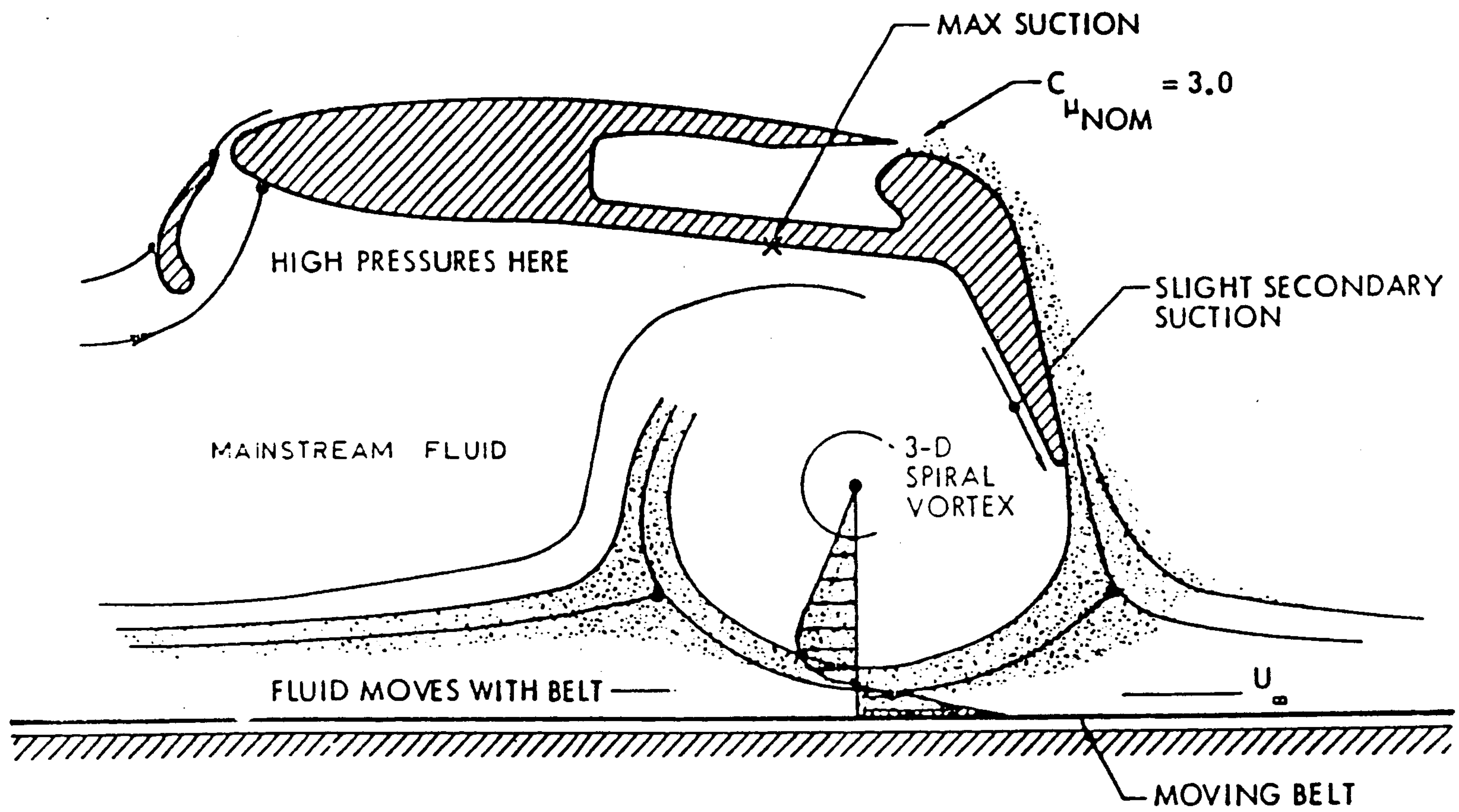


Figure 15.- Formation of trapped, underwing vortex at low altitude and high jet momentum. (Ref. 27)

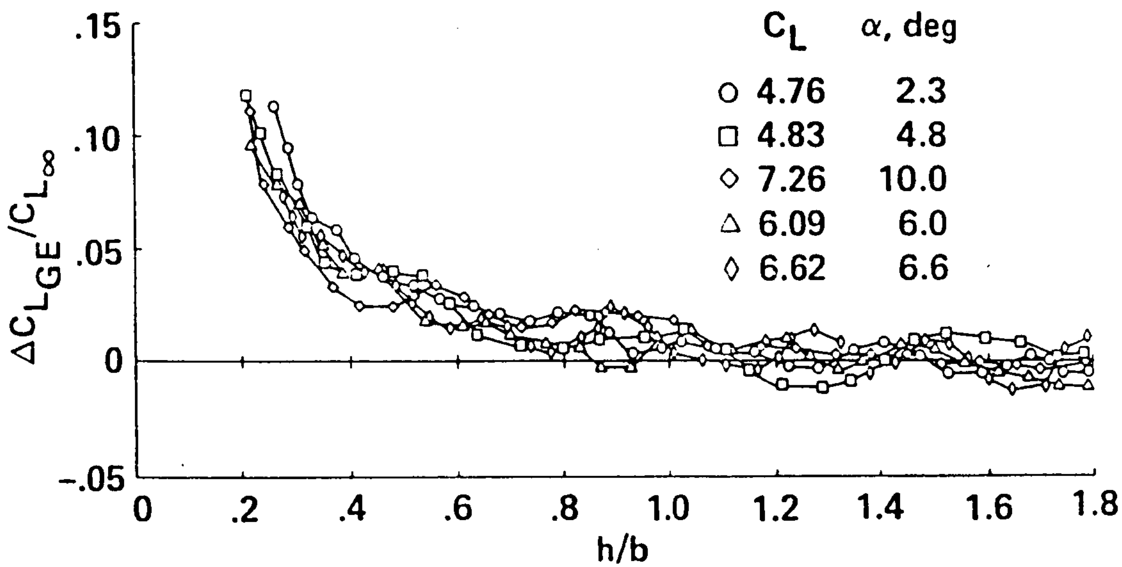


Figure 16.- Lift gain due to ground proximity experienced on the QSRA aircraft flight tests.

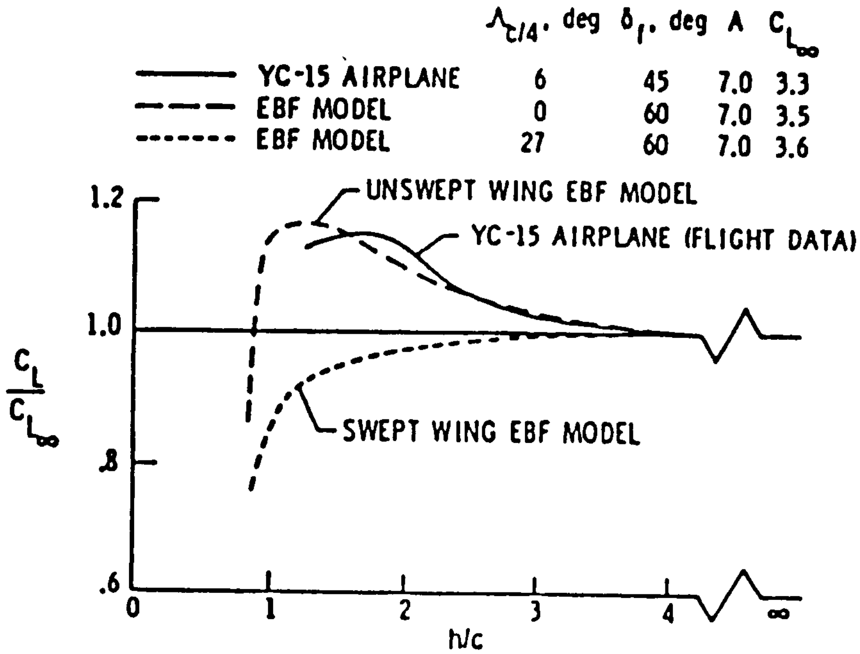


Figure 17.- Comparison of EBF flight and wind-tunnel data.

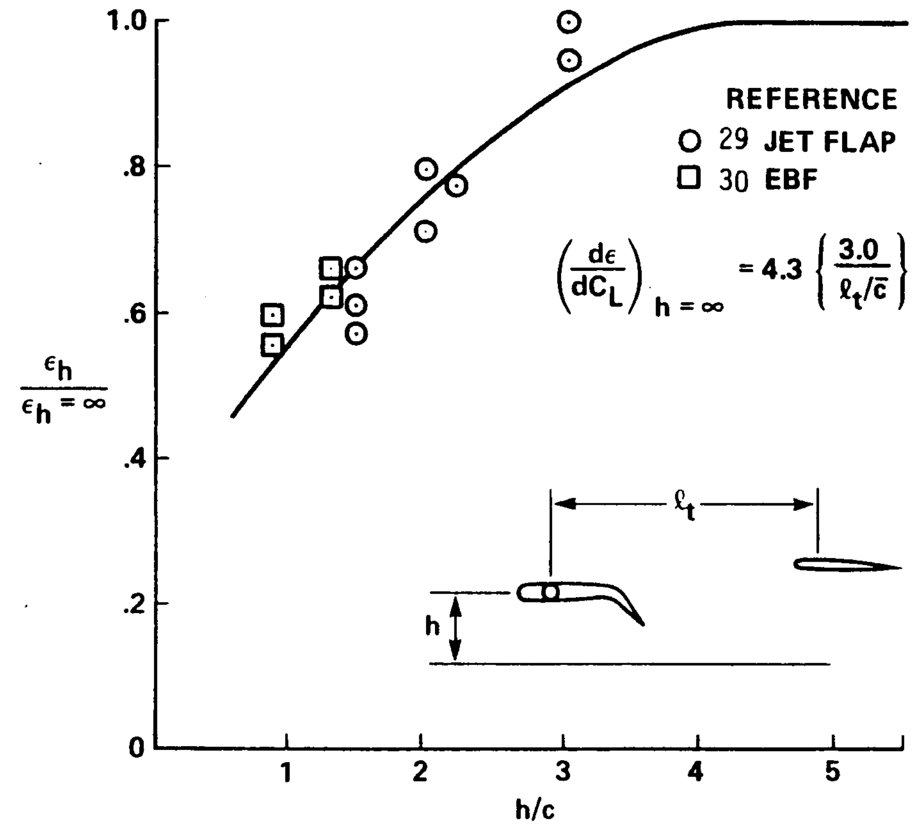
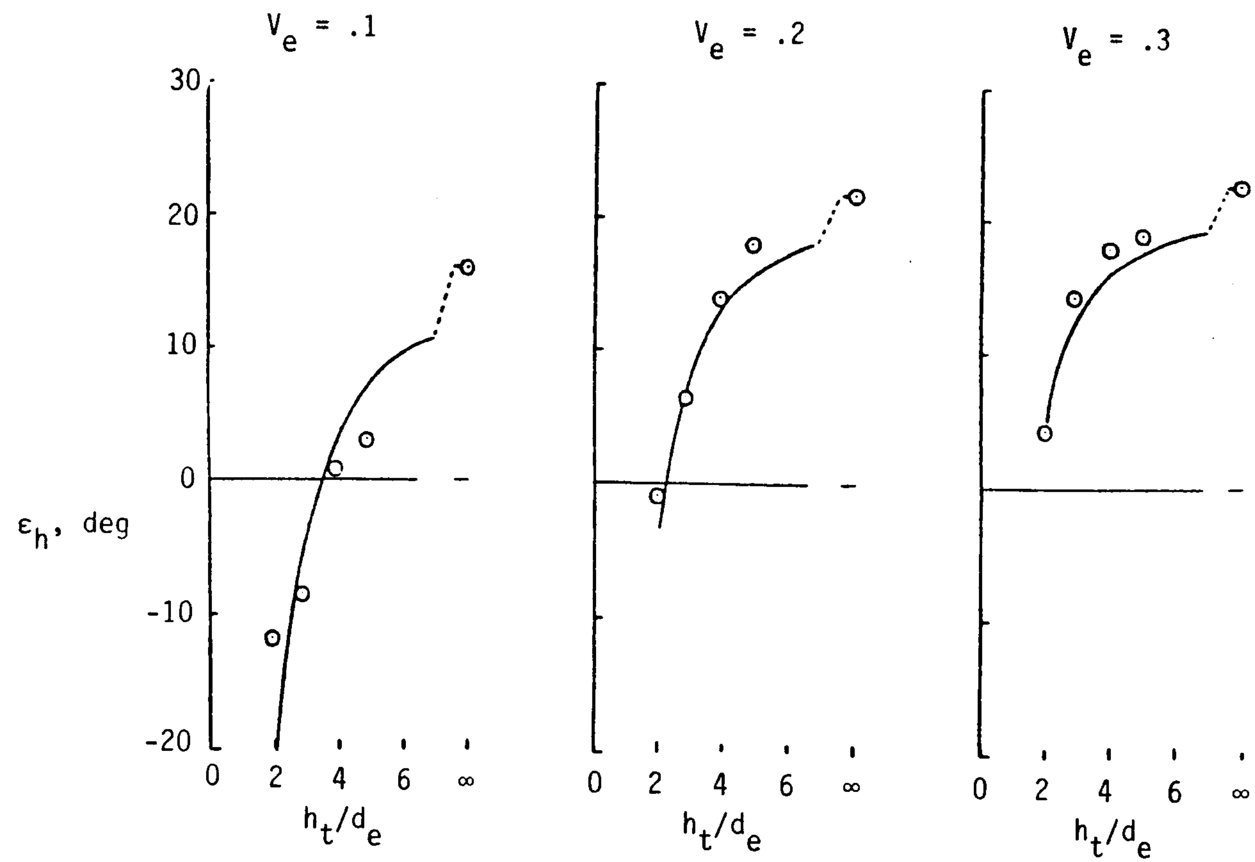


Figure 18.- Effect of ground proximity on downwash. (Ref. 9)



δ_j = 65°, α = 9°

Figure 19.- Effect of ground on downwash behind Harrier-type configuration. (Ref. 31)

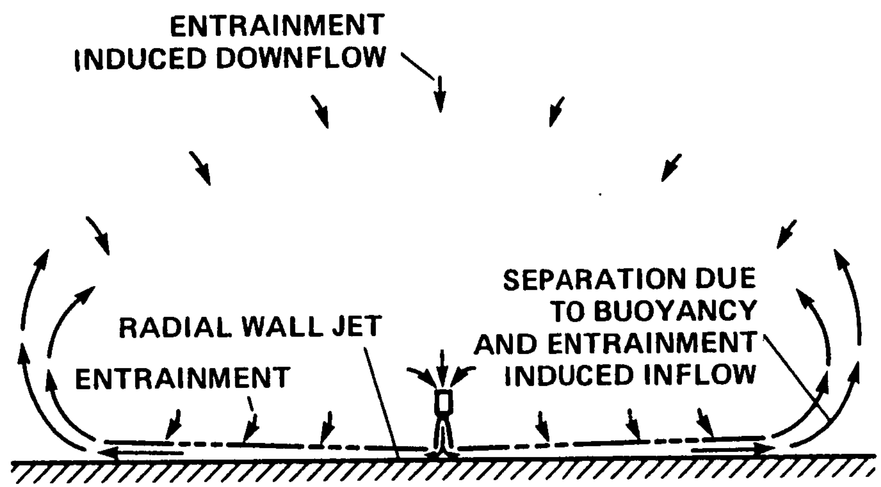


Figure 20.- Far field ingestion.

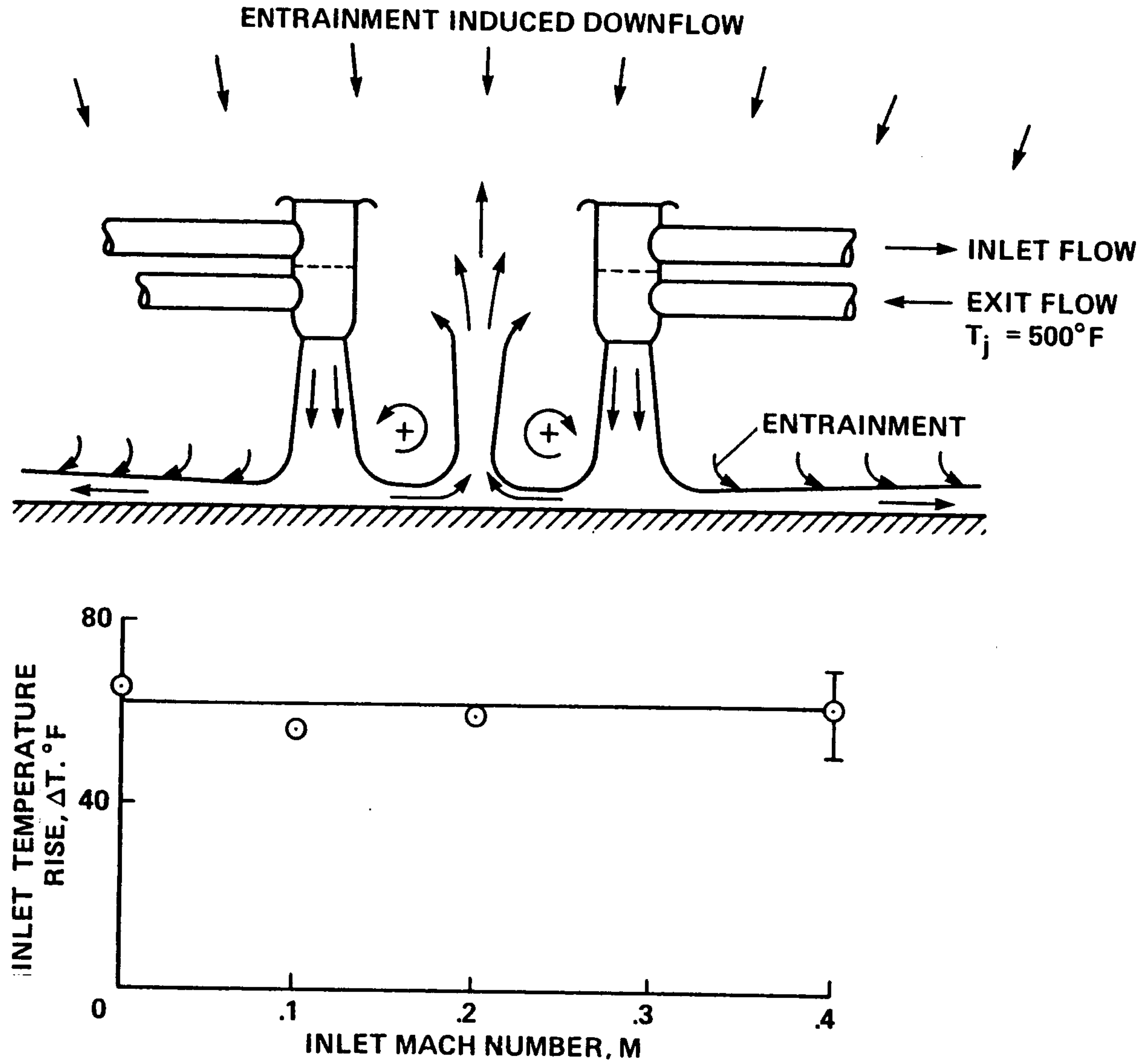


Figure 21.- Inlet temperature rise with two isolated jets. (Ref. 11)

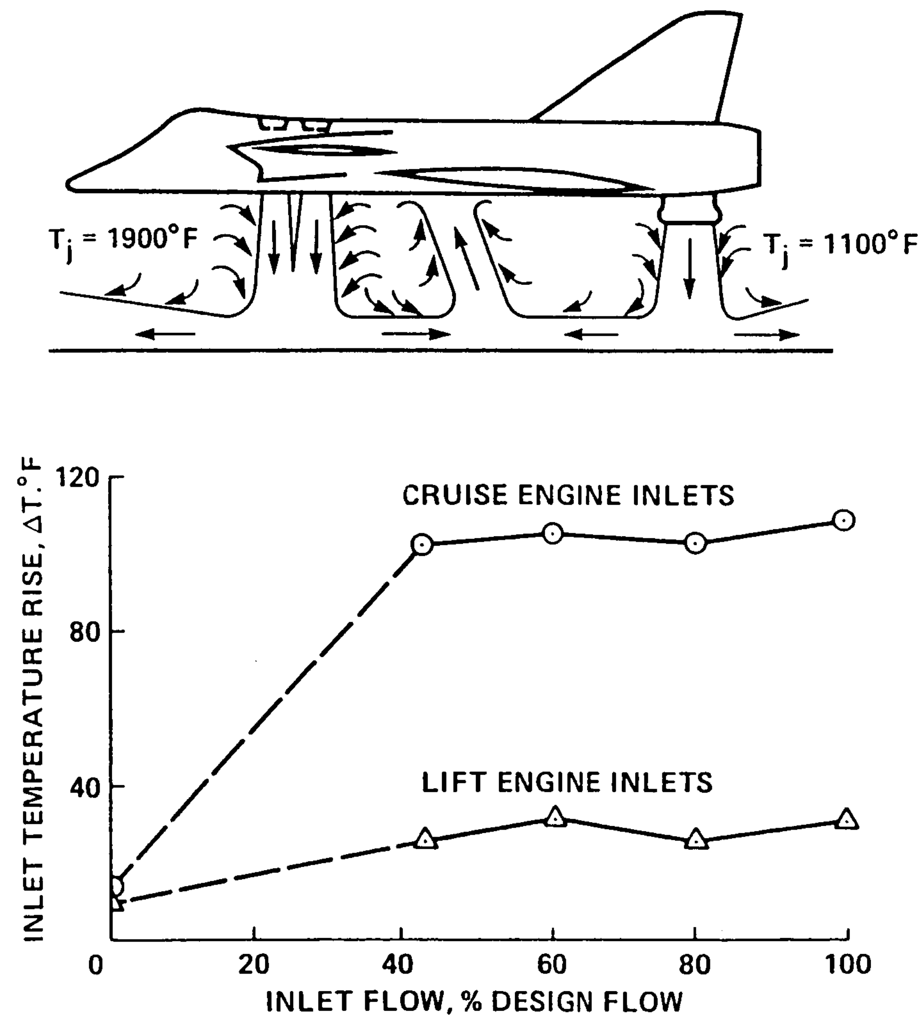


Figure 22.- Inlet temperature rise with fountain impingment. (Ref. 23)

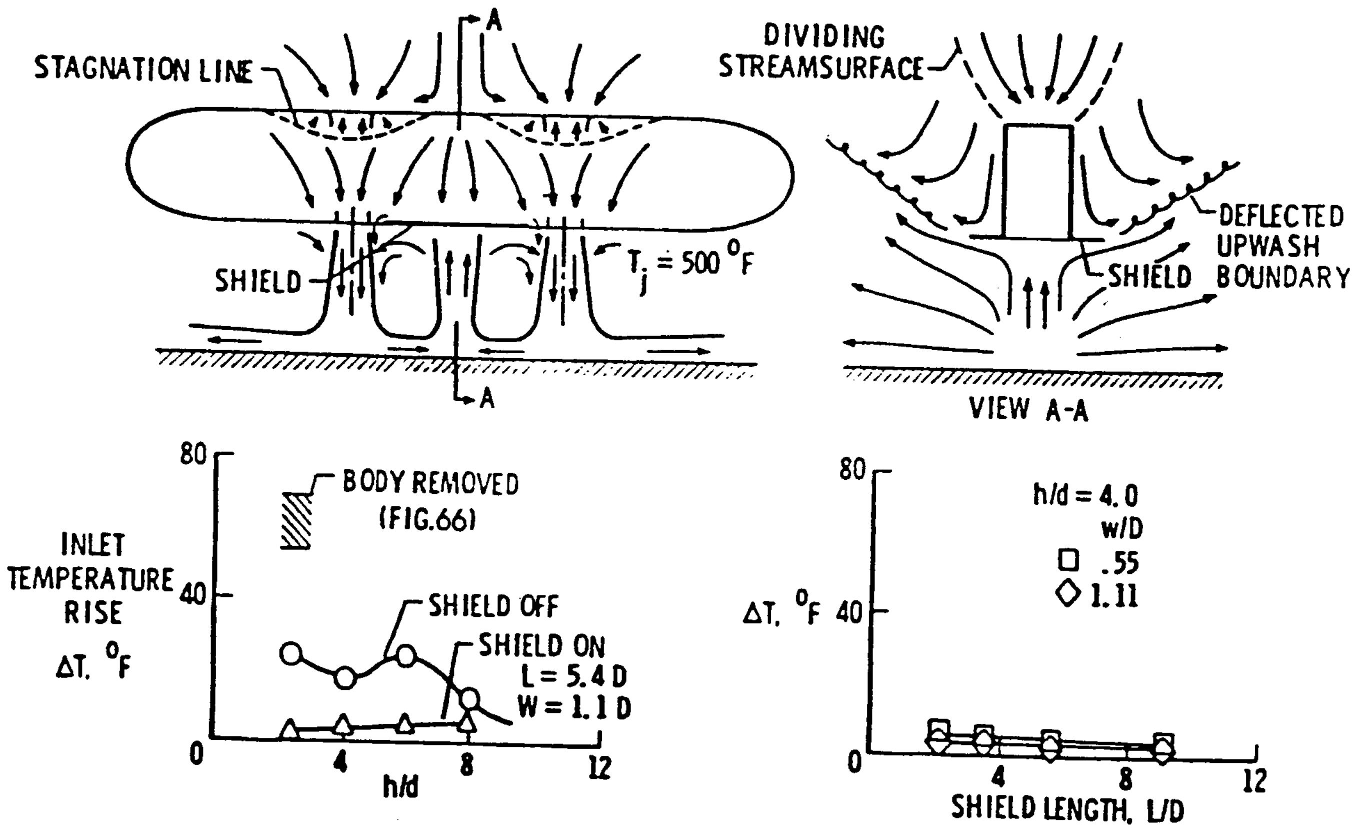
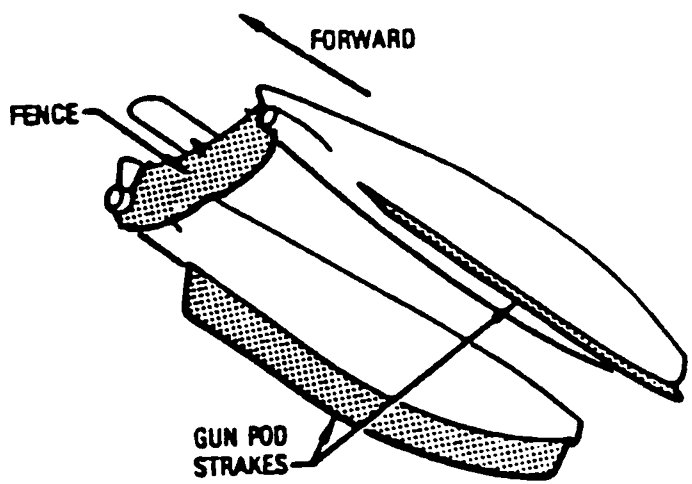


Figure 23.- Effect of exit plane shields. (Ref. 32)



LIDS Installation on AV-8B model

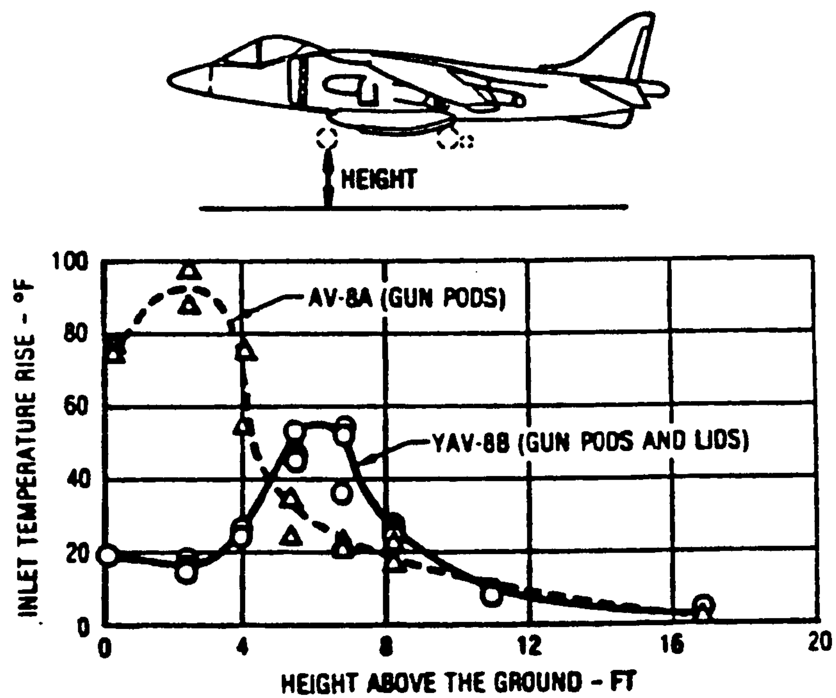


Figure 24.- Effect of flow control devices. (Ref. 33)

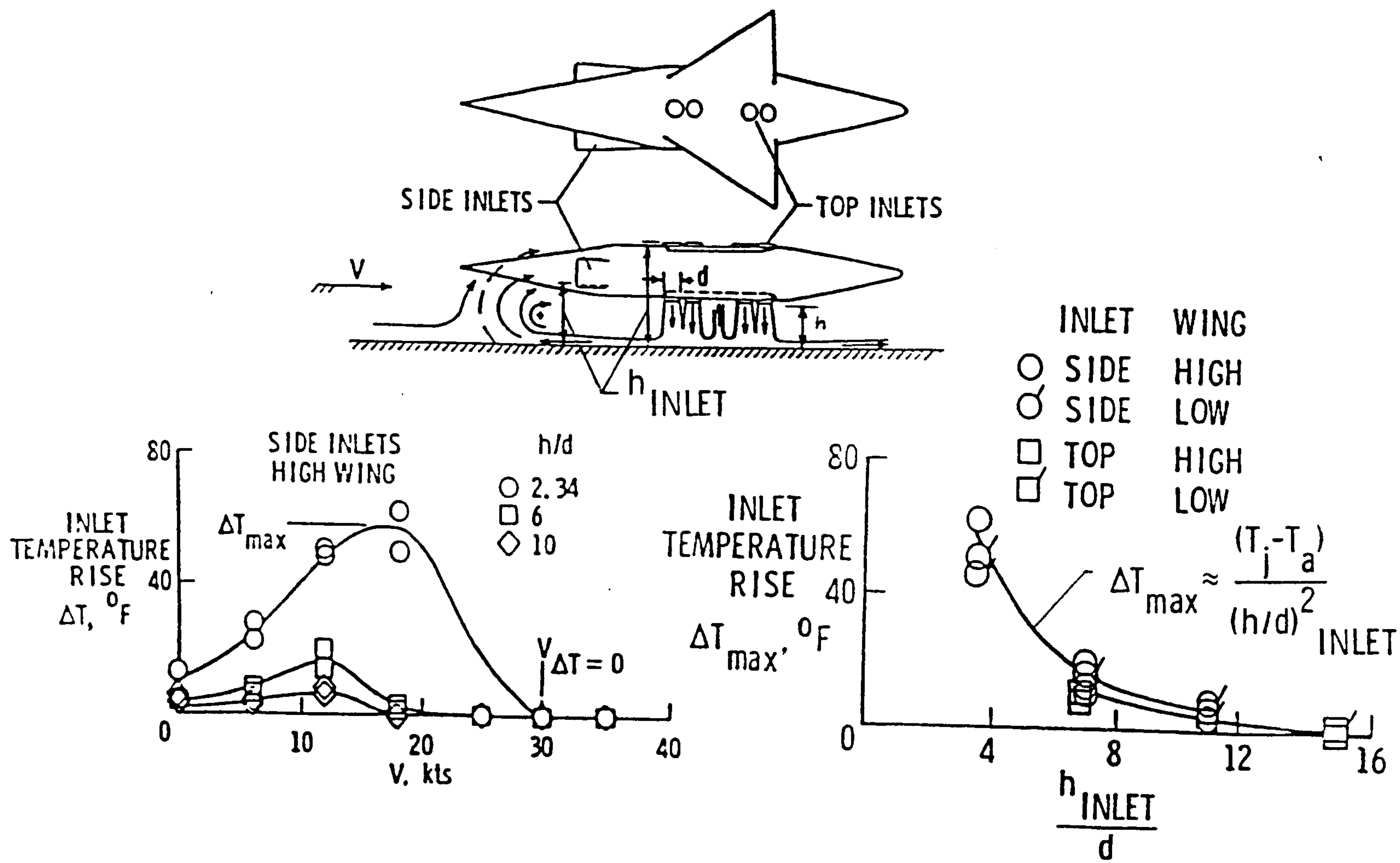


Figure 25.- Effect of height and velocity; four-jet in-line configuration. (Ref. 34)

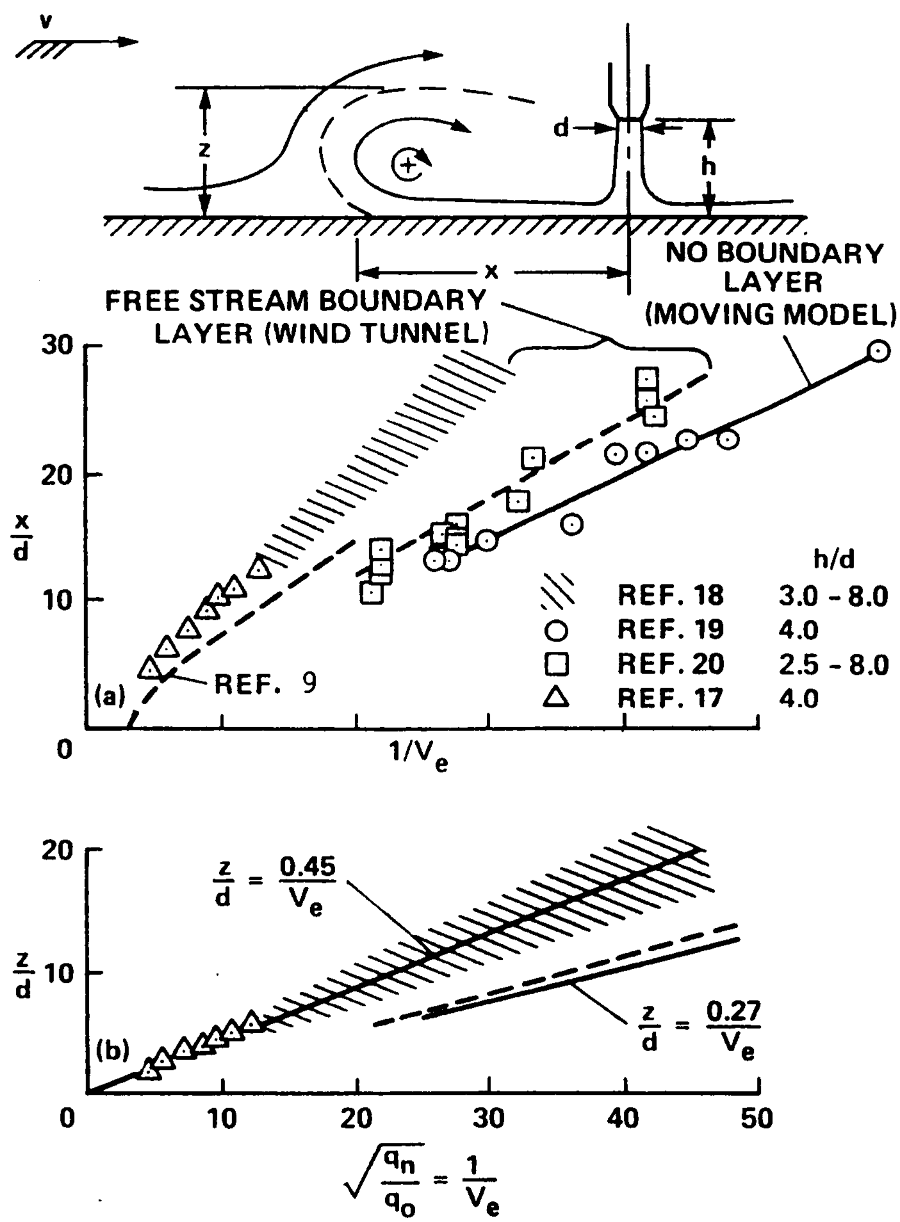


Figure 26.- Size of ground vortex recirculating flow region generated by a single jet.

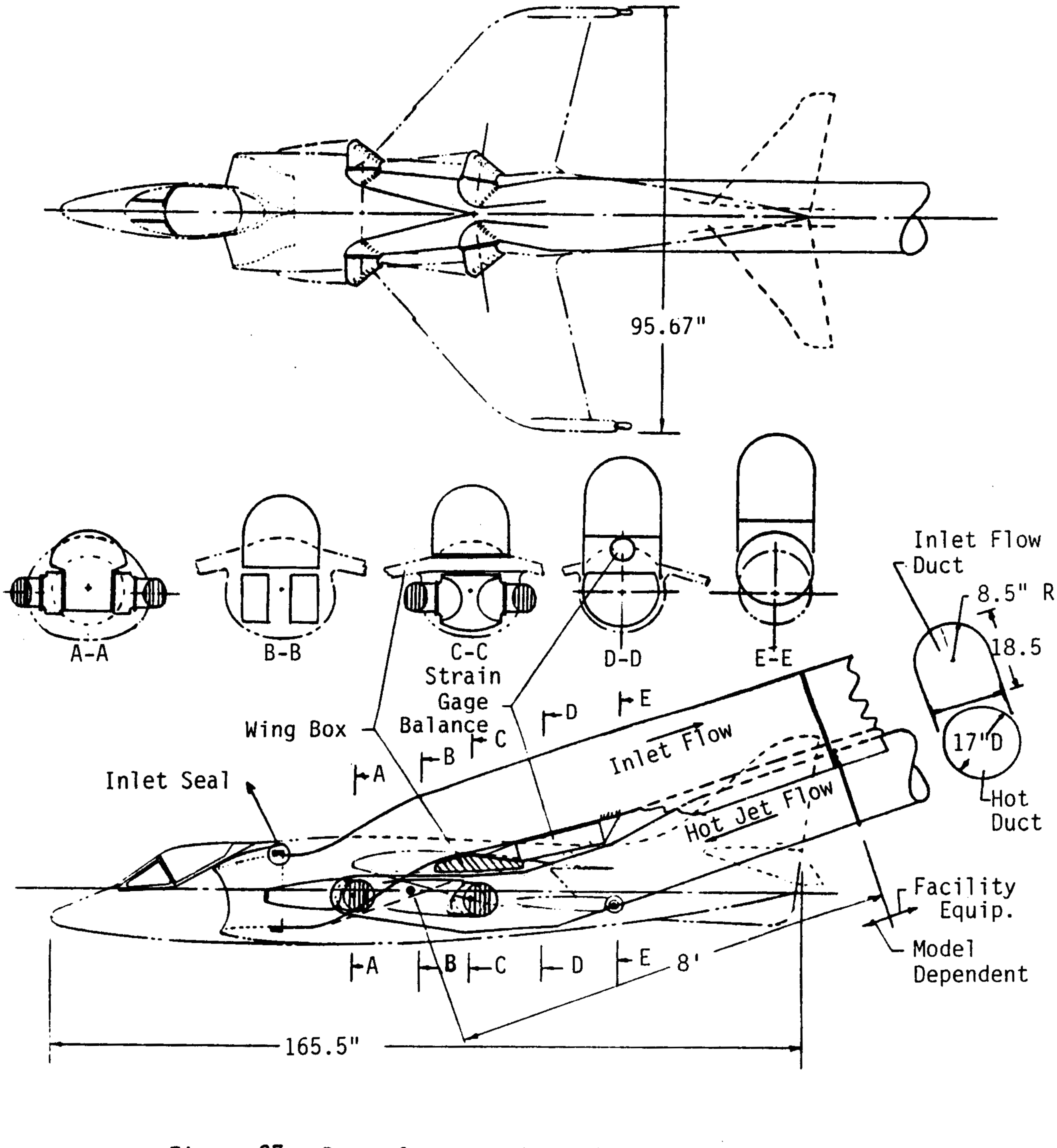


Figure 27.- Remotely powered Harrier-type model.

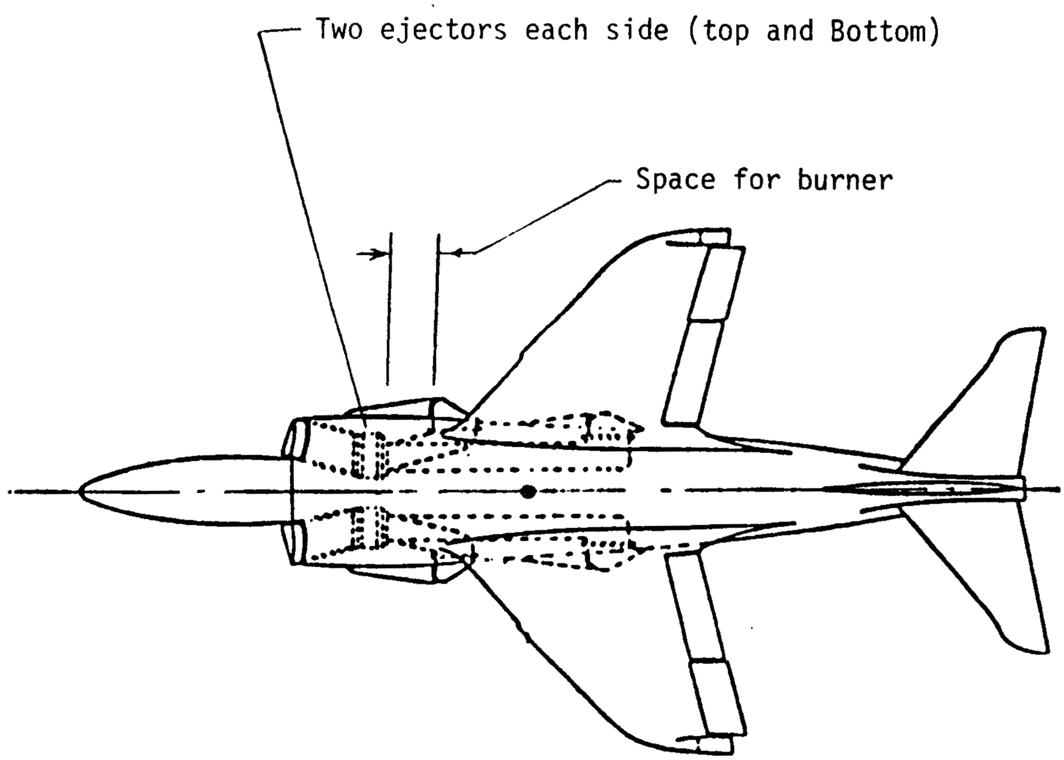


Figure 28.- "Hot Ejector" powered Harrier-type model.

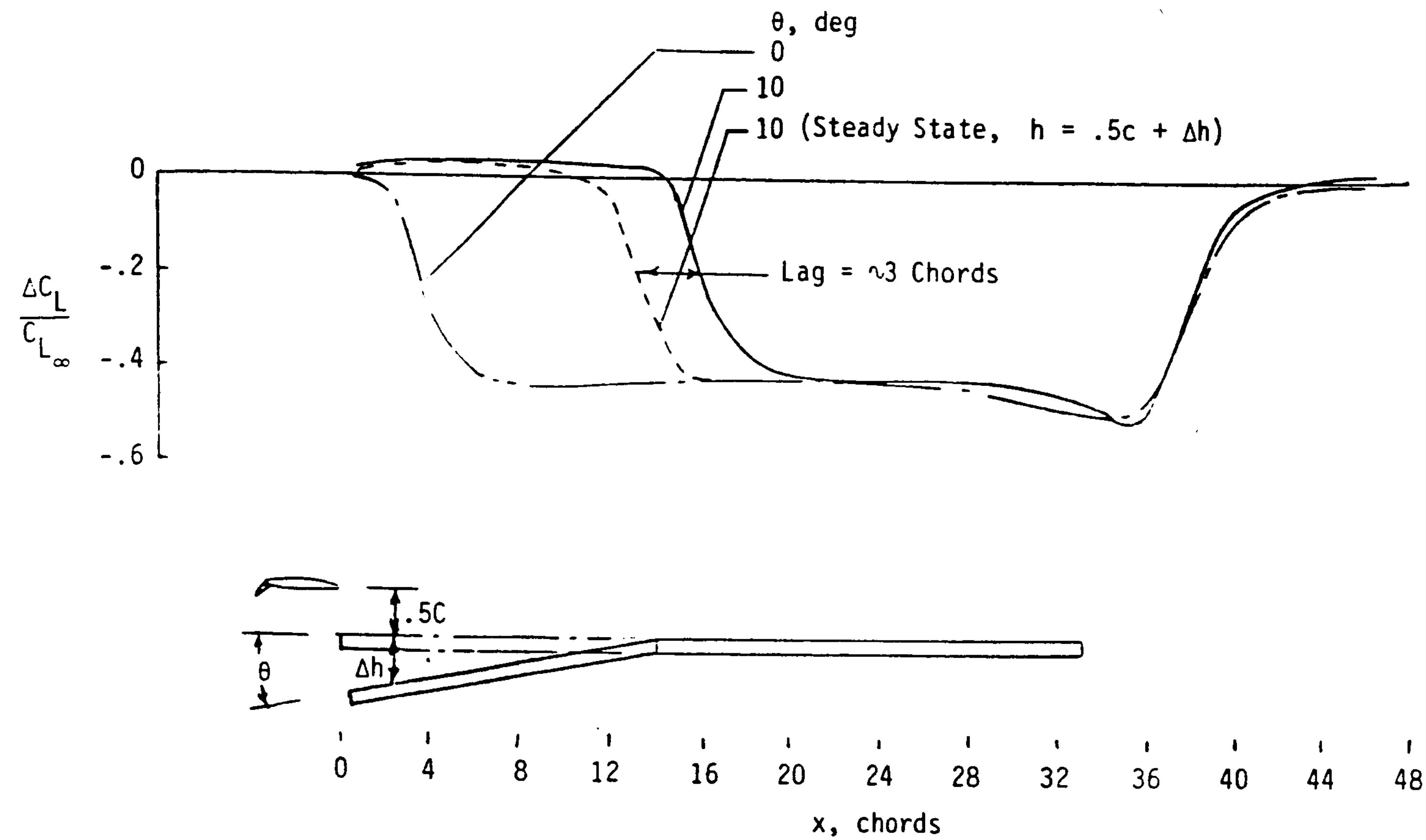


Figure 29.- Moving model tests show lay in development of jet flap ground effects. $C_{L_\infty} = 9.5$, (Ref. 25)

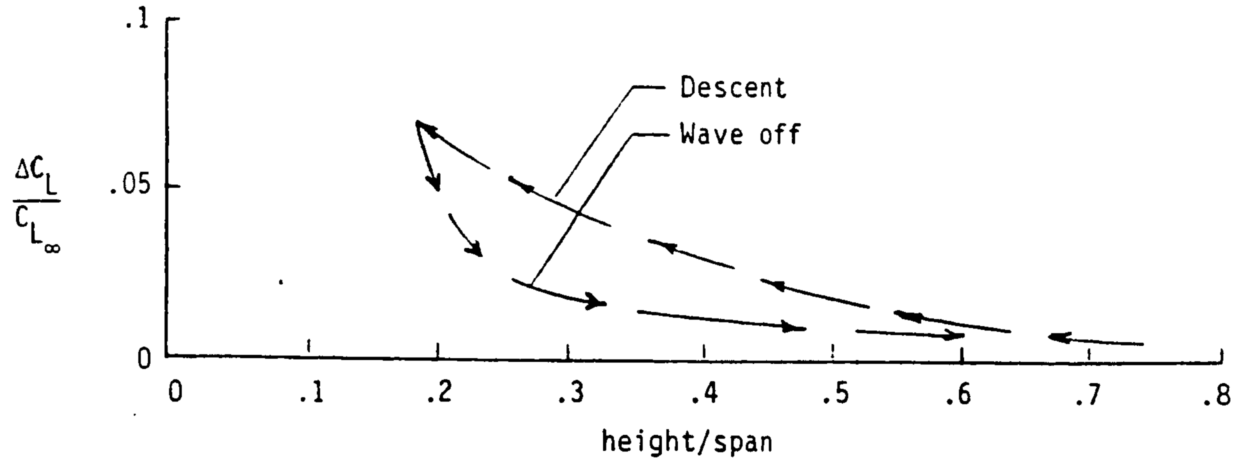


Figure 30.- Touch-and-go landings show ground effect hysteresis. $C_{L_\infty} \sim 2.5$, (Ref. 41)

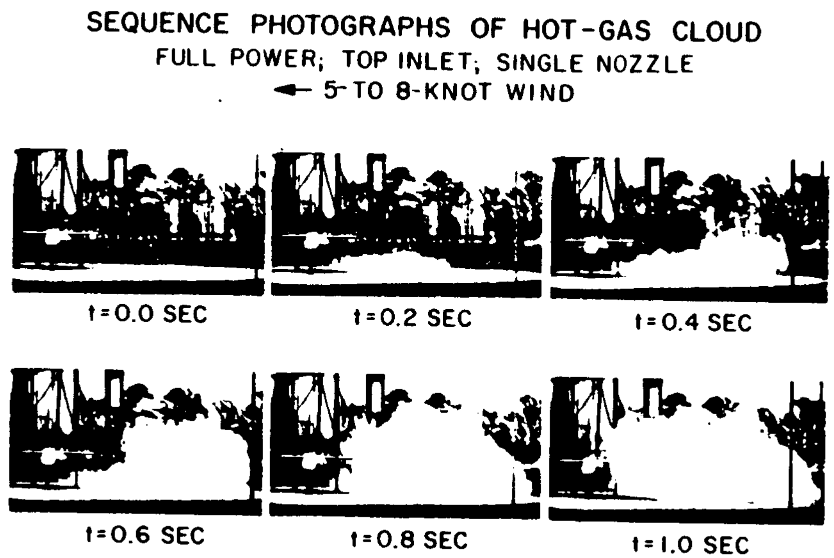


Figure 31.- Development of Hot-Gas cloud. (Ref. 42)

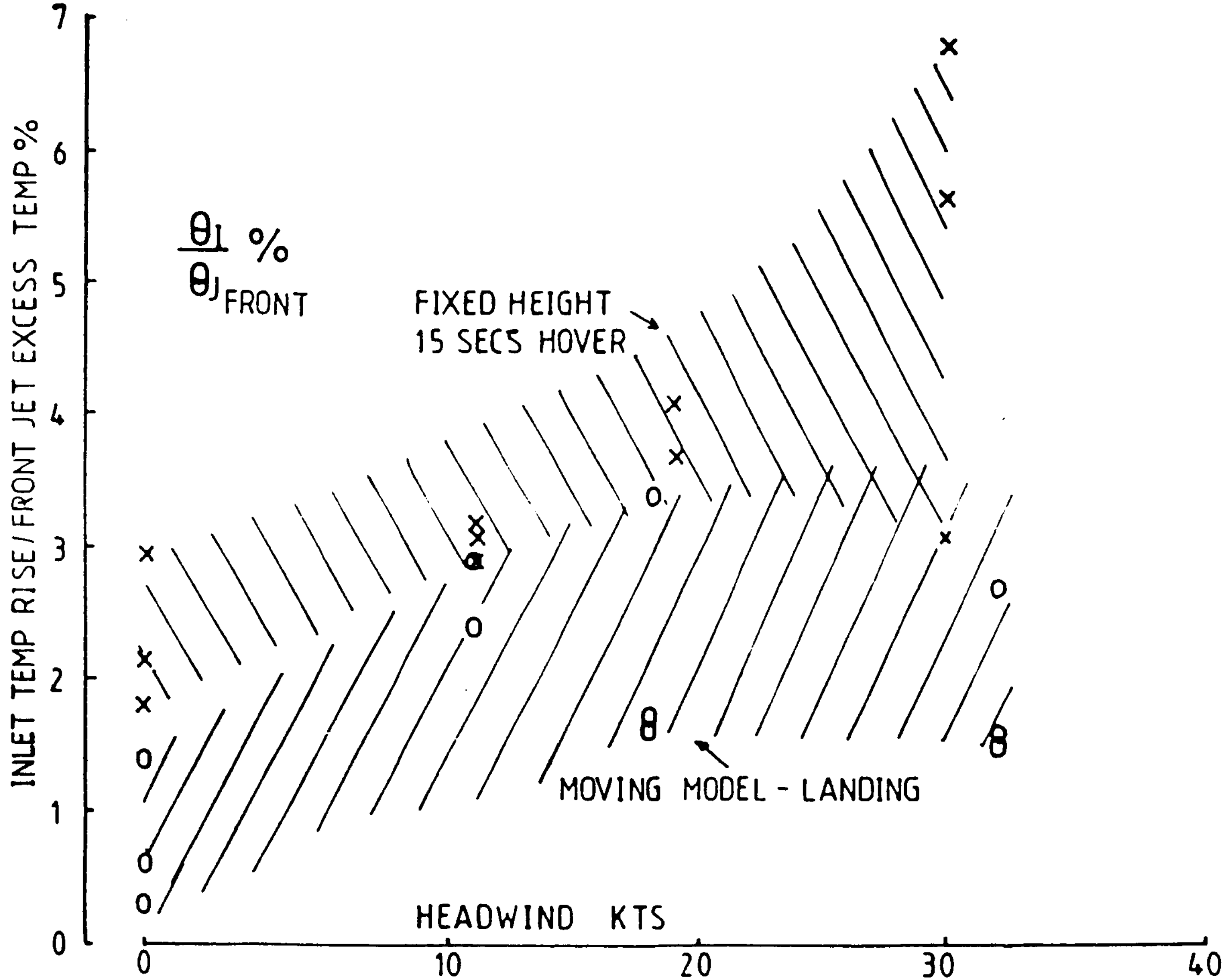


Figure 32.- Comparison of inlet temperature rise measured by moving model in landing descent with fixed height data. (Paper No. 11 of Ref. 1)

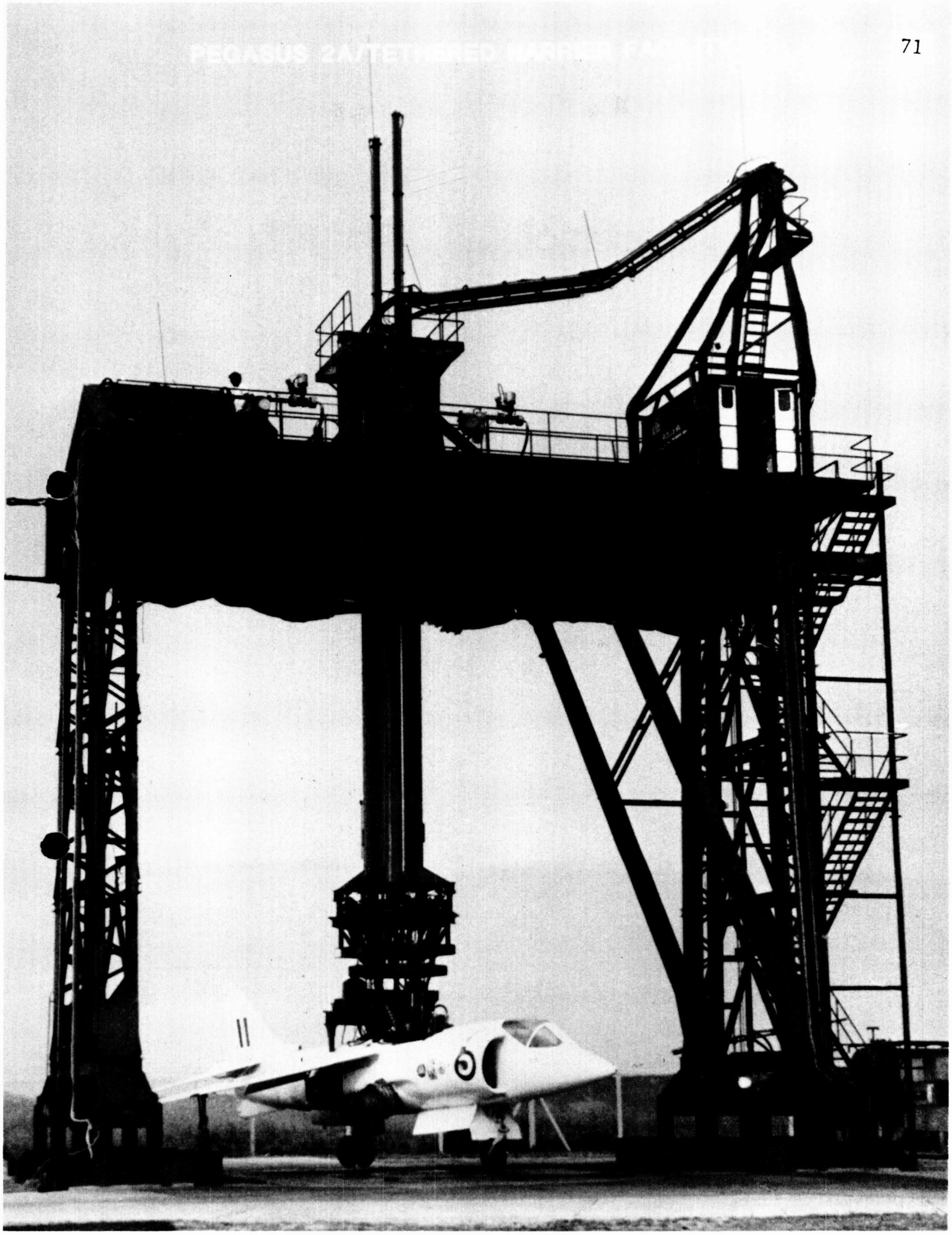


Figure 33.- Rolls-Royce dynamic rig for studing the effect of landing sink rate on hot gas ingestion.

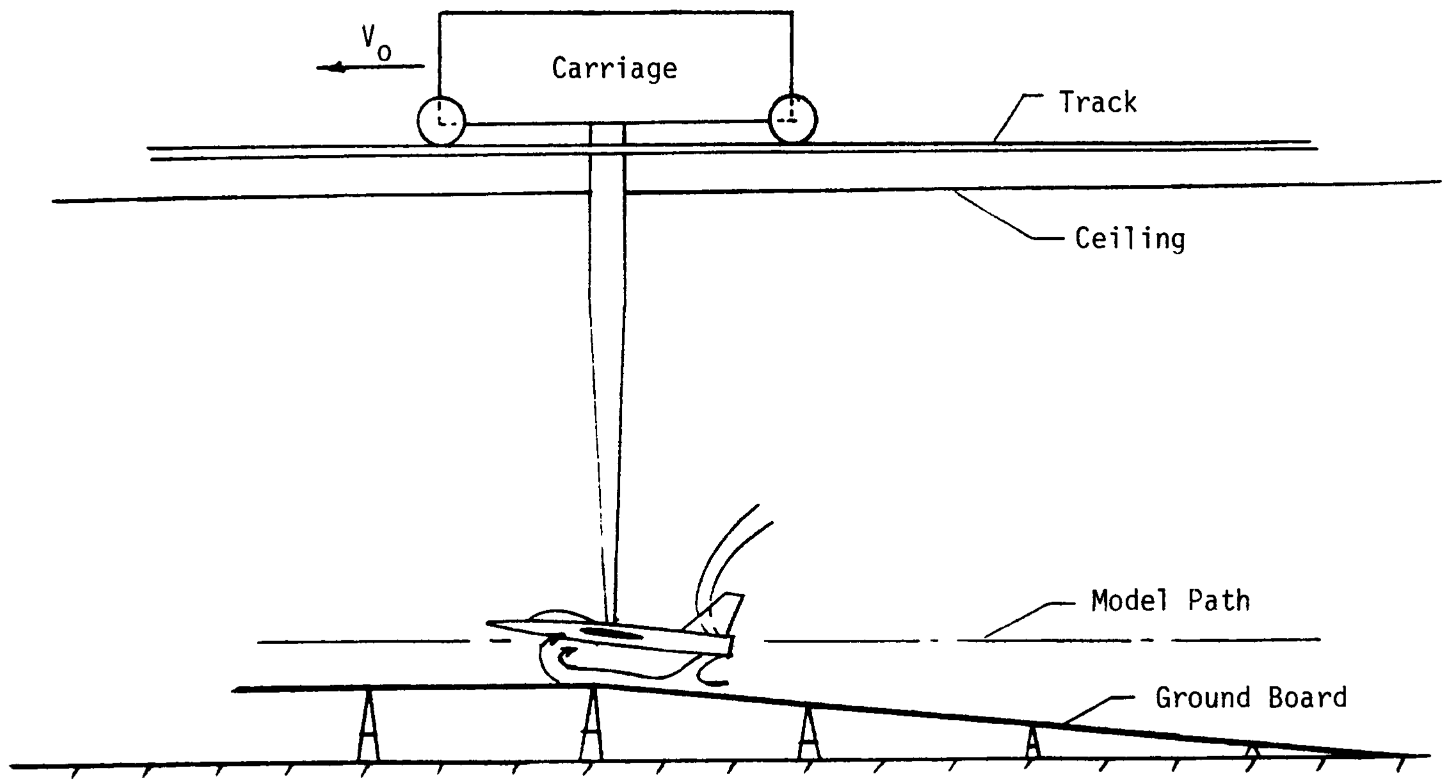


Figure 34.- Moving model facility for studying thrust reverser effects in ground effect.

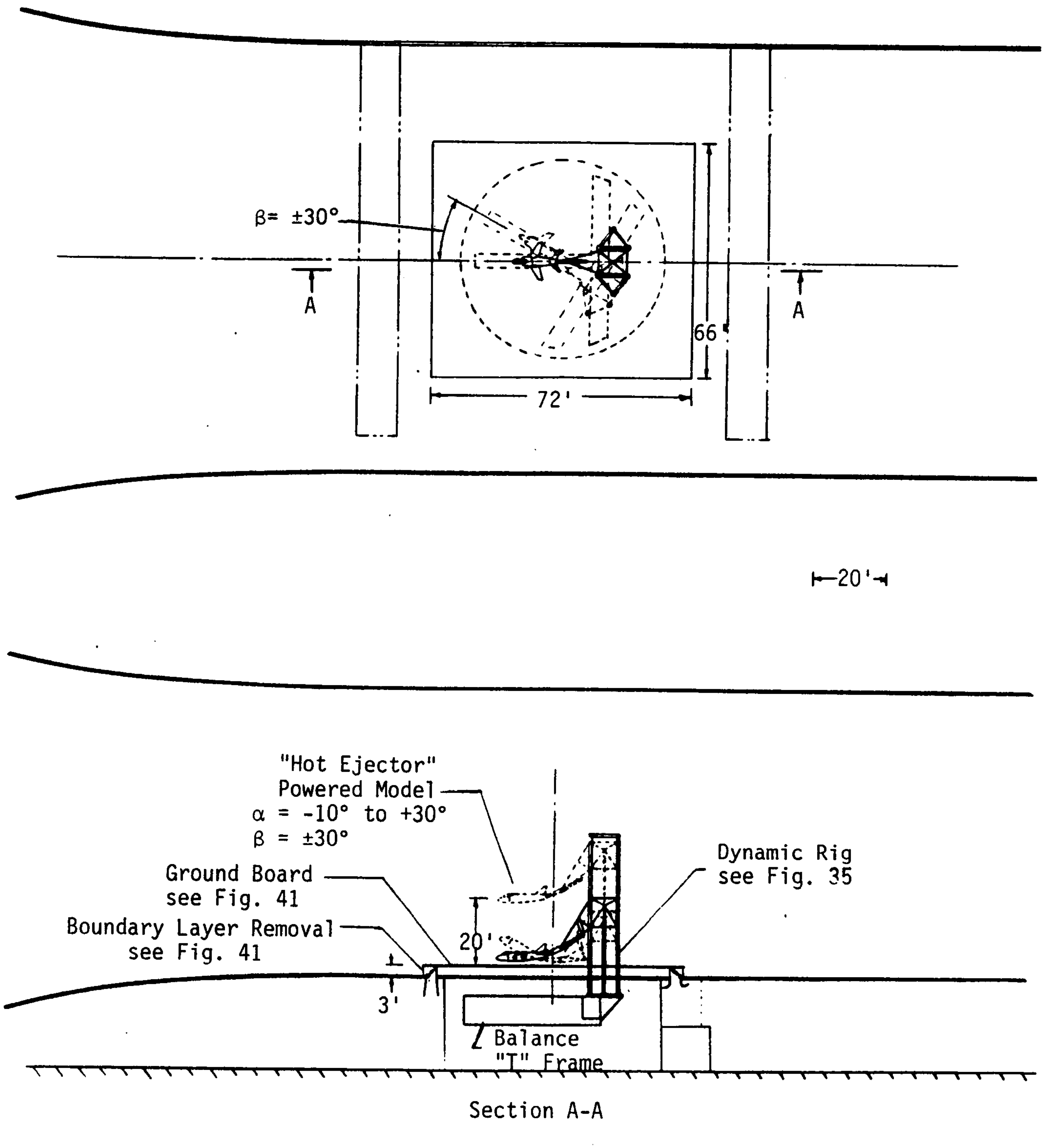


Figure 35.- General arrangement of dynamic rig and ground board installation.

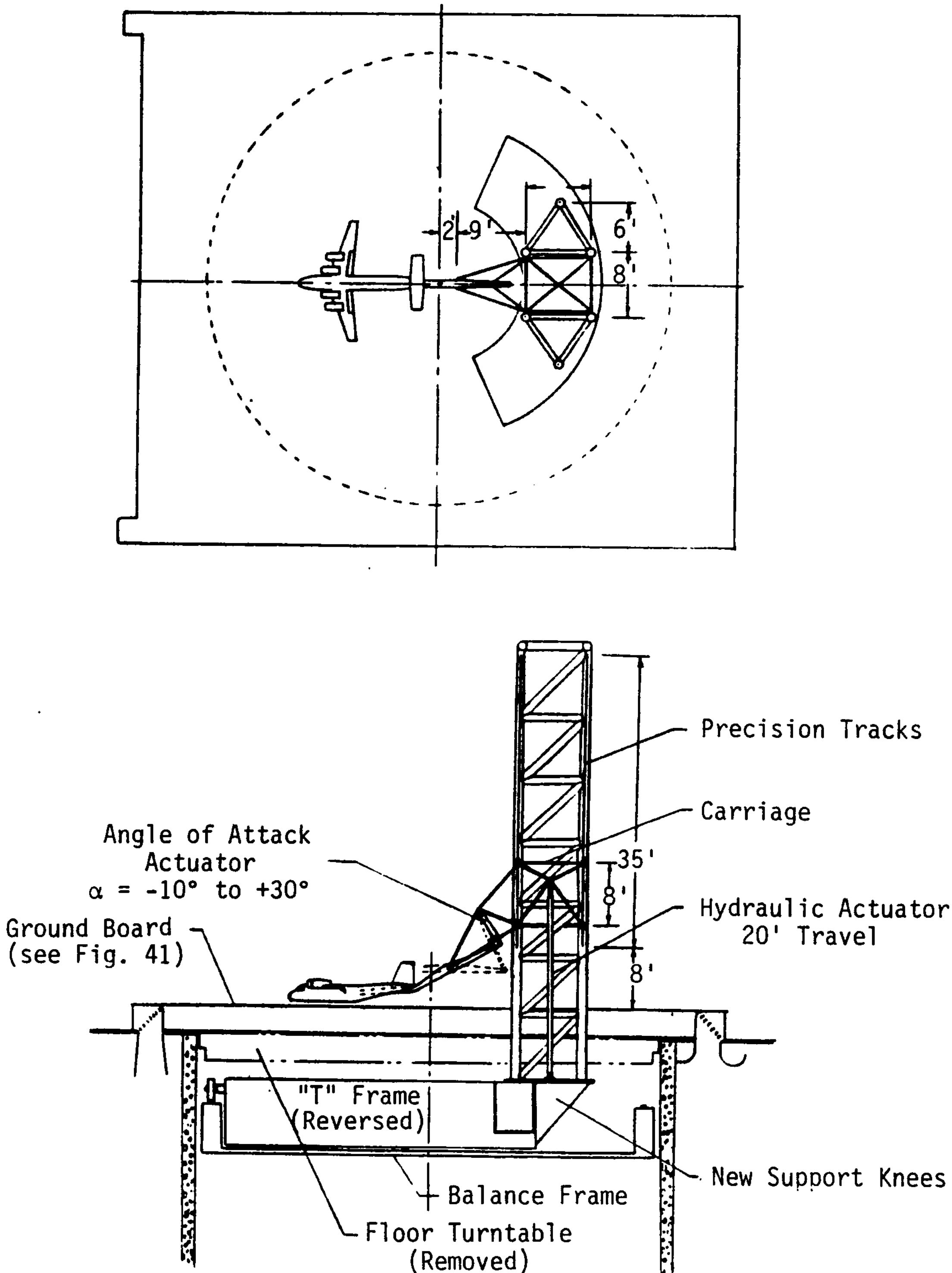


Figure 36.- Installation of dynamic rig on model support system.

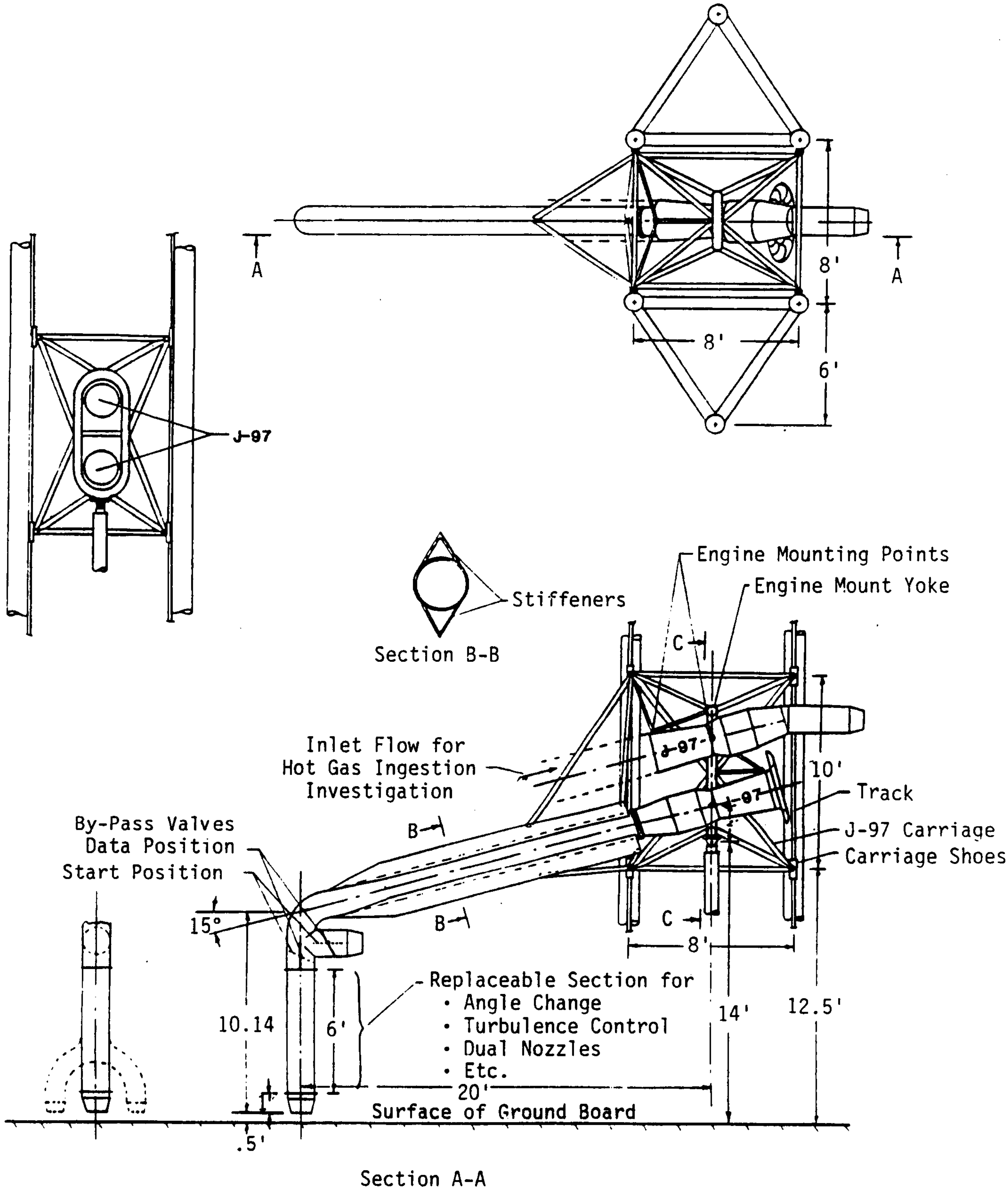
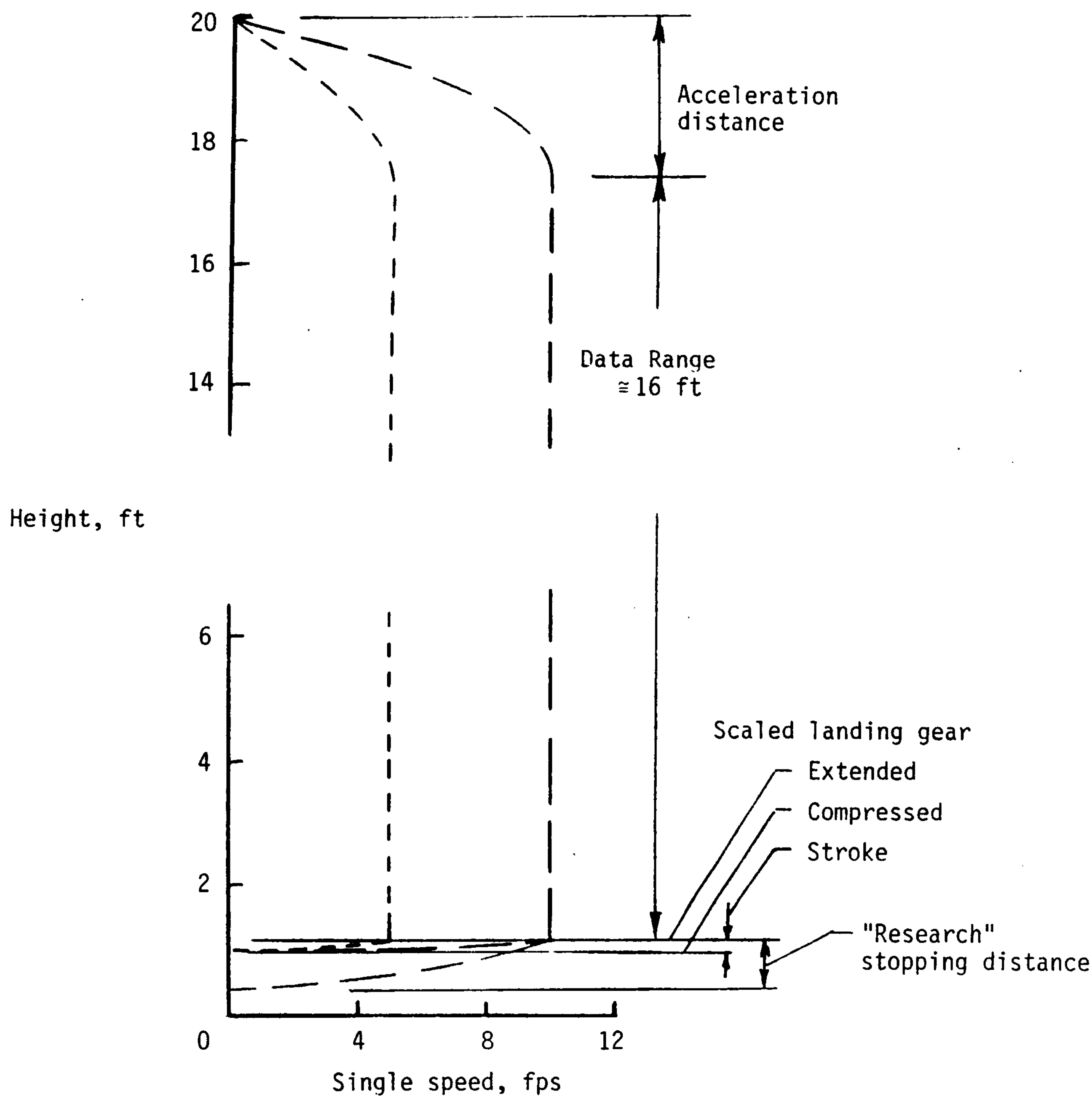
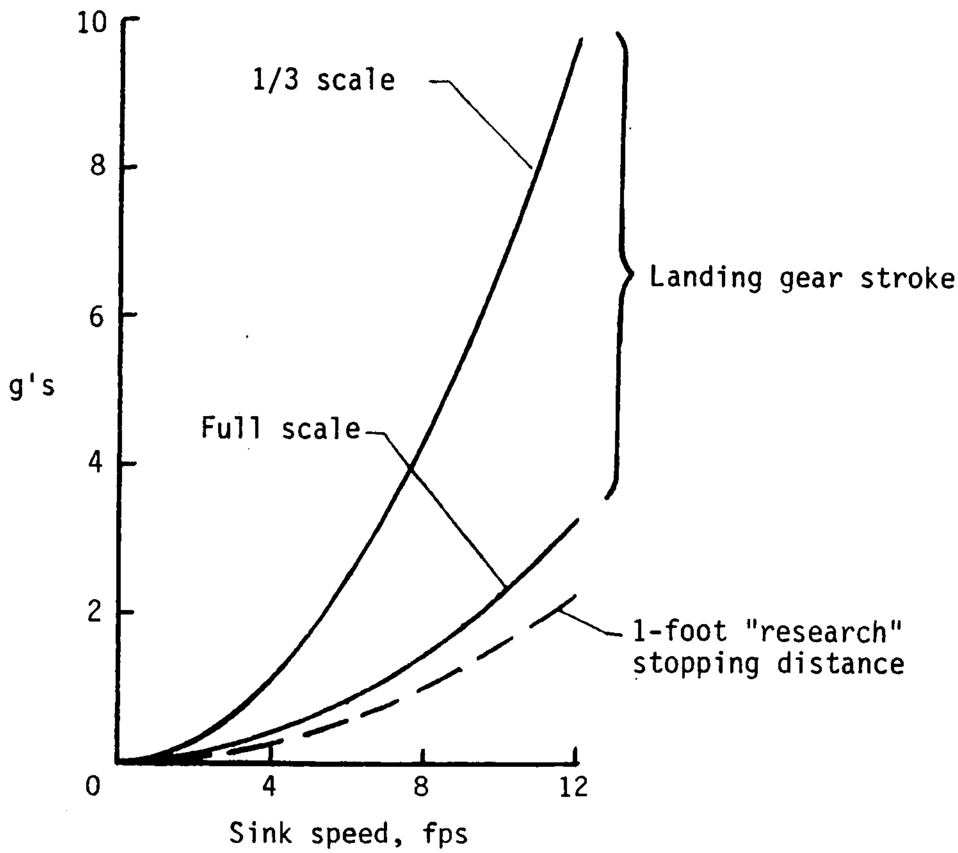


Figure 37.- J-97 Engine installation and carriage.



a) Typical height/sink-speed profiles.

Figure 38.- Typical simulated landings.



b) Stopping decelerations.

Figure 38.- Concluded.

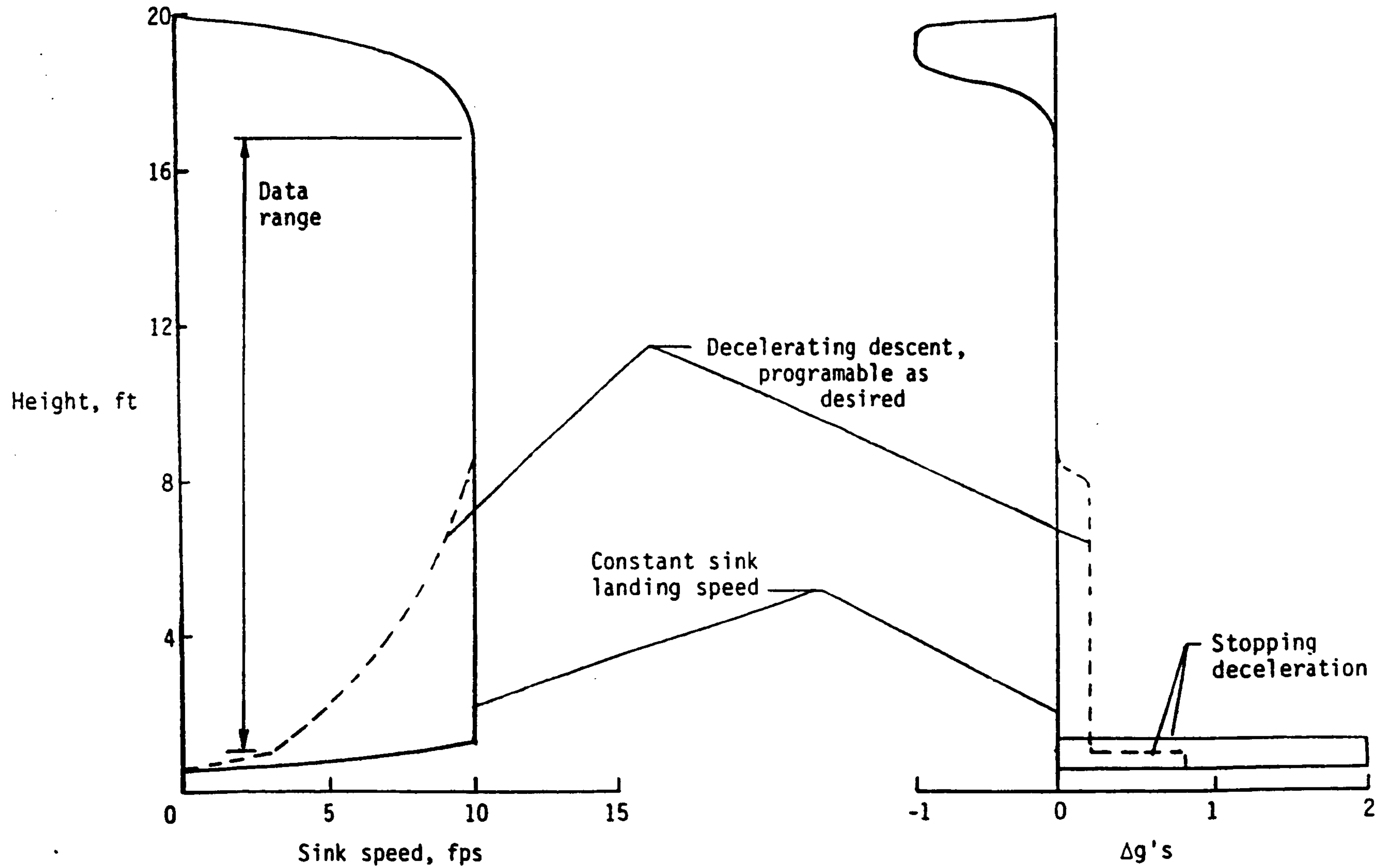


Figure 39.- Variable sink rate landings.

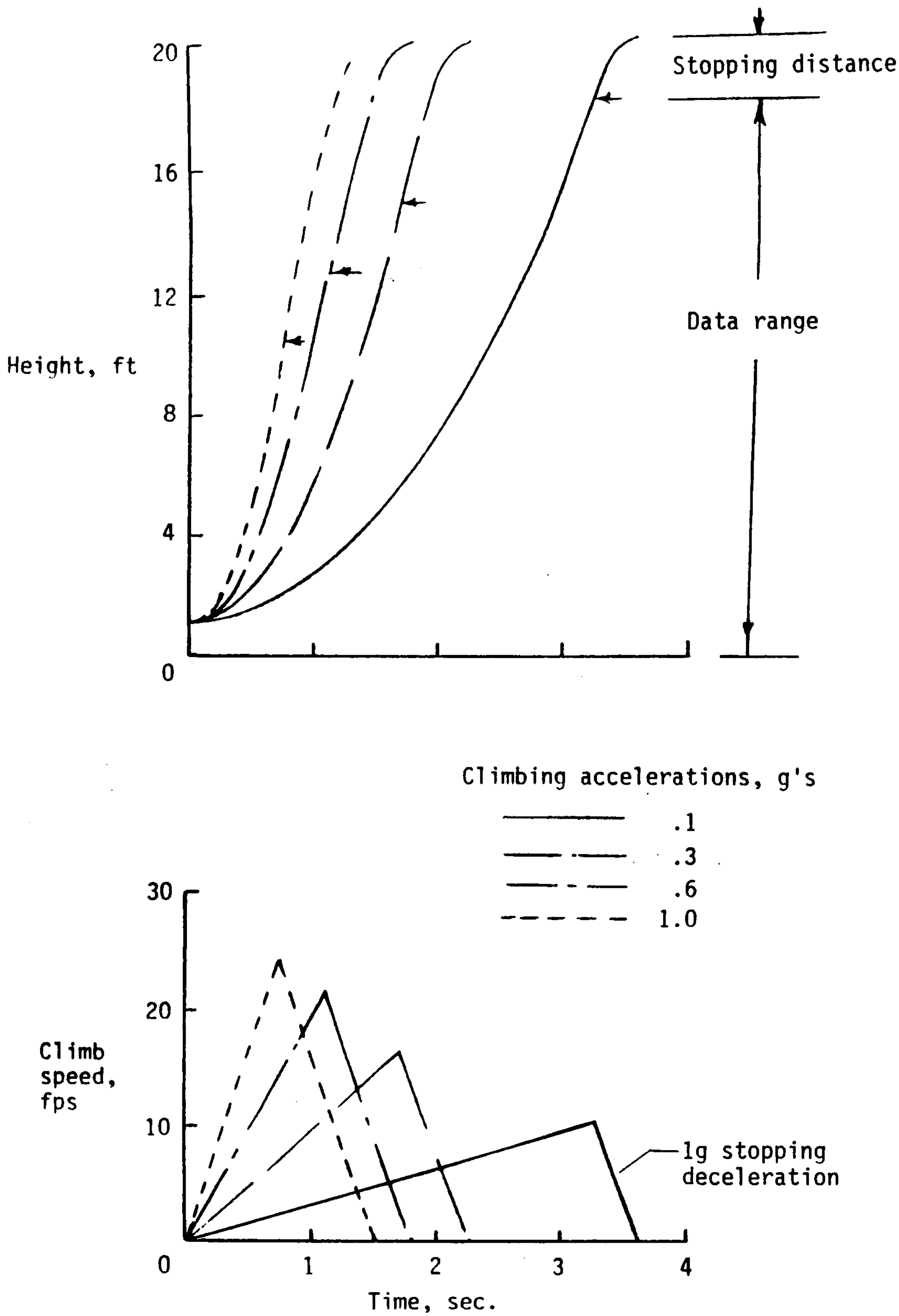


Figure 40.- Simulated take-offs.

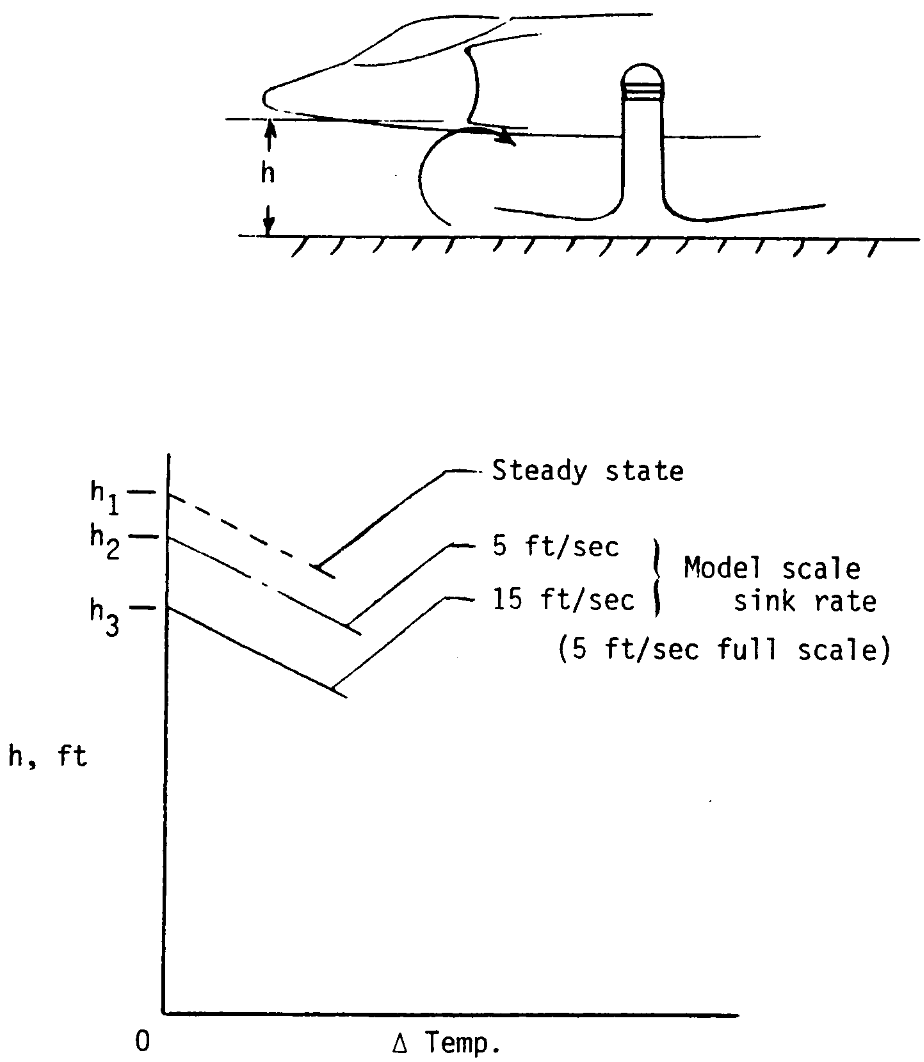


Figure 40.- Effect of rate of descent on the onset of hot gas ingestion.

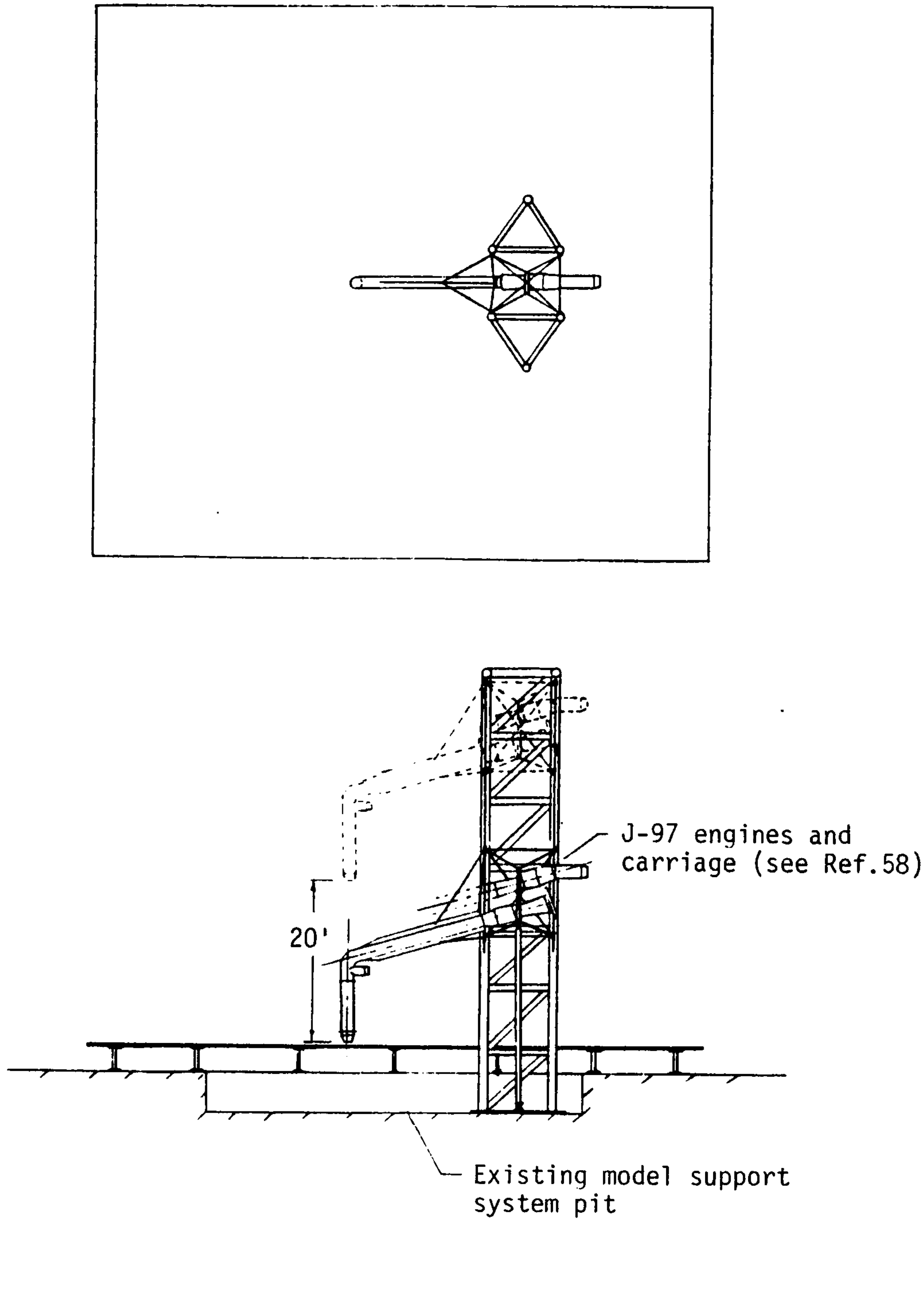


Figure 41.- Installation of dynamic rig and J-97 carriage on outdoor static test facility.

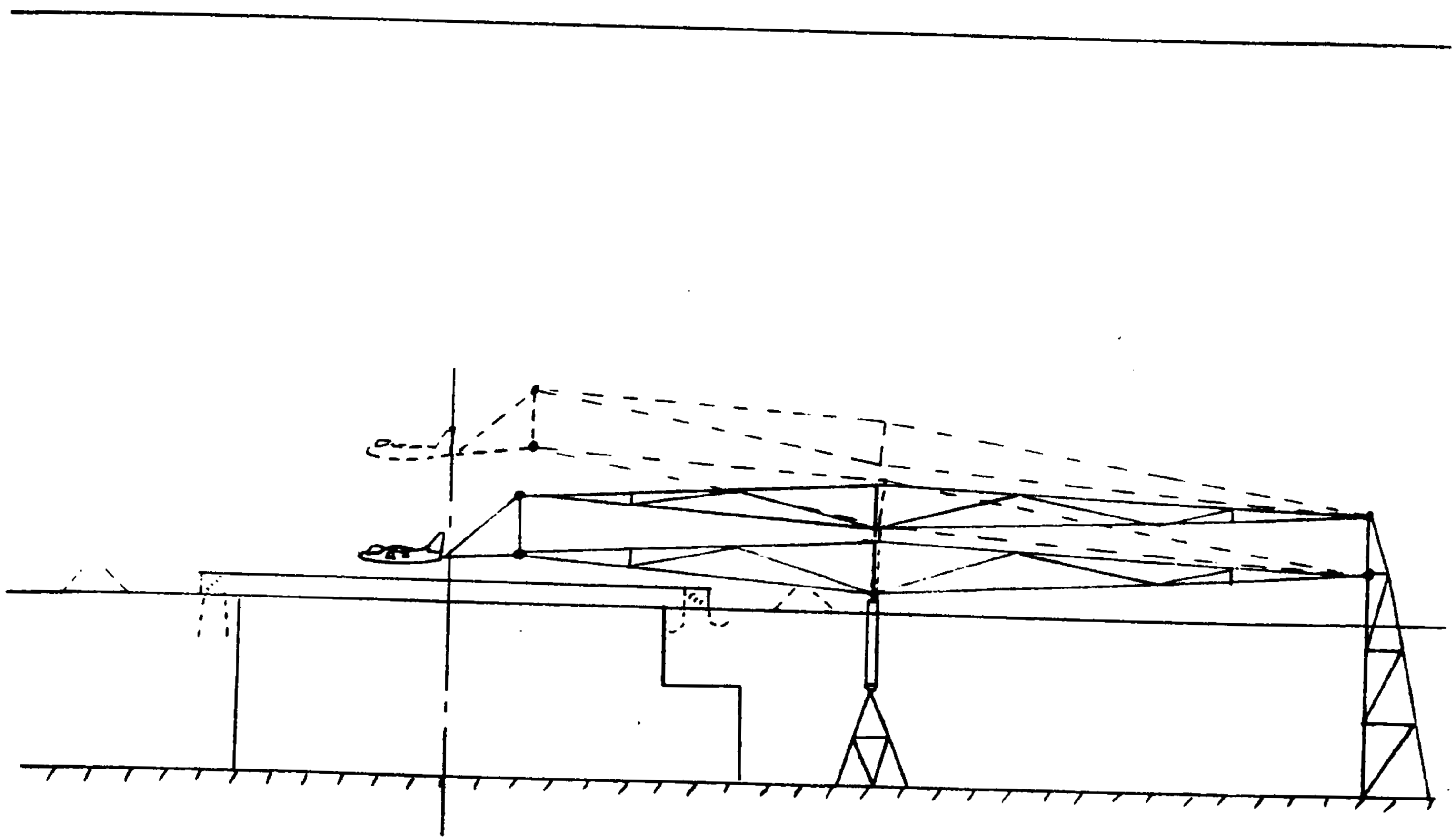


Figure 42.- Possible alternative dynamic rig concept.

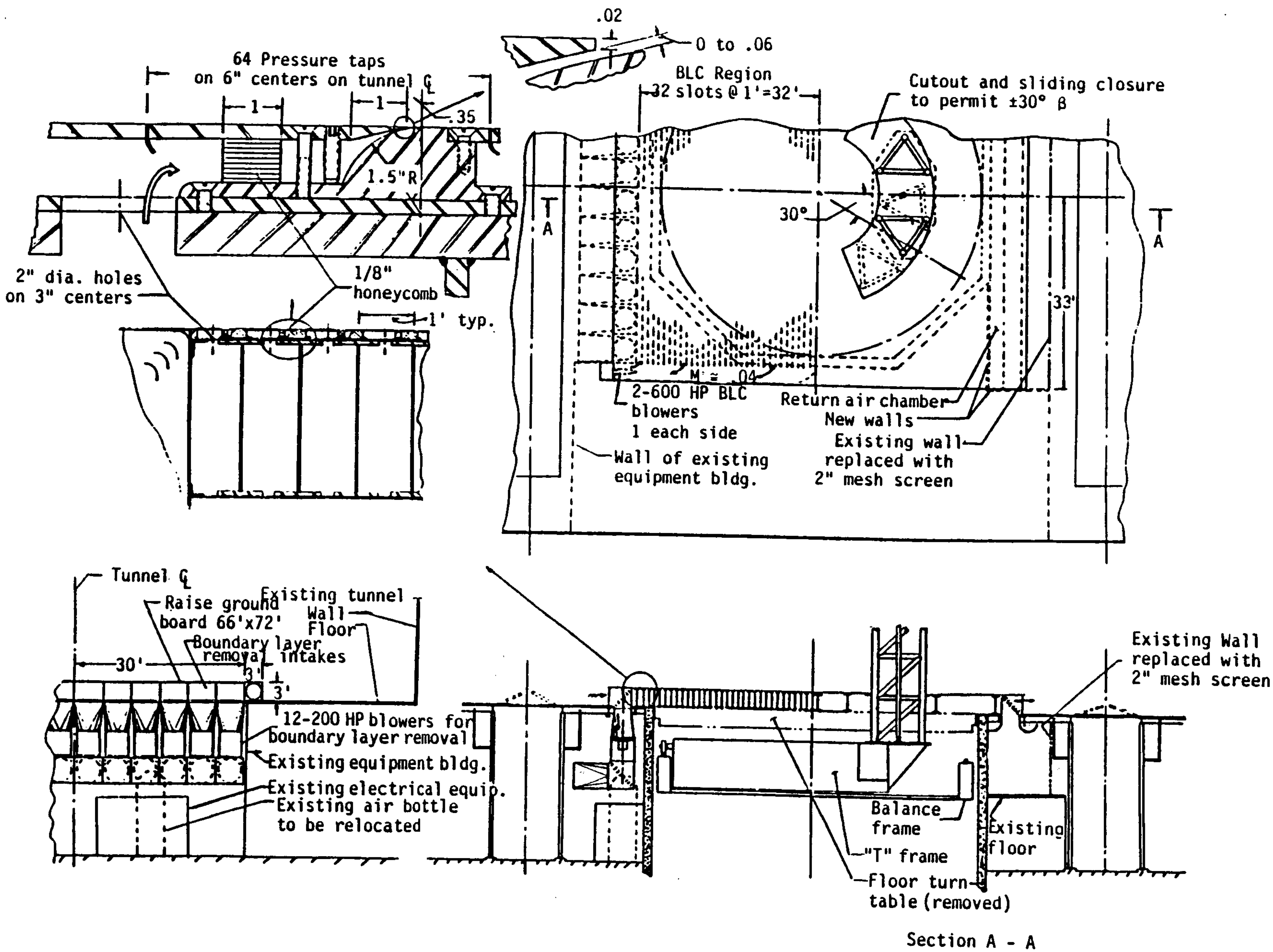


Figure 43.- Blowing BLC ground board concept.

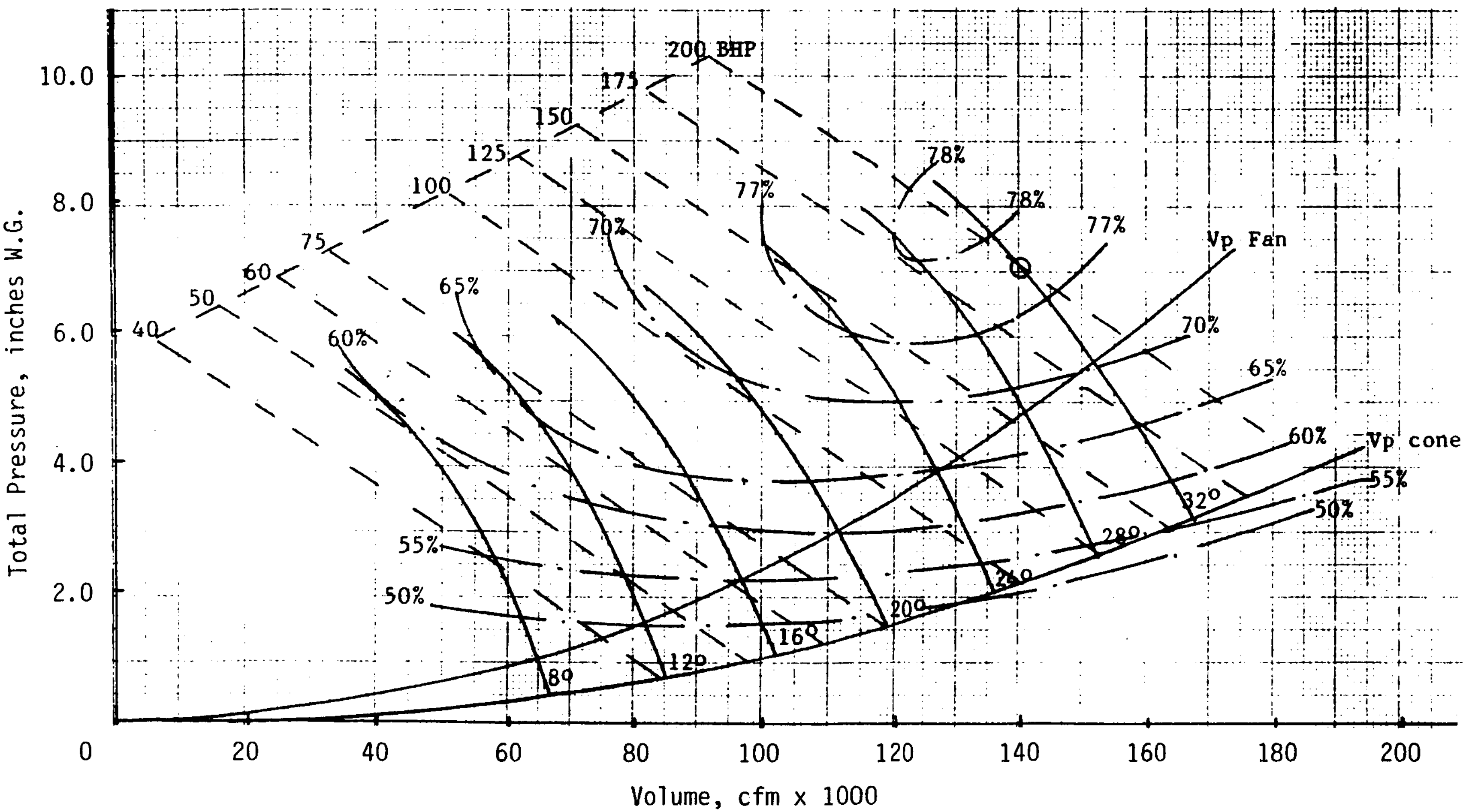


Figure 44.- Performance map for a typical commercial blower.

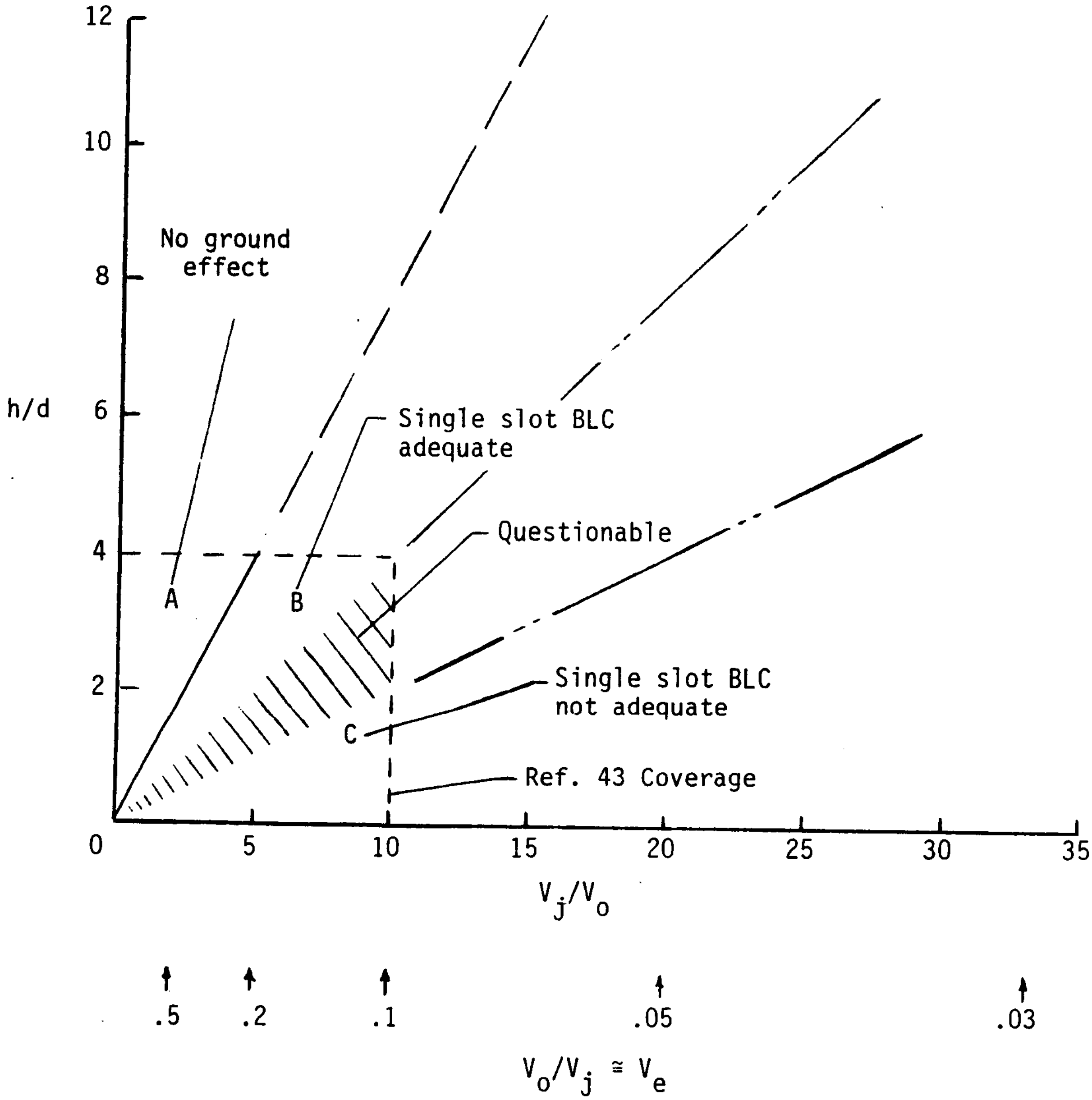
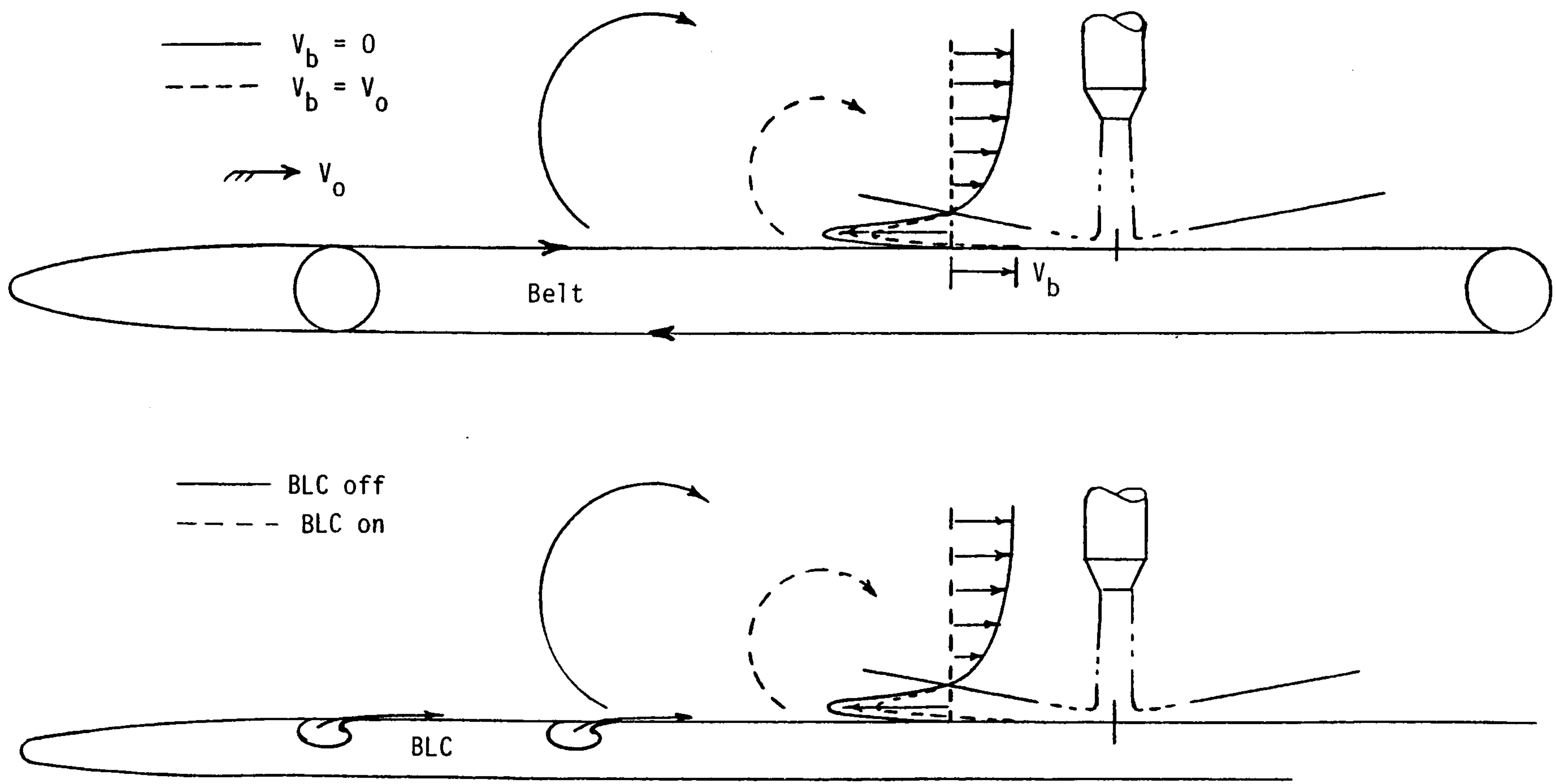


Figure 45.- Height/velocity-ratio range in which sinqle slot BLC is adequate. (Ref. 43)



What BLC configuration and blowing rate are required to match flow field over belt?

Figure 46.- Effect of belt and BLC on flow field in ground effect.

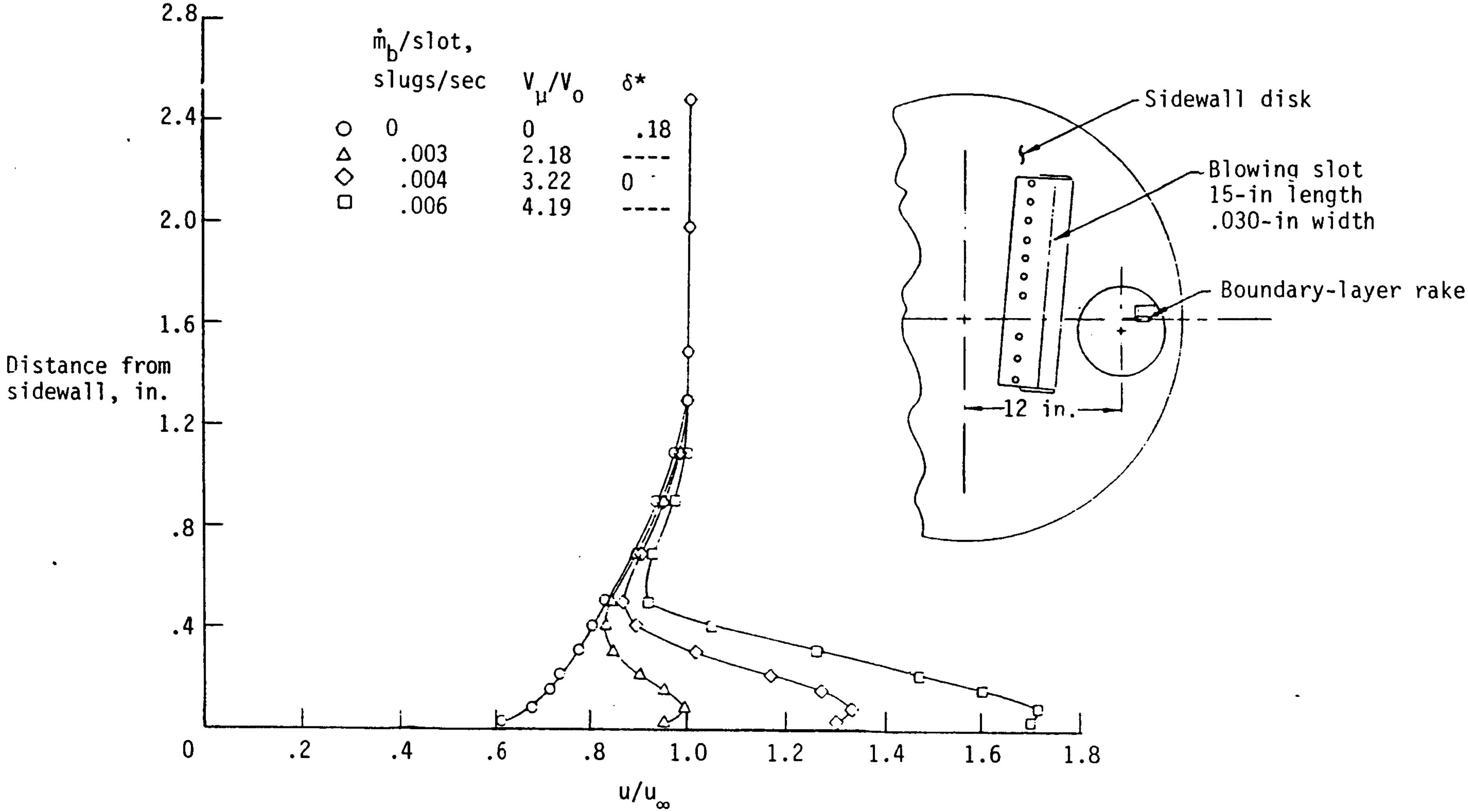


Figure 47.- Effect of tangential blowing (BLC) on boundary-layer velocity profiles on sidewall of Langley LTPT test section.

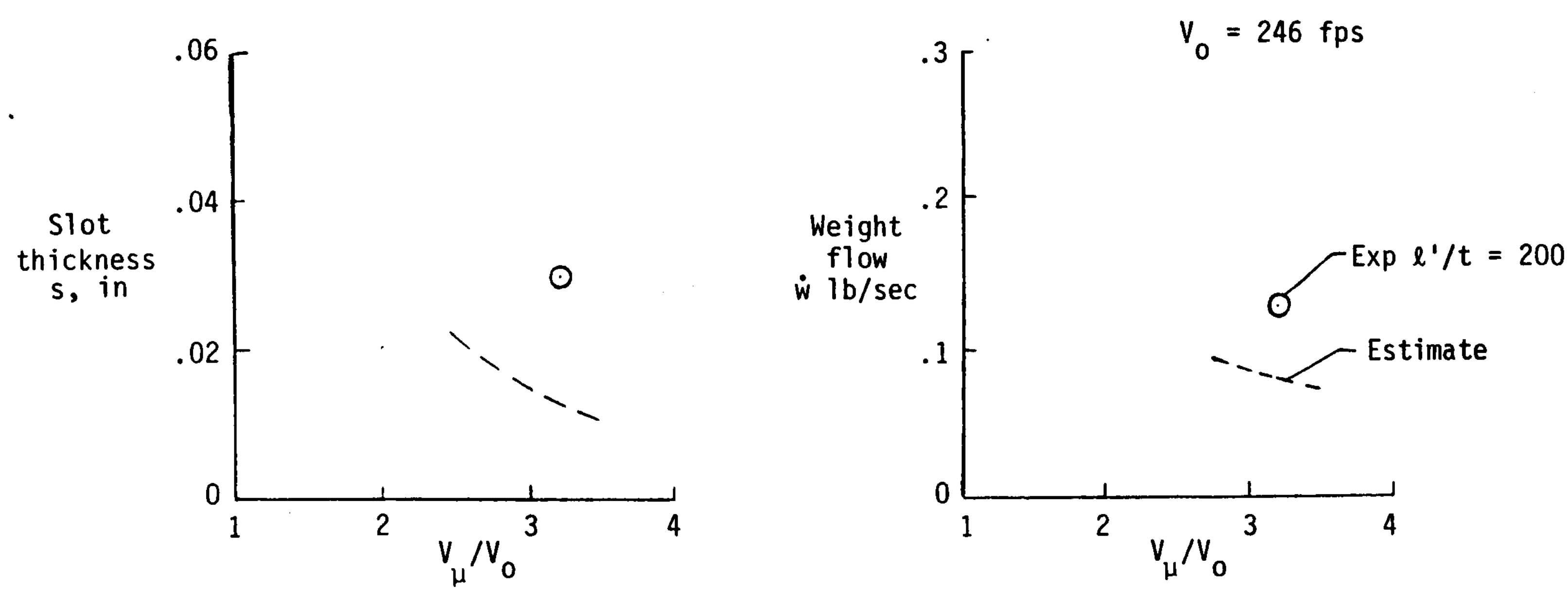


Figure 48.- Comparison of estimates with actual blowing required in LTPT. (Ref. 44)

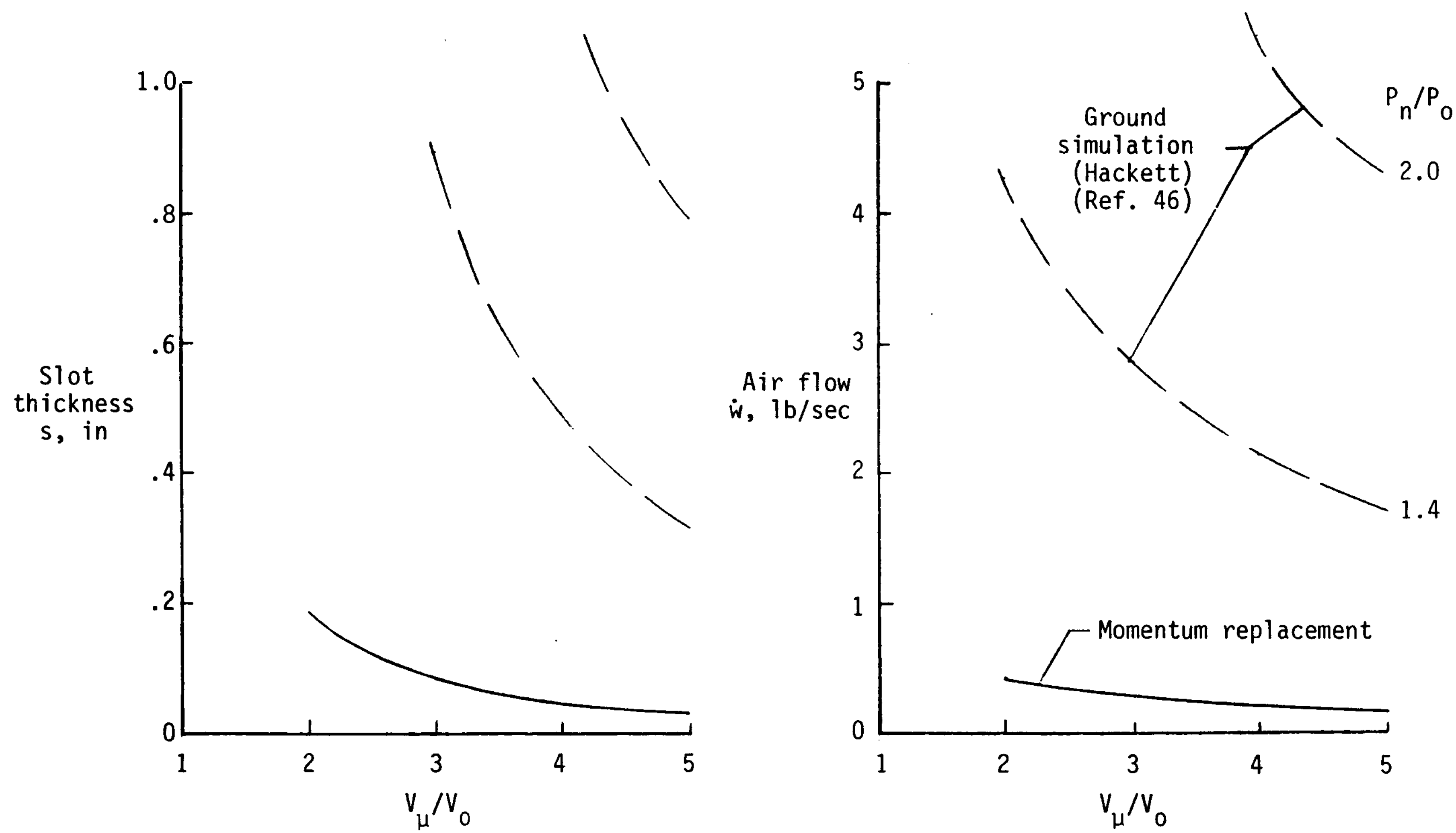
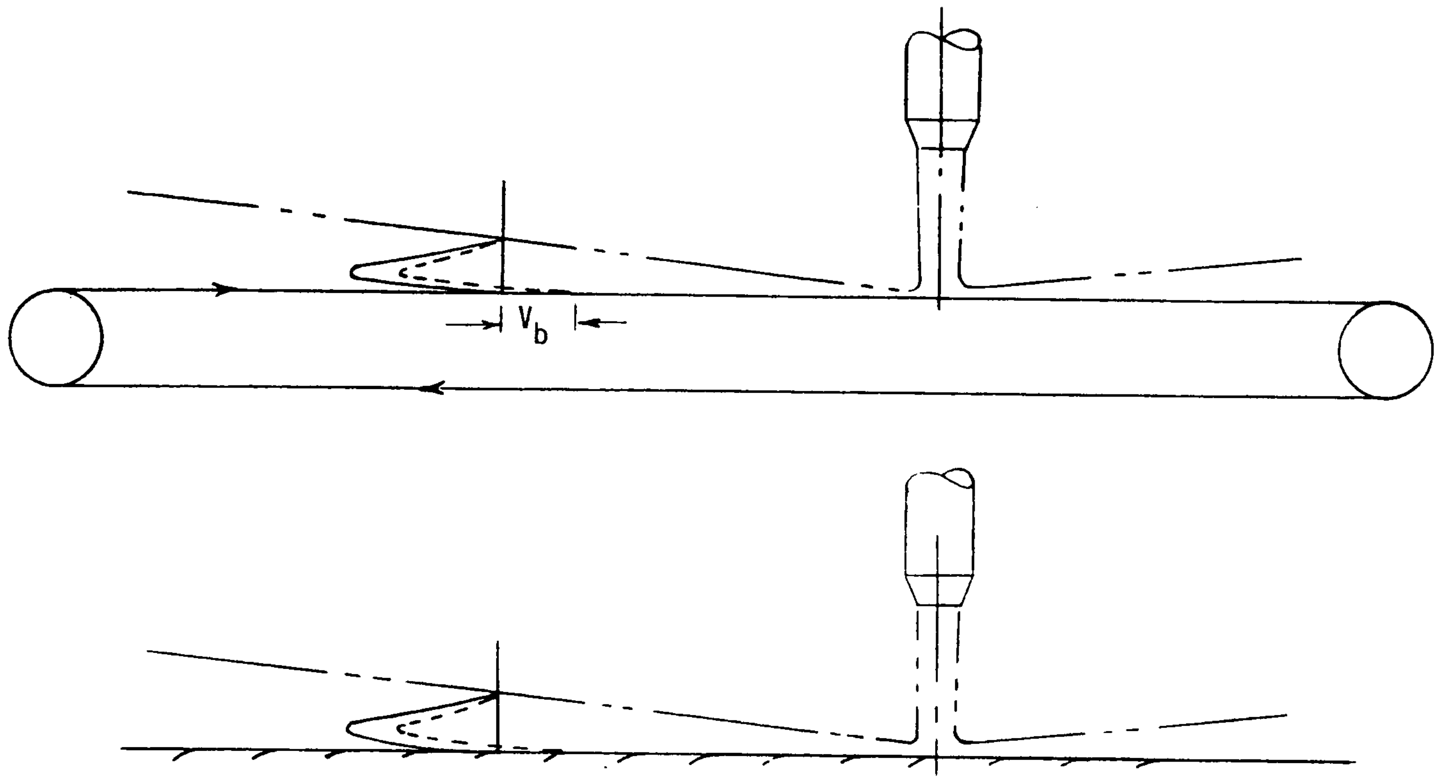


Figure 49.- Comparison of estimates of blowing requirements for BLC (momentum replacement) with required for ground simulation using a single slot (Ref. 46) in 80 x 120 foot test section.



What BLC configuration and blowing rate are required to match wall jet decay over belt?

Figure 50.- Effect of belt and BLC on wall jet. $V_o = 0$

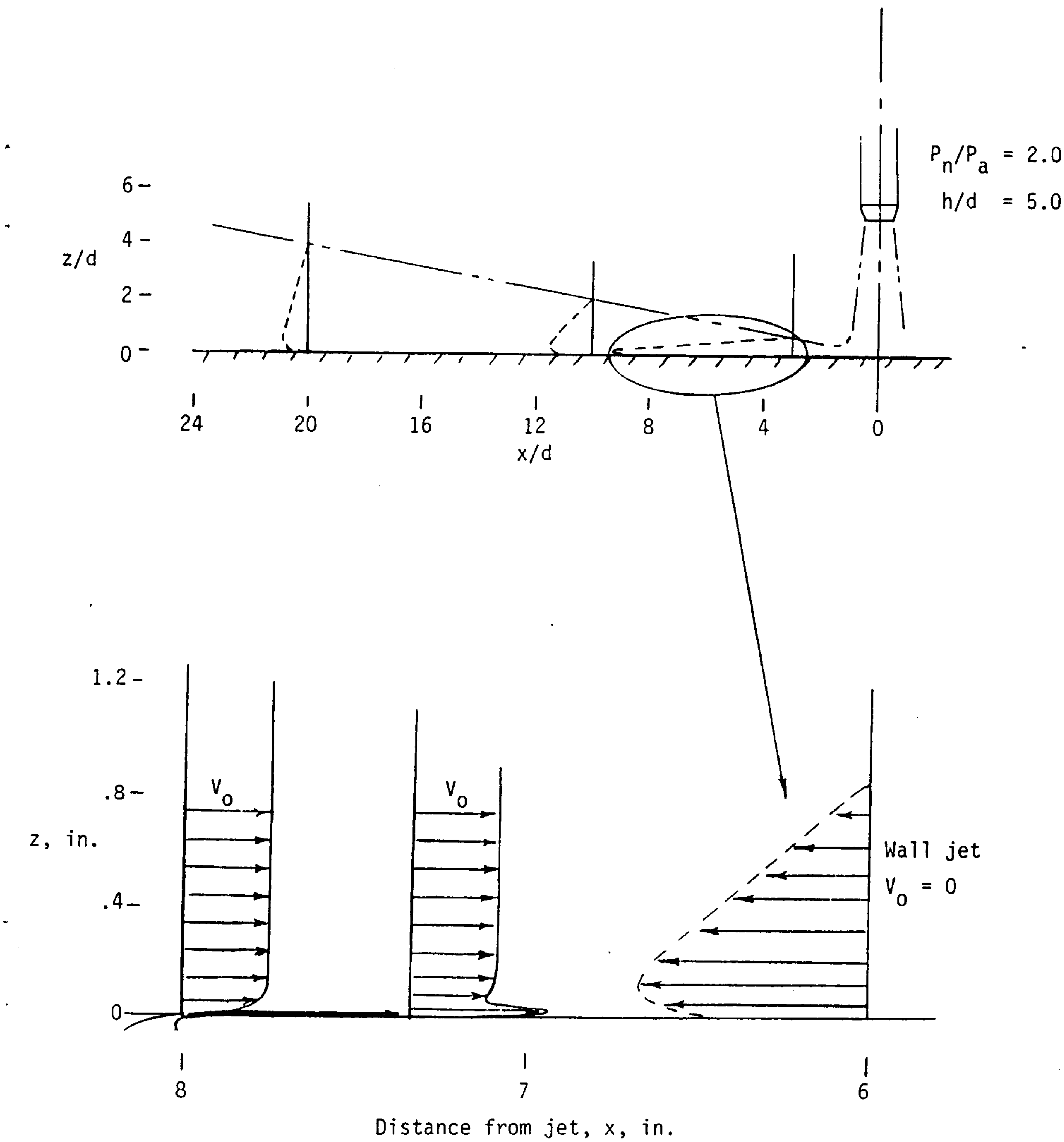


Figure 51.- Estimated boundary layer and wall jet profiles assuming 2-inch slot spacing.

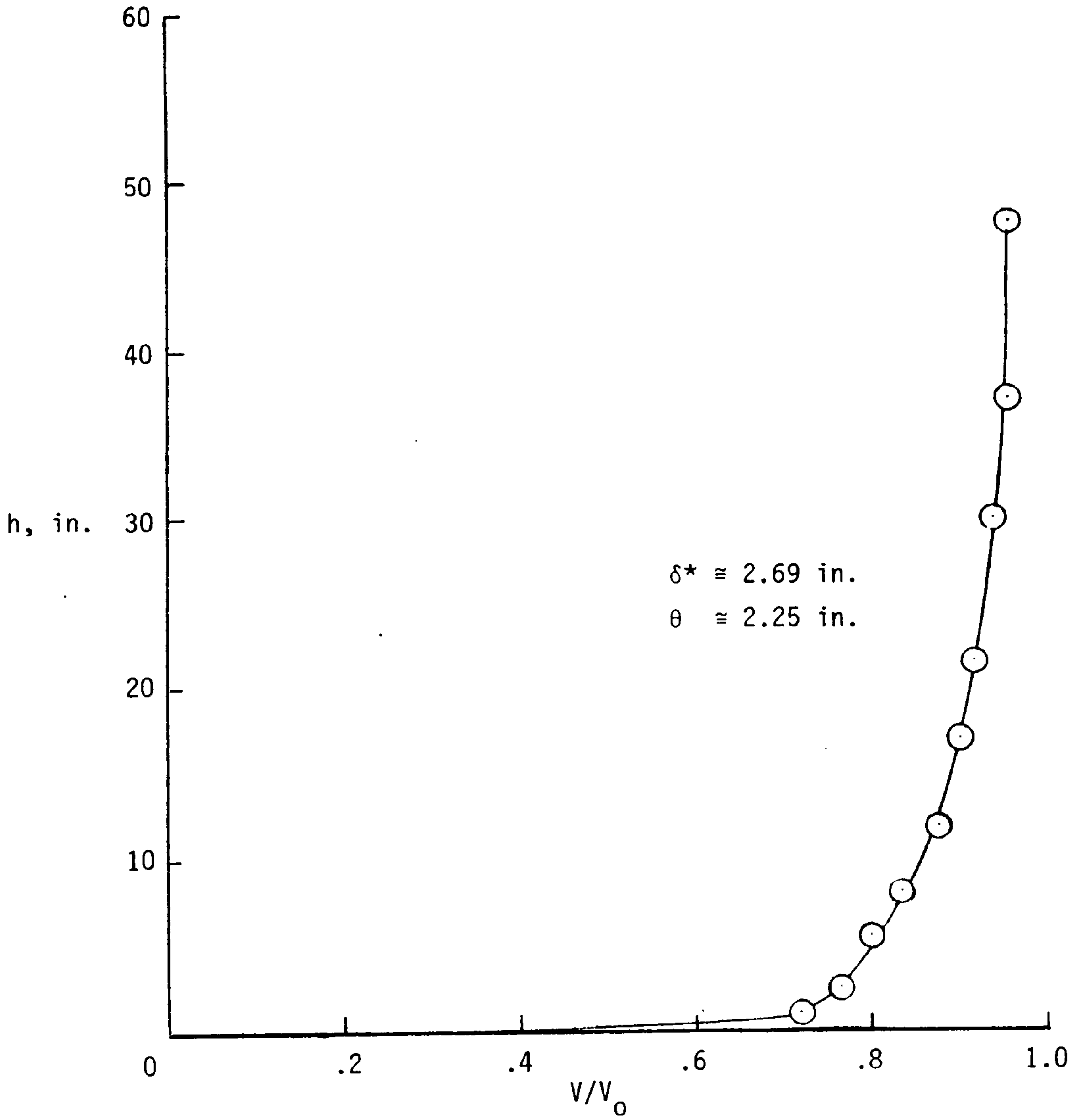


Figure 52.- Boundary layer on floor of 80 x 120 foot test section.

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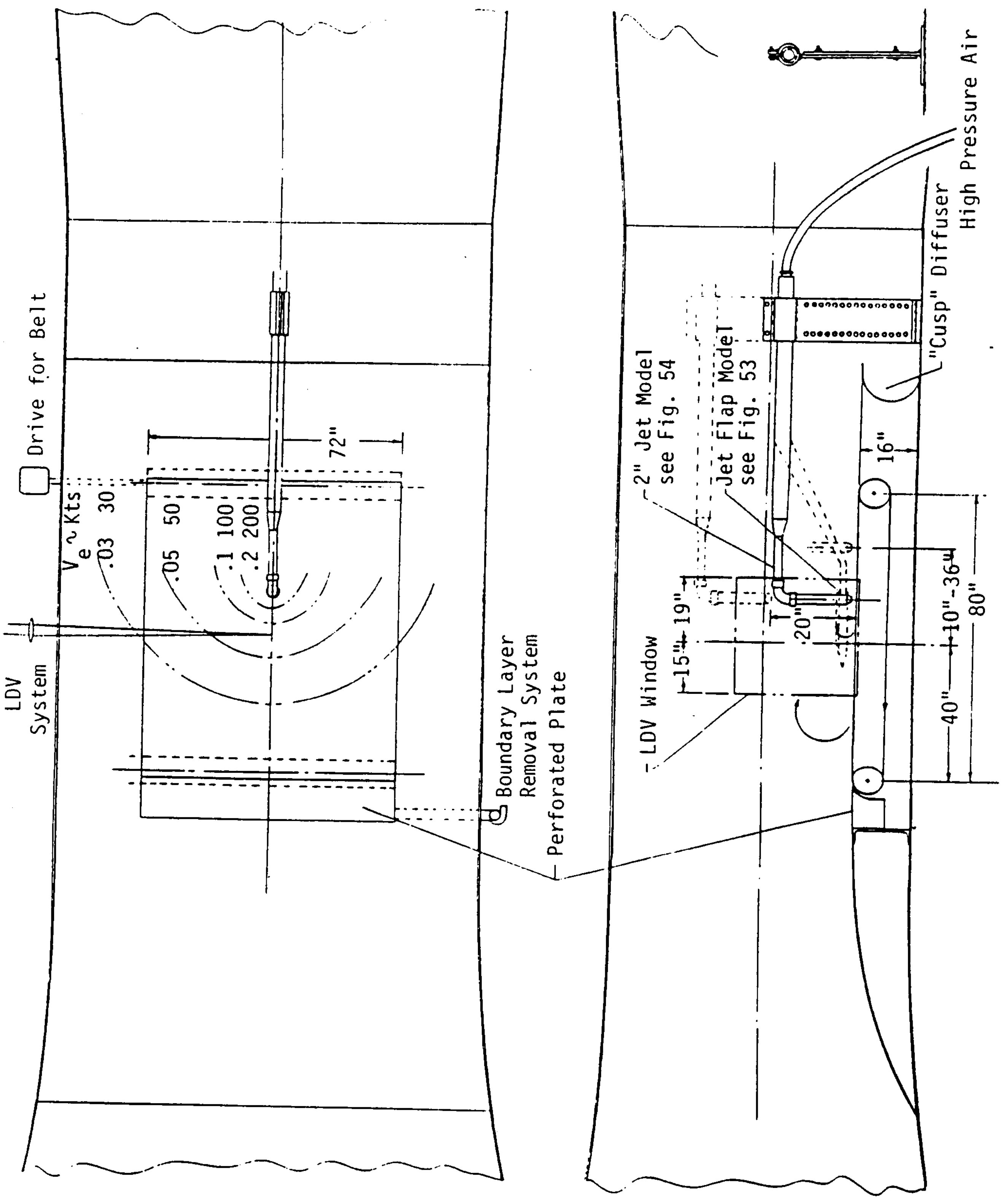

Figure 53.- Belt installation in 7 by 10 foot tunnel.

C-2

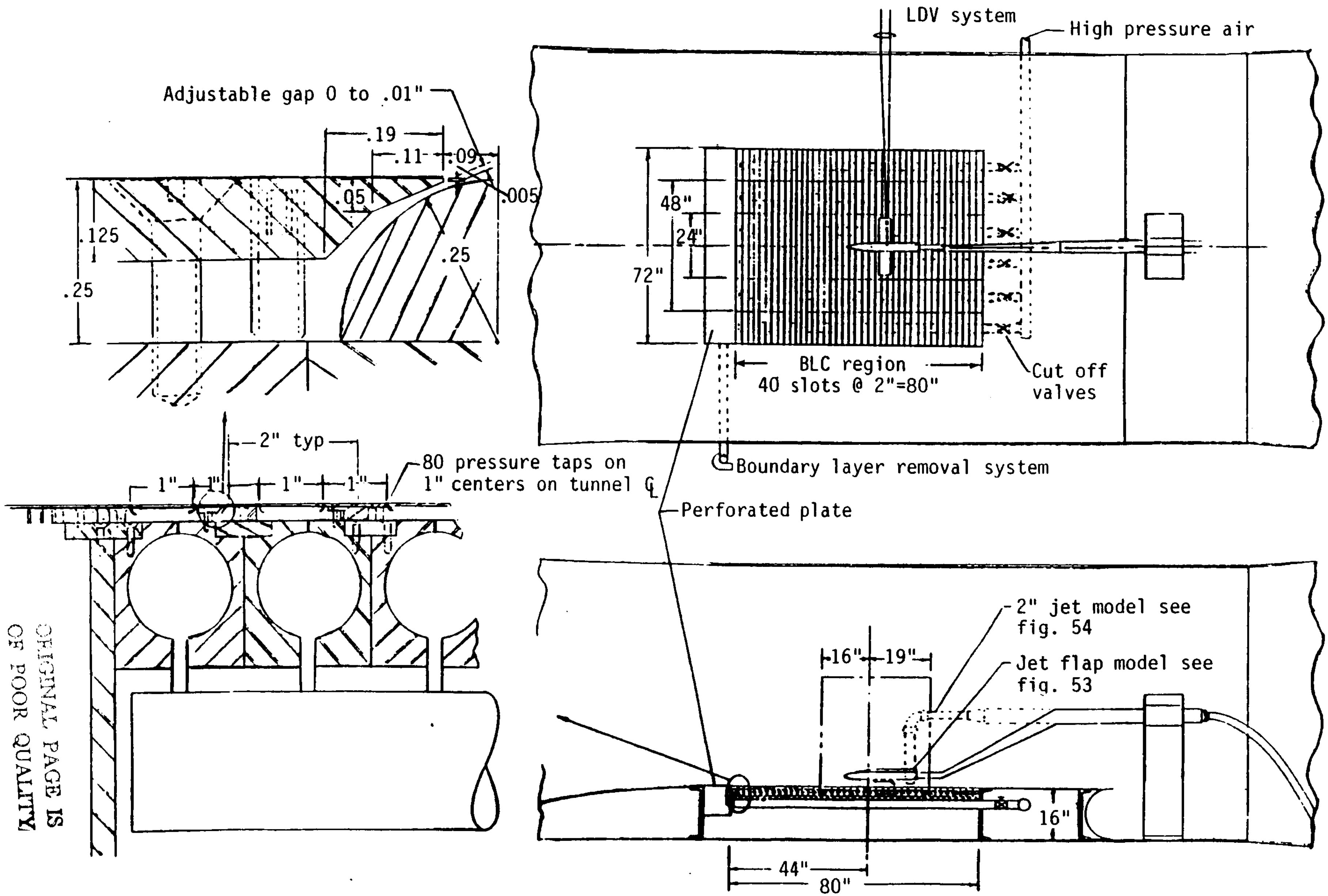

Figure 54.- BLC ground board in the 7 x 10 foot tunnel.

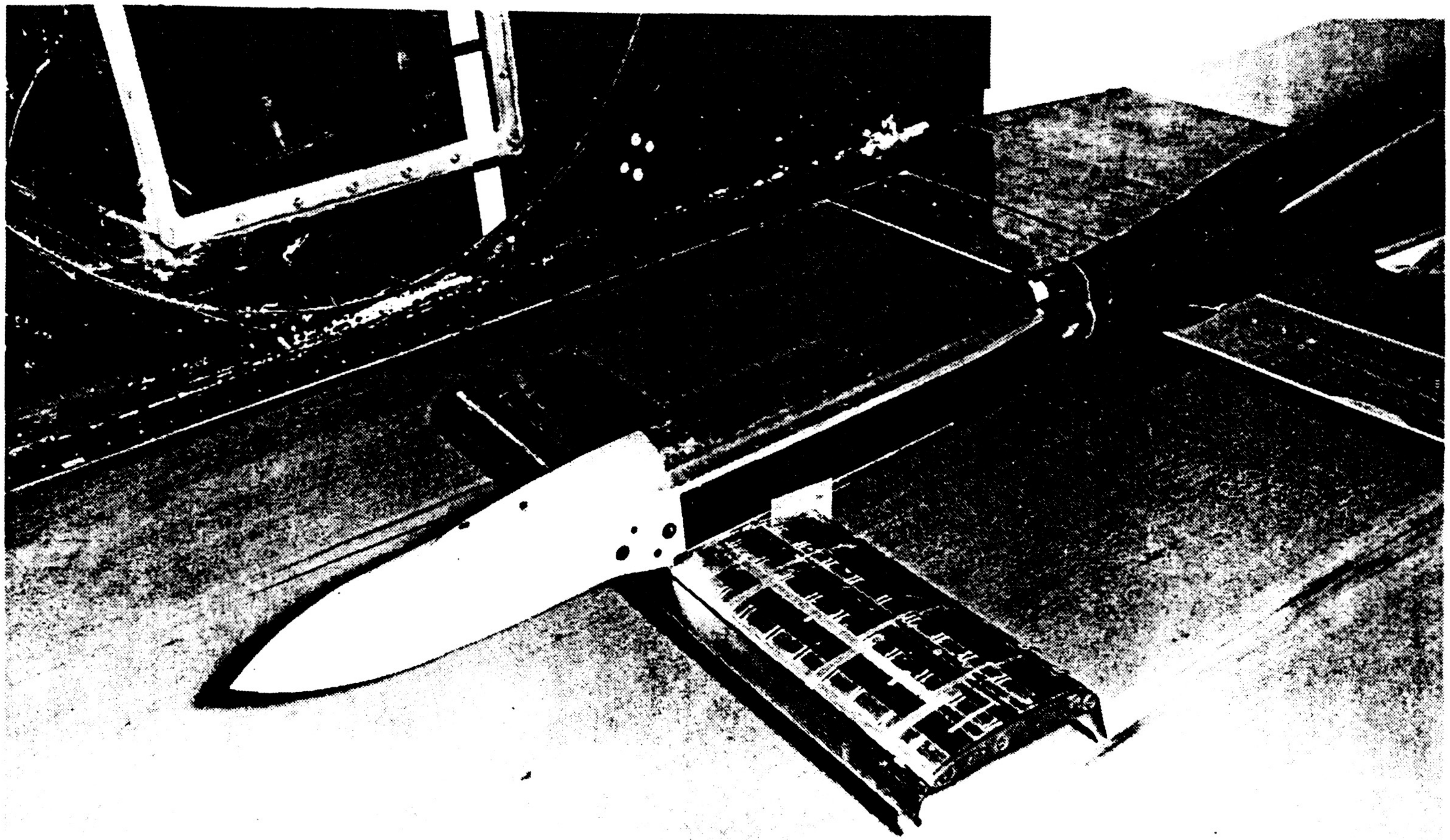

Figure 55.- The knee blowing jet flap model used in Ref. 43.

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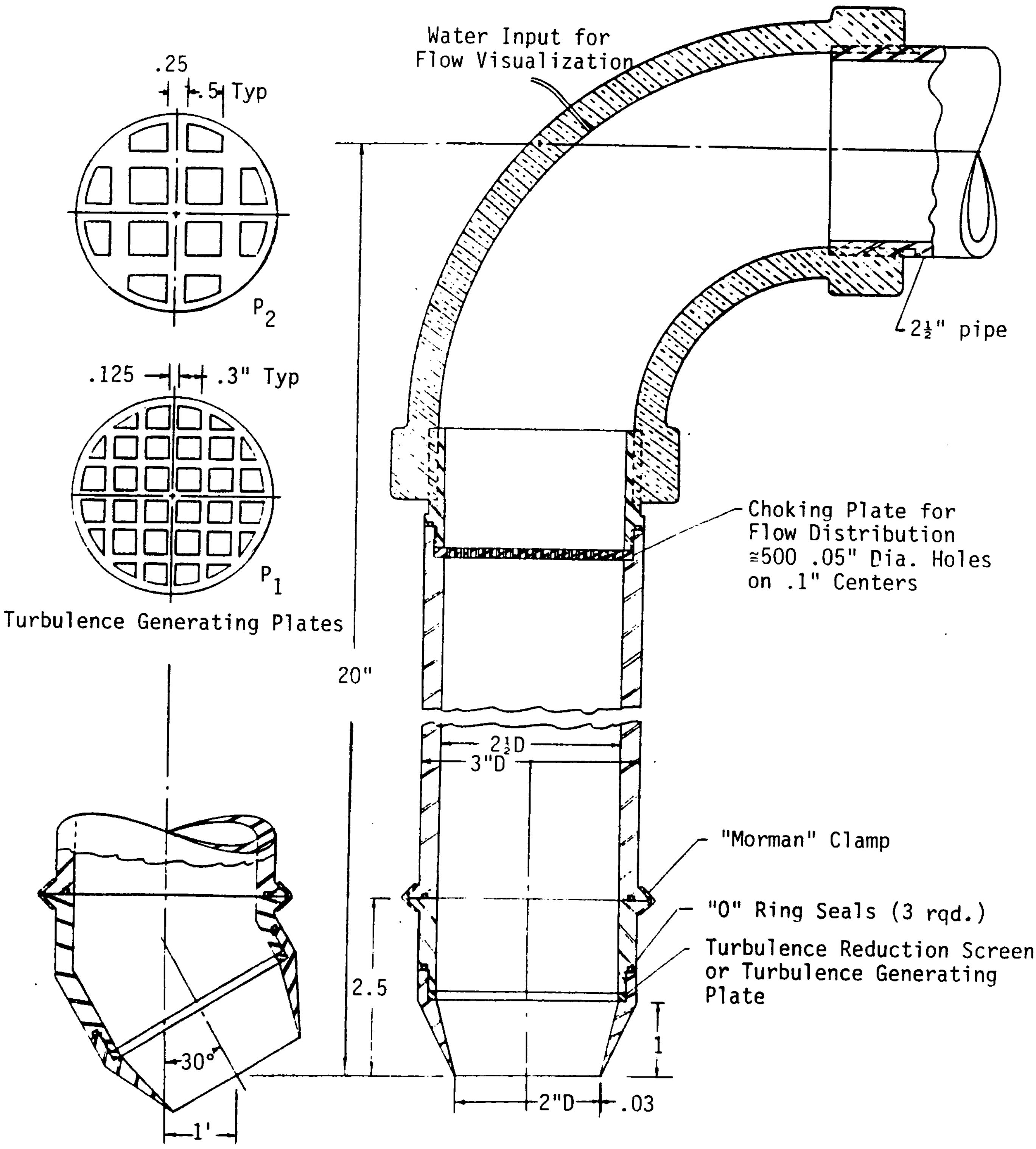
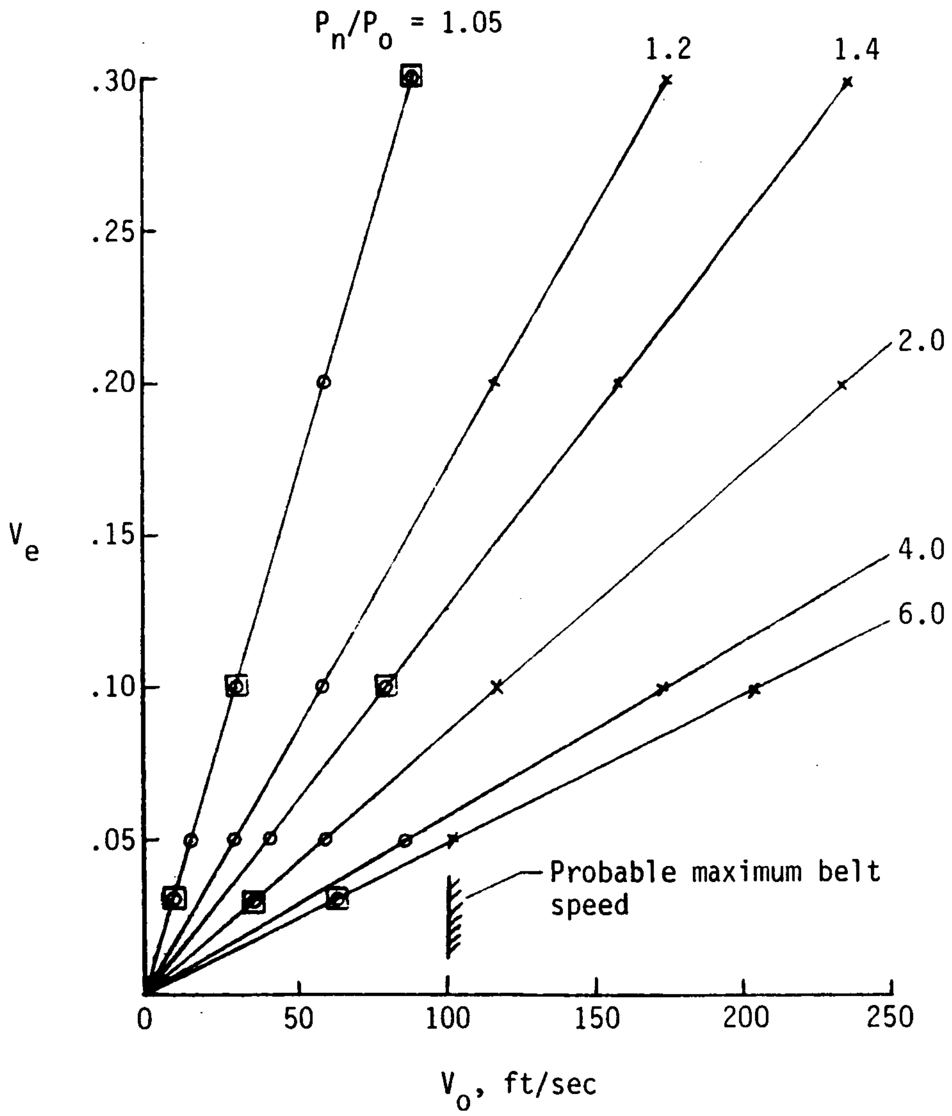


Figure 56.- Details of 2-inch jet model.



Free Stream Velocity, V_o, fps

P_n/P_o \ V_e	1.05	1.2	1.4	2.0	4.0	6.0
.03	8.7			35		60
.05	14.5	28.6	39	58	86	100
.10	29	57	78	116	171	201
.20	58	114	156	232		
.30	87	171	234			

Extended range tests over BLC ground board

Tests over belt

XX To be used in BLC ground board development

Figure 57.- Test matrix for 2-inch jet model in the 7 × 10 tunnel.

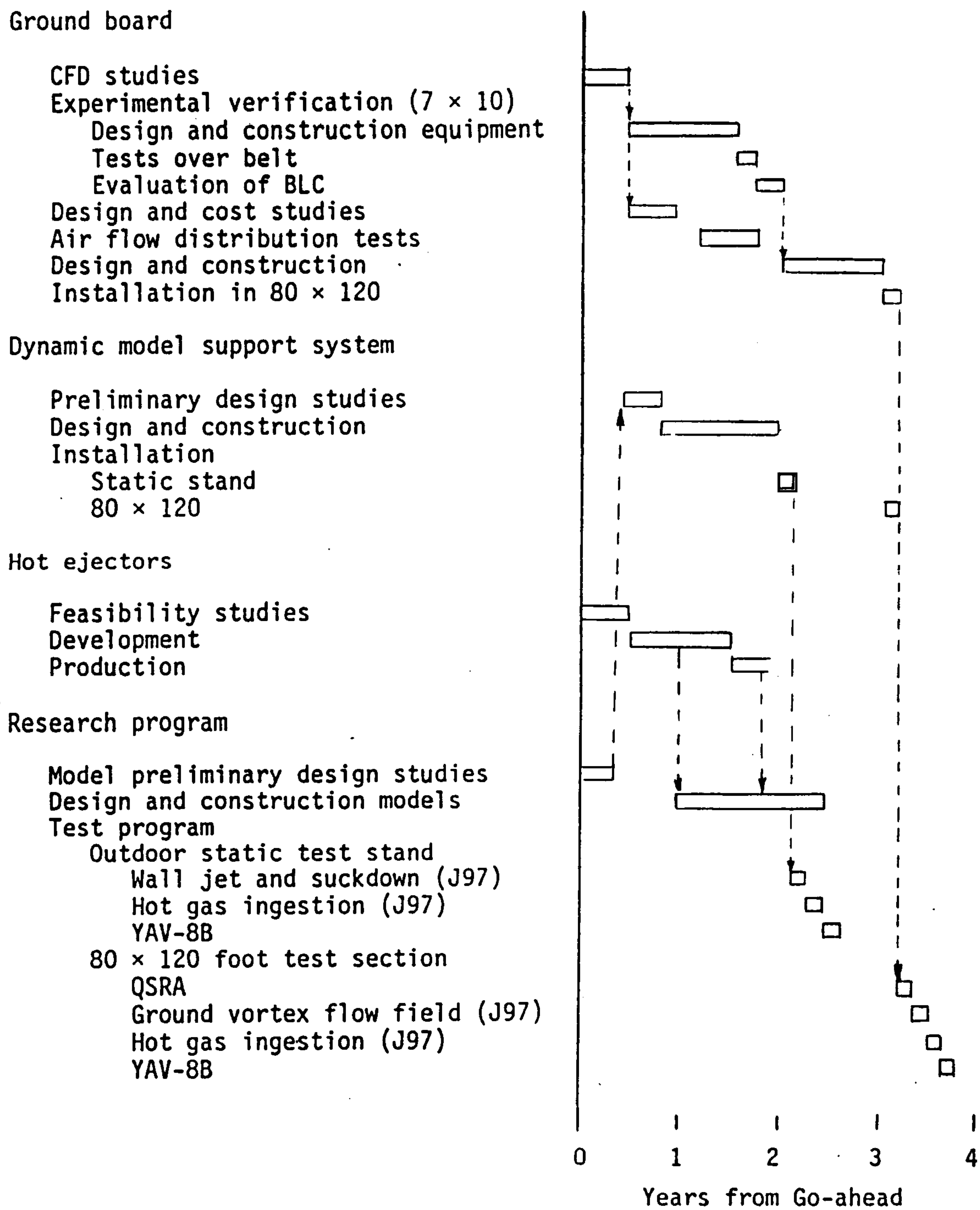


Figure 58.- Suggested development and test schedule.

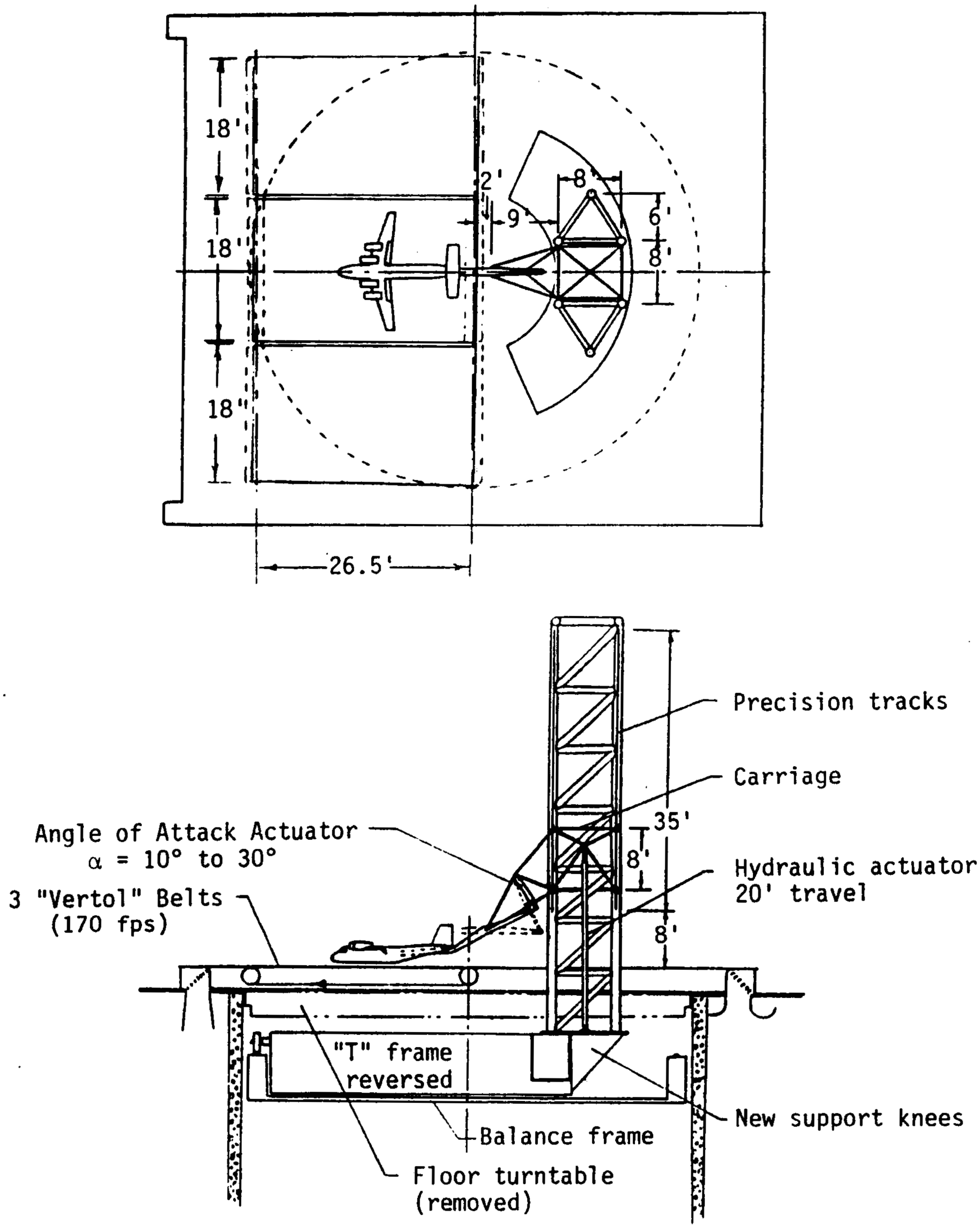


Figure 59.- Alternative "belt" ground board installation

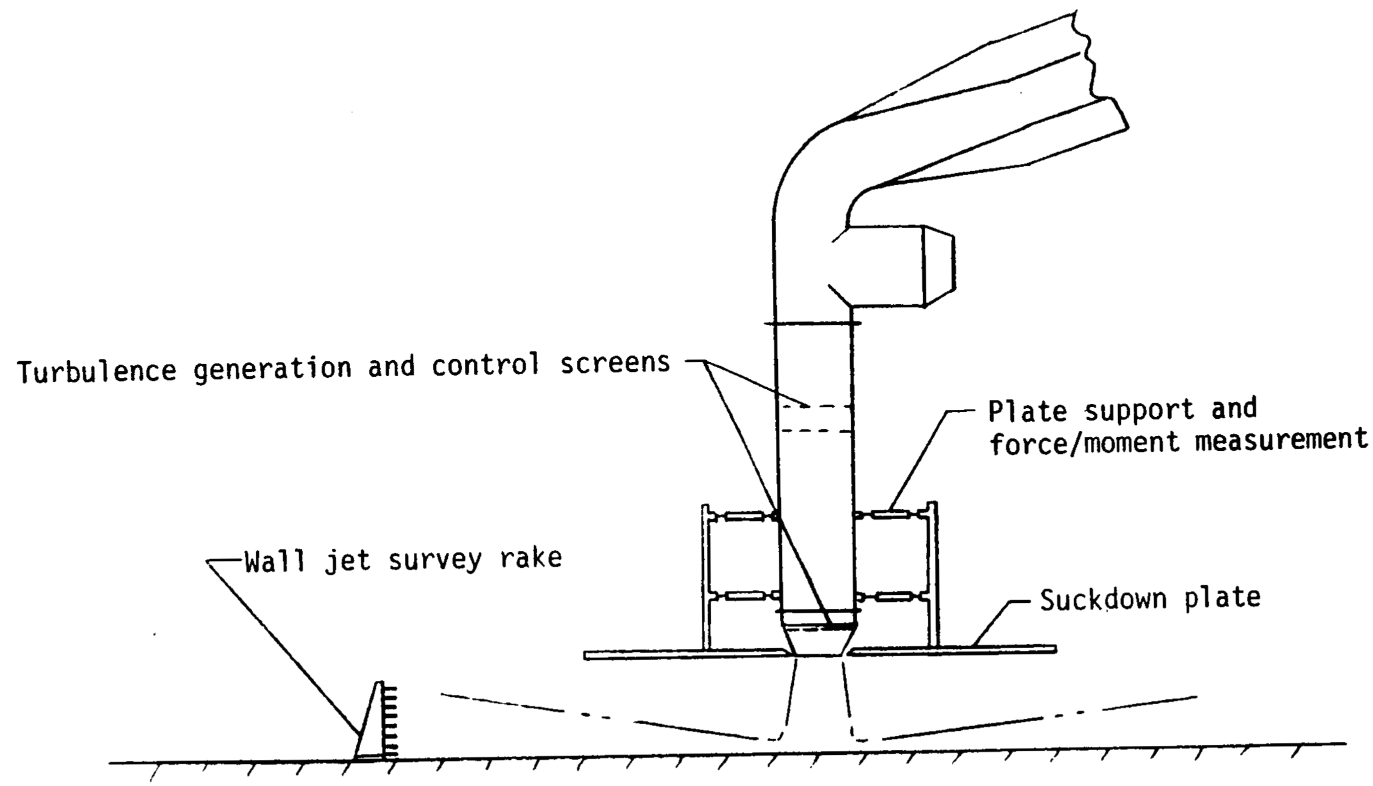


Figure 60.- Schematic of set-up for fundamental studies of effect of turbulence on suckdown.

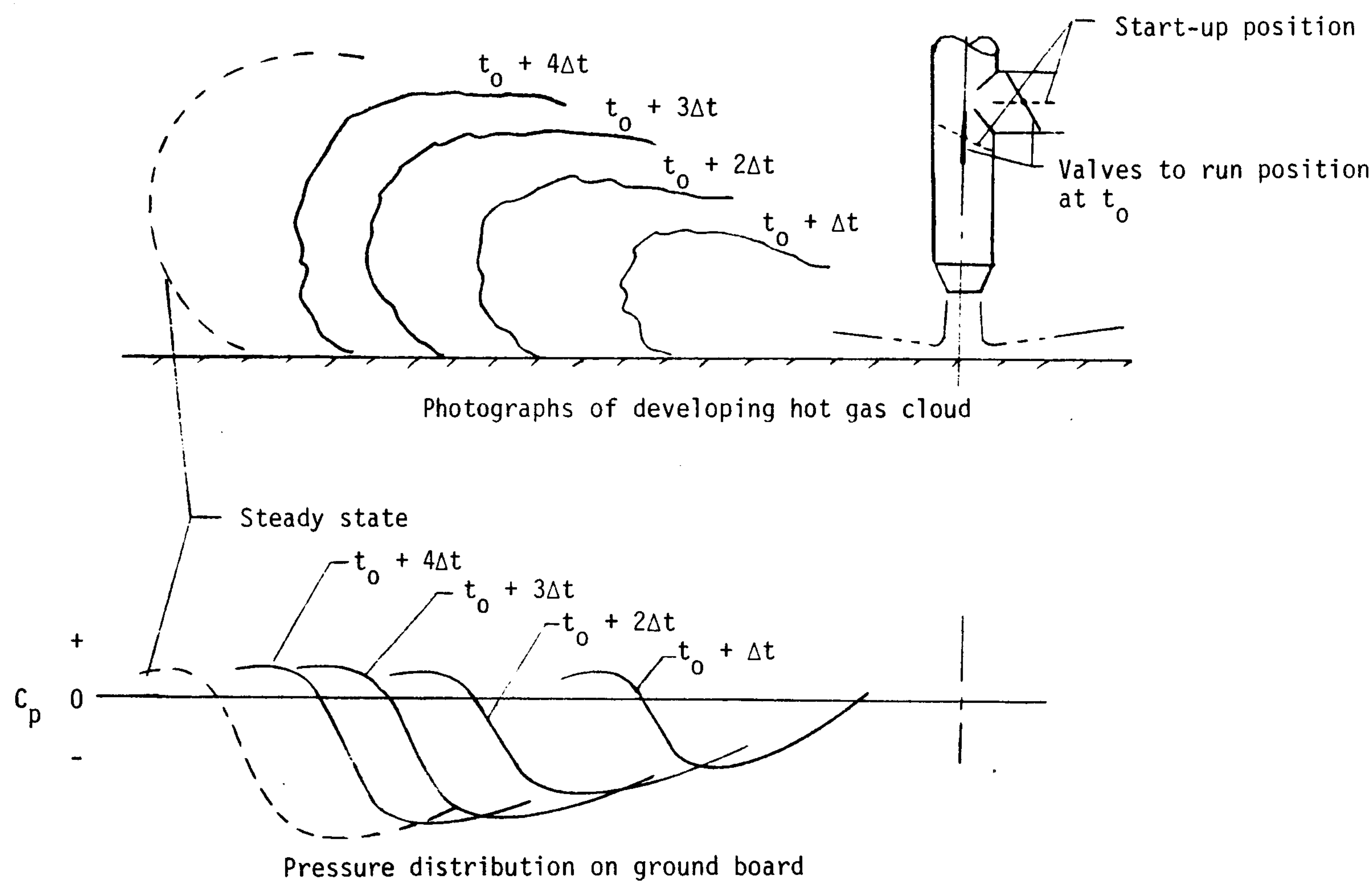


Figure 61.- Time history of flow field development.

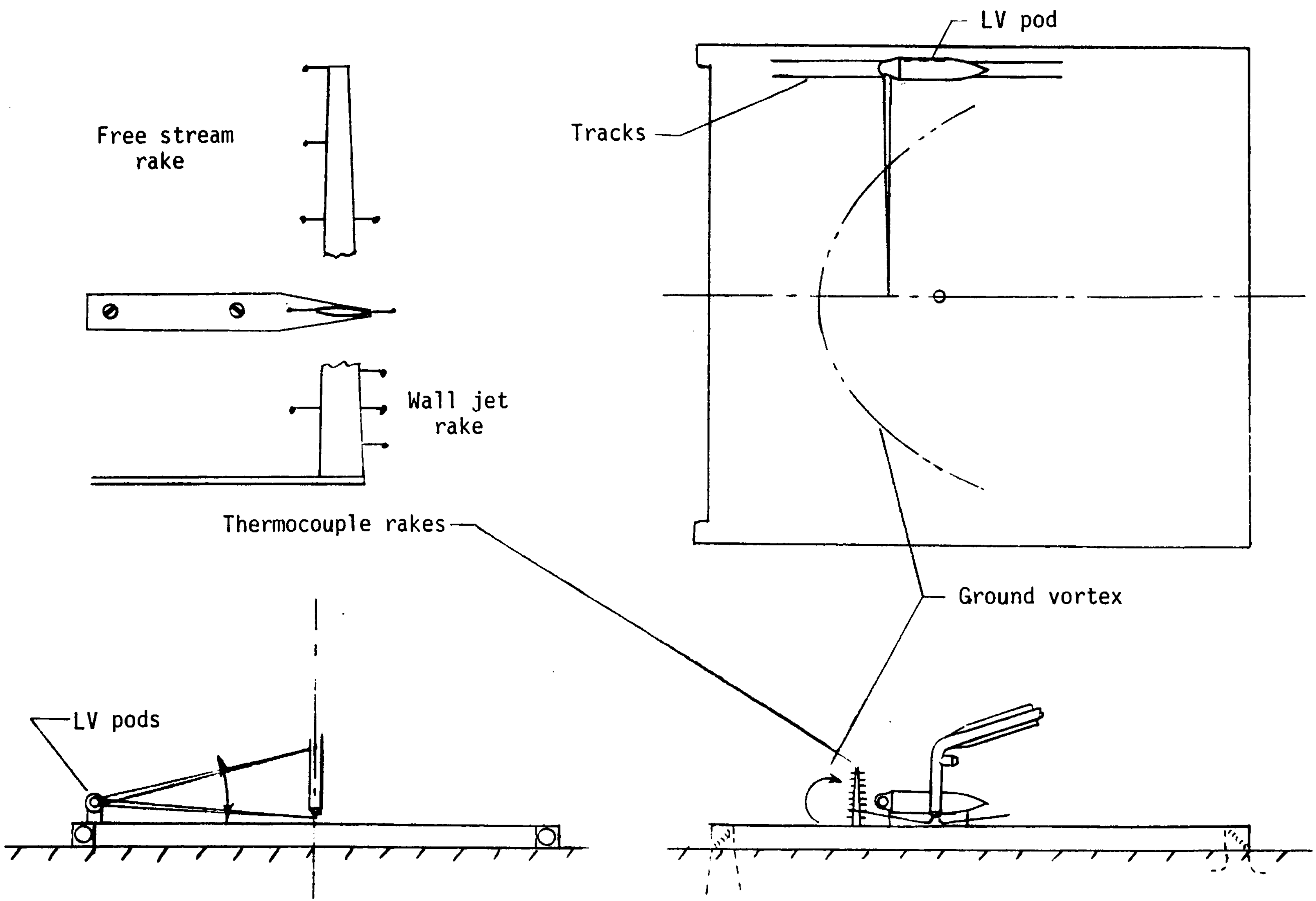


Figure 62.- Installation of laser velocimeter system and thermocouple rakes.

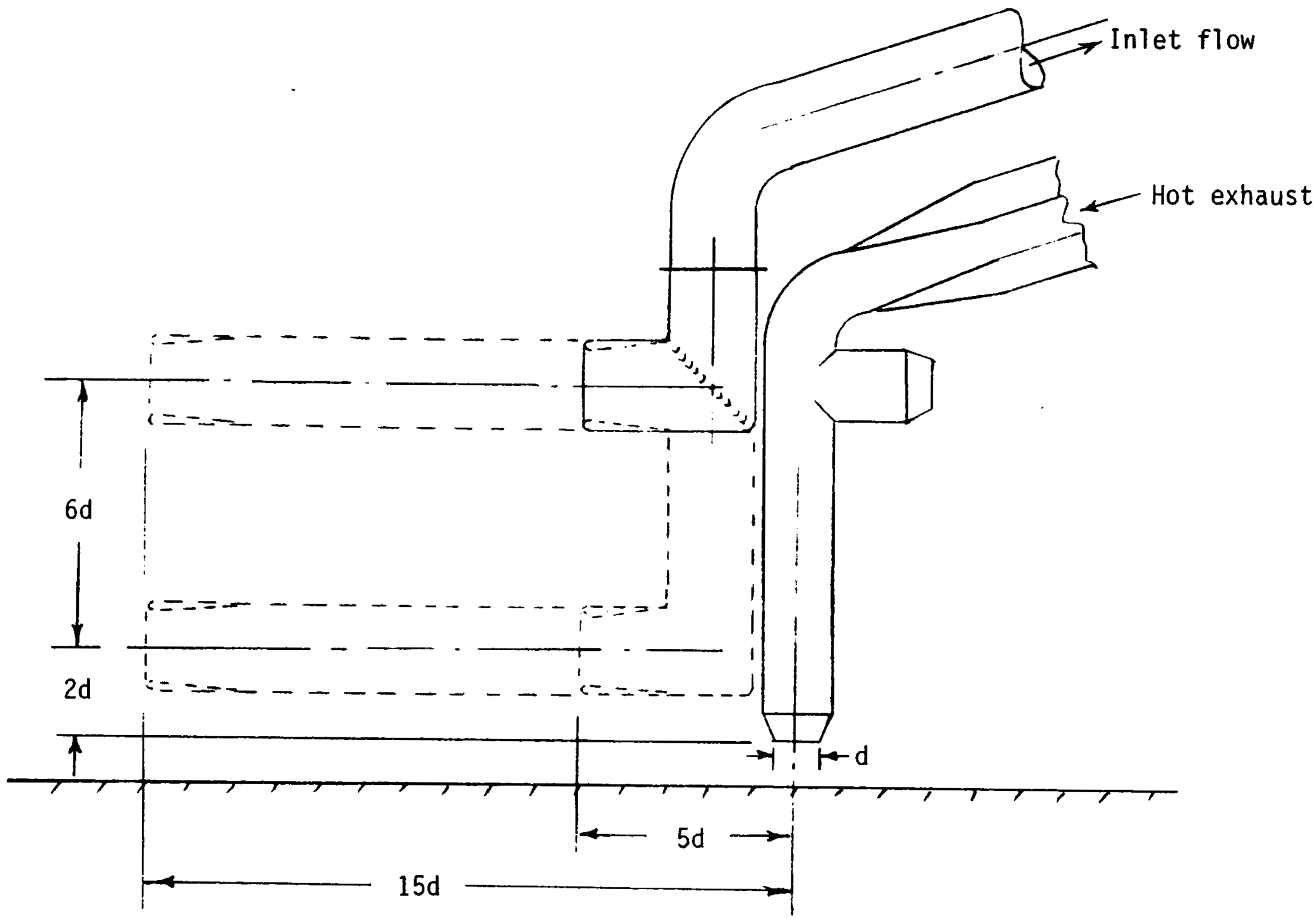


Figure 63.- Inlet locations for hot gas ingestion studies.

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16. Abstract

The current understanding of the effects of ground proximity on V/STOL and STOL aircraft is reviewed. Areas covered include 1) single jet suckdown in hover, 2) fountain effects on multijet configurations, 3) STOL ground effects including the effect of the ground vortex flow field, 4) downwash at the tail, and 5) hot gas ingestion in both hover and STOL operation.

The equipment needed for large scale testing to extend the state of the art is reviewed and developments in three areas are recommended as follows:

1) Improve methods for simulating the engine exhaust and inlet flows.

2) Develop a model support system that can simulate realistic rates of climb and descent as well as steady height operation.

3) Develop a blowing BLC ground board as an alternative to a moving belt ground board to properly simulate the flow on the ground.

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