HOT-GAS INGESTION AND JET INTERFERENCE EFFECTS FOR JET V/STOL AIRCRAFT

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SUMMARY

Tests have been conducted in the Langley full-scale tunnel and the Langley 7- by 10-foot tunnels to investigate three of the problems that are unique with jet-powered VTOL aircraft. These problems are: (1) hot-gas ingestion, (2) aerodynamic suck-down, and (3) jet interference in transition flight. The tests concerning hot-gas ingestion were conducted on a large-scale fighter-type model which had a J85 turbojet engine mounted in the fuselage to provide the model exhaust and inlet flow during the tests. Results of the hot-gas ingestion tests showed that aircraft configuration - particularly the exhaust and inlet arrangement - and surface winds can greatly alter the ingestion problem. Deflecting the engine exhaust gases rearward and making rolling take-off to stay ahead of the hot-gas field appears to be one solution to the hot-gas ingestion problem. Another solution is to design the aircraft so that components such as wings shield the engine inlets from the direct path of the hot exhaust gases. The state of the art of hot-gas ingestion is still in an exploratory stage. It is certainly not such that one could accurately predict the inlet air temperature rise for any particular configuration or operating condition. Only gross predictions of ingestion tendencies of new configurations could be made within the scope of the present available data. At the present time, therefore, it should be considered necessary, in the development of a VTOL airplane, to make hot-gas ingestion tests of the particular configurations and operating conditions that are expected to be encountered.

Tests concerning the aerodynamic suck-down and jet interference have been conducted on a number of small-scale models. The results of these investigations have shown that the design principle that should be used to reduce the aerodynamic jet interference effects, on ground and during transition, are in conflict with the design principles that should be employed to reduce hot-gas reingestion effects. It is recommended that future test programs should be coordinated and related, in a manner such that both aerodynamic interference tests and hot-gas reingestion tests will be made on identical configurations, though not necessarily the same model.

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FOR JET V/STOL AIRCRAFT

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INTRODUCTION

Since the advent of the turbojet-powered VTOL aircraft several serious problems have been recognized. Three of these problems are: (1) hot-gas ingestion which occurs when the engines ingest their own exhaust or air heated by the exhaust, (2) aerodynamic suck-down, and (3) jet interference in transition flight which results from the jet efflux beneath the aircraft. The purpose of the present paper is to examine these three problem areas in some detail with a review of some recent test information relating to these problems.

The general exhaust and inlet flow patterns that cause hot-gas ingestion are shown schematically in figure 1 for still air and with surface winds. A single, fuselage mounted lift engine is illustrated for simplicity. Multiple engine configurations would complicate the flow patterns; however, this same general flow pattern will still exist. In still air the main part of the exhaust flow will be carried far away from the aircraft and probably will not get reingested into the engine. As the mainstream flows outward it entrains surrounding air, however, and slows down. The entrainment process is highly turbulent and some of the heated air is shed, and when these hot gases rise, because of buoyancy, they are close enough to the inlet to be sucked in, resulting in elevated temperature in the engine inlet. In still air, therefore, the hot-gas ingestion problem is related to the near-field flow.

The exhaust and inlet flow patterns with surface winds, however, are quite different. The exhaust flow is blown back toward the aircraft, and in some cases, very hot inlet air temperatures occur before the aircraft can accelerate up and away from the hot-gas field.

The hot-gas ingestion problem is serious because of the reasons shown in figure 1. The elevated inlet air temperatures cause a loss of engine thrust; and in some instances very rapid inlet temperature increases or large inlet temperature distortions across the engine face can result in engine stall. Some of the factors involved in the hot-gas ingestion phenomenon have been found to be (fig. 1): (1) buoyancy of the hot exhaust, (2) surface winds, and (3) aircraft configuration.

Although hot-gas ingestion is recognized as a serious problem (refs. 1 and 2), very little systematic research of a generalized nature has been done, and most of the generalized research that has been done has been at small scale. (See refs. 2 and 3.) It is not certain that known scaling parameters are applicable in all cases, so large-scale testing needs to be done until the scaling parameters are verified. Because of this need for large-scale test information, the NASA Ames Research Center initiated an investigation utilizing the large-scale model shown in figure 2. The model was of a relatively specific airplane configuration having in-line lift engine arrangements with aft, side-by-side mounted lift-cruise engines. The results of the investigation are reported in references 4 and 5. In order to provide additional large-scale information of a more generalized nature the Langley Research Center initiated an investigation to study the problem of hot-gas ingestion of several jet VTOL fighter-type configurations. A photograph of the model is shown in figure 2. The tests were conducted outdoors (ref. 6) and in the Langley full-scale tunnel for four exhaust nozzle arrangements with test variables of model height above the ground, wing height, engine inlet position, and wind speed. The data presented herein will be limited to those that were obtained during the Langley tests which were felt to be more generalized than the Ames Research Center investigation.

NOTATION

C_T	thrust coefficient, T/qS
D_e	equivalent diameter; diameter of a single nozzle having the same area as the sum of several nozzles of a multijet configuration, ft
h	height of model above ground, ft
ΔL	increment in lift due to interference, lb
ΔL_b	increment in lift due to ground proximity, lb
M_X	rolling moment, ft-lb
ΔL_g	increment in lift due to ground proximity, lb
ΔM	increment in pitching moment due to interference, ft-lb
q	free-stream dynamic pressure, lb-ft^2
S	wing area, ft^2
T	thrust, lb
V_j	jet velocity, ft/sec
V_∞	free-stream velocity, ft/sec

δ_f flap deflection angle, deg

δ_j jet deflection angle, deg

ρ_j air density in jet, slug-ft^3

ρ_∞ free-stream air density, slug-ft^3

$(V/V_j)_e$ effective free-stream-to-jet-exit-velocity ratio, $\sqrt{\dfrac{\rho_\infty V_\infty^2}{\rho_j V_j^2}}$

MODEL AND TESTS DESCRIPTION

Hot-Gas Ingestion Model

The model used in the Langley investigation was approximately a 1/3-scale VTOL jet-fighter configuration. The exhaust and inlet arrangements used are shown in the sketches of figure 3. The side nozzle arrangement is somewhat similar to that of the Hawker-Sidley P.1127. Although forward-facing side inlets are illustrated, top inlets (directly over the nozzles) were also tested for all nozzle configurations except the side nozzle configuration which was tested with side inlets only. The general arrangement of the model showing the engine-inlet and exhaust relationships is shown in figure 4. The engine was mounted horizontally in the fuselage with the engine inlet attached to a plenum which allowed inlet air to be taken from either a top inlet position or forward-facing side inlets. The wing could be mounted in either a high or a low position on the fuselage.

Hot-Gas Ingestion Tests

The tests were conducted for an exhaust nozzle pressure ratio of about 1.8 and an exhaust gas temperature of 1200° F. The single nozzle diameter was 12 inches (30.48 cm) which was also the effective diameter of all the test configurations.

Since with exhaust nozzles vertical hot-gas ingestion would normally begin at the time of engine start, and since some time must be allowed for stabilizing engine conditions before recording data, some method is obviously needed to remove the hot gases from the vicinity of the model during this initial engine start and stabilization period. The method used during the subject investigation was remotely controlled exhaust nozzles capable of deflection angles of straight down and 25° rearward. In order to establish realistic time intervals, discussions were held with NASA pilots who have flown jet VTOL aircraft, and it was decided to conduct all of the Langley tests in the following manner: (1) start the engine and stabilize at idle speed with nozzles deflected rearward 25°; (2) advance the throttle to obtain 80-percent engine rpm and then deflect the nozzles straight down; (3) pause about 3 seconds (simulating time for pilot checks), and then (4) advance the throttle to full power. After running at full power for about 10 seconds the test was terminated by shutting off the engine. This 10-second interval provided ample time to establish the operating level of the inlet air temperatures.

All the data obtained during the tests were recorded on oscillograph recorders in the form of time-history information utilizing bare-lead 0.005-inch (approximately 0.013 cm) thermocouples. Each of the side inlets had 18 thermocouples and top inlets had 9 thermocouples. A typical time history is shown in figure 5. The time histories shown are in the upper and lower portion of the left-hand inlet of the side inlet, rectangular nozzle configuration for a nozzle height of about one-nozzle diameter. The inlet air temperatures are seen to rise very quickly, following downward nozzle deflection, and are seen to vary in a very erratic manner. The inlet air temperature rise data presented herein are the average temperature increase in the inlet that occurs between the instant of downward nozzle deflection to a relatively stabilized temperature condition following the attainment of full-engine thrust. The engine thrust level is indicated by the nozzle pressure with time shown also on figure 5.

RESULTS AND DISCUSSION

Hot-Gas Ingestion

Still air.- The inlet air temperature rise in still air of all the nozzle and inlet configurations investigated is shown in figure 6 for a range of nozzle heights above the ground in effective nozzle diameters. The wing used was a high-mounted delta wing.

For convenience, the inlet air temperatures of the two forward inlets of the top, multiple inlet configurations were averaged and are presented herein. The rearmost two inlets experienced somewhat lower temperatures because of wing shielding.

With either top or side inlets the inlet air temperature rise was quite low for the single and in-line nozzle configurations, but the rectangular and side nozzle configurations resulted in very high values of inlet air temperature rise. The inlet air temperature rise is seen to be very dependent upon the nozzle and inlet position. The very large inlet air temperature rise experienced by the rectangular nozzle arrangement is believed to be the result of the fountain of hot gases that forms between the ground-impinging jets. This fountain of hot gases spreads around the fuselage and quickly arrives in the vicinity of the inlets before it has had time for much mixing with the surrounding air and is, therefore, still very hot. The side inlet, rectangular nozzle arrangement has very high inlet air temperatures near the ground (the order of 100° F at a nominal landing gear height of about 1.5 diameters). Of particular interest, however, is that the inlet air temperature rise in general decreases very rapidly with increasing height and would probably be of little concern by the time the aircraft had risen 5 to 10 nozzle diameters above the ground.

Surface winds.- The effect of surface winds on the test configurations is shown in figure 7. It is assumed that the aircraft would be headed into the existing wind, so that data are presented for head wind conditions. The inlet air temperature rise in degrees Fahrenheit is presented as a function of wind speed in knots for a model height of about one effective nozzle diameter for a high-delta-wing configuration.

As previously stated, surface winds have been found to be cause for concern, and the reason becomes apparent here. The inlet air temperature rise, in general, is seen to increase with very low headwinds. Of particular interest, however, is that at forward speeds of the order of 30 knots, the hot-gas ingestion problem has just about disappeared. It should be pointed out that the inlet temperature for the single-jet configuration indicates a significant temperature rise even for high-speed wind conditions, particularly for the side inlets. The exact phenomena involved are not understood at this time; however, it is felt that the single-jet case is not a practical configuration and it was included in this program to provide a base of reference. The observation of smoke ejected through the exhaust nozzles shows that the exhaust gases are swept rearward and below the inlets for speeds greater than about 30 knots. This suggests a technique for eliminating the problem of hot-gas ingestion. The technique is one called a rolling vertical take-off and has frequently been proposed. For the particular configurations of the present paper, the pilot could leave the nozzles deflected rearward until forward speeds the order of 30 knots were reached and at that time could deflect the nozzles downward and take off without experiencing any hot-gas ingestion. Of course vertical take-off from a raised grating would be effective in reducing hot-gas ingestion, but the raised grating would present logistic and other problems for operational military aircraft. The rearward nozzle deflection technique cannot be used to avoid the problem of hot-gas ingestion during vertical or very low-speed landing, however, since a near vertical nozzle orientation would be required to support the aircraft in a condition of horizontal equilibrium. It appears that small rearward nozzle deflections would not eliminate the hot-gas environment near the ground. Tilting the engine nozzles apart or some other technique may be effective in reducing the hot-gas ingestion during vertical landings, however. In any case, some method other than slow forward translation speeds, must be used for the elimination of hot-gas ingestion on landing. Even though some reduced thrust could be tolerated, because landings are normally made at reduced weight, any hot-gas ingestion that could cause one or more engines to stop operating could not be tolerated during a landing maneuver.

In general, the side inlets are seen to result in higher values of inlet air temperature rise than the top inlets (fig. 7), and the various nozzle arrangements are seen to result in very different amounts of ingestion. Aircraft configuration - particularly the inlet and exhaust nozzle arrangement - is seen, therefore, to be a major factor in the hot-gas ingestion problem.

Wing position.- In addition to the obvious configuration variables of inlet and nozzle arrangement, the placement of the wing on the fuselage was also found to be an important parameter. The effect of wing height on the inlet air temperature rise of the rectangular and the in-line nozzle arrangements with top inlets for a zero wind condition is shown in figure 8. Inlet air temperature rise is shown as a function of model height above the ground in effective nozzle diameters. The wing in a low position is seen to greatly reduce the inlet air temperatures at all test heights of the rectangular nozzle configuration, but has little effect on the in-line nozzle configuration which had very low inlet air temperatures with either wing position. The reason for the low inlet air temperature, as noted by observing smoke from the exhaust nozzles, was that the low wing caused the upward-flowing hot gases to be deflected outward and away from the inlets. The in-line arrangement has a much less intense fountain than the rectangular arrangements and therefore shows little temperature rise with either a high or a low wing. The effect of fore or aft inlet location is illustrated in figure 9. The temperature rise data are for the rectangular nozzle configuration with top inlets for a range of nozzle heights and wind speeds. The temperatures of the two forward inlets and the two rear inlets were averaged. The relatively unprotected forward inlets have higher inlet temperatures than do the rear inlets. The reason for the lower rear inlet temperature is that the wing shields these inlets from the direct upward flow of hot gases.

Temperature distortion.- As stated in the outset, one of the main reasons for concern about the hot-gas ingestion problem is that very rapid inlet air temperature rises and/or very uneven temperatures across the face of the engine inlet can cause compressor stall resulting in engine flameout. Engine stall has been experienced by several investigators and, in particular, by the Ames and Langley experimenters. Of course, an engine stall cannot be tolerated in a jet VTOL aircraft so means of preventing the stall must be found. To illustrate the very rapid rise in inlet air temperatures following downward nozzle deflection and the very large temperature distortions that can occur across the face of the engine, the data of figure 5 will be reviewed. The time-history plot is for the rectangular nozzle configuration with side inlets with the model height at about one effective nozzle diameter. The two oscillograph traces represent the inlet temperature existing at two locations of the left-hand inlet for a zero wind condition. The inlet air temperature near the bottom of the inlet is seen to rise almost immediately following downward nozzle deflection to about 150° F with very rapid variations in the temperature. These rapid rises and variations are known to precipitate engine stall. The upper temperature probe location indicates very rapid changes in temperature also, but the temperature level is of the order of 50° F. Comparison of the two traces shows the large distortions of temperatures that can occur across the face of a jet VTOL engine. Distortions of this magnitude or less (100° across the engine face) are also known to aggravate the stall problem.

Although the engines used in the Ames and Langley investigations are early versions of turbojet engines and are known to be very susceptible to stall, the newer engines of today, because of their very high performance, will probably be just as susceptible to these inlet temperature conditions. In addition to the inlet temperature problem, rapid fluctuations of inlet pressures are also known to result in engine stall on some occasions. Because the stall problem cannot be tolerated on a jet VTOL aircraft, these inlet air temperature rise and pressure fluctuation problems should continue to be given much consideration by the V/STOL engine manufacturers.

It should be reemphasized that one of the principal factors of hot-gas ingestion is aircraft configuration, that is, how the engine nozzles and inlets are arranged. The problem with multiple nozzle arrangements is that the exhaust gas tends to flow upward between the nozzles where it may reach the vicinity of the inlets very quickly while it is still very hot. The solution to this situation appears to be to group the engine nozzles in such a manner that the hot-gas fountain effects are minimized; by placing the inlets in an area removed from the direct path of the hot exhaust gases; and by designing the aircraft so that components, such as the wing, shield the inlets from the direct path of the hot gases. The other main cause of hot-gas ingestion is ground winds. In this case the problem is that winds tend to blow the far-field gases back toward the aircraft and into the inlets before these gases have had time to mix with the surrounding air and cool off. This problem of winds is difficult to assess since different configurations are affected differently by winds. One solution to the problem, and perhaps the configuration problem as well, appears to be to deflect the engine exhaust so that it is directed away from the aircraft and to make rolling takeoffs to stay ahead of the hot-gas field.

One observation that should be made from the foregoing presentation is that the state of the art of hot-gas ingestion is still in an exploratory stage. It is certainly not such that one could accurately predict the inlet air temperature rise for any particular configuration or operating condition. Only gross predictions of ingestion tendencies of new configurations could be made within the scope of the present available data. At the present time, therefore, it should be considered necessary in the development of a VTOL airplane, to make hot-gas ingestion tests of the particular configurations and operating conditions that are expected to be encountered.

Aerodynamic Interference Effects

Ground effects for hovering flight.- The hot-gas reingestion data just discussed as well as other work to date has indicated that the design principles which should be employed to minimize hot-gas reingestion are in direct conflict with those that should be used to minimize the well-known aerodynamic suck-down in ground effect. For example, the hot-gas reingestion work indicated that use of a low wing is quite powerful in reducing inlet temperature rise. However, from the aerodynamic suck-down in ground effect point of view, the high wing is preferred (ref. 7). Also the rectangular array which produces a favorable pressure region between the jets to reduce the aerodynamic suck-down (ref. 7) also produces high inlet temperatures as does spacing the jet exits further apart. As is well known, in addition to the loss of thrust from hot-gas ingestion when hovering near the ground, there is the aerodynamic lift loss resulting from the proximity of the ground during hovering flight as illustrated in figure 10. The flow characteristics are shown for a single-jet nozzle with air exhausting vertically through a flat plate at a height h above the ground. As the air from the jet impinges on the ground, it flows outward along the ground as shown. The entrainment of the surrounding air in this flow pattern creates regions of negative (suck-down) pressure. The flow pattern for multiple jet arrangements is also illustrated in figure 10. The main difference between the single and multiple jet flow patterns, of course, is the interaction of the flow between the jets of the multiple jet arrangement which results in the so-called fountain effect that creates positive pressures in the region between the jets.

Single-jet model tests.- The aerodynamic suck-down for the single-jet case is well understood and full-scale characteristics for single-jet configurations can be predicted quite well as shown by the data presented in figure 11. The increment of lift due to ground ratioed to the net thrust is plotted as a function of ground height expressed in effective nozzle diameters for full-scale flight tests and scale model tests of the X-14A airplane. L. A. Wyatt (ref. 8) has derived, from a correlation number of single-jet model tests, an empirical method to determine the effects of ground on the lift of single-jet configurations. For comparison with the model- and flight-test data, a calculated curve for the X-14A airplane, using the method of Wyatt, is also shown in figure 11. Since the jets of the X-14A are so closely spaced, it has been assumed that they act essentially like a single jet. It can be seen that the full-scale flight results are in good agreement with both the scaled model tests and the calculated results using the method of Wyatt. For this type of configuration, the hot-gas reingestion problem would be primarily due to winds.

Multijet model tests.- The serious problems of compromise between design for minimum hot-gas ingestion and aerodynamic suck-down occur for the multijet case. Although the suck-down for many multijet configurations has been investigated and many of the results have been published in the literature, the story for multijet configurations is not as clear at this time as for single jets. However, an interesting trend can be seen in the results (fig. 12) of a systematic investigation of a wing body with several different arrangements of multiple jets made by Wilhelm Seibold (ref. 9). Since the out-of-ground lift losses were not subtracted from the data of this group of tests the combined losses due to base pressure and ground effects have been plotted as the ratio of interference lift to thrust as a function of ground height to the fuselage lower surface expressed in effective nozzle diameters (fig. 12). The basic configuration consisted of four engines arranged in a cluster near the center of the wing body. The delta-wing planform was a midwing configuration. The single-jet case was obtained by ejecting air from the right near nozzle only and the results are indicative of the general trends previously shown for the single jets. The two rear jets were tested together and since the spacing for this configuration was further apart than the X-14A model tests the data show a reversing of the lift loss due to ground at very low ground heights. As the number of jets is increased to four, the lift losses become smaller. As the spacing between the jet exits increased, as is shown by the other two four-jet configurations, the interference lift becomes favorable at ground heights above approximately two effective jet diameters. The results shown here indicate a consistent trend toward reduction of lift loss with clustering the engines exits and with spacing the engines apart so as to enlarge the model area experiencing favorable pressure regions resulting from the jet interaction on the ground under the model. The increase on spacing would, however, be expected to aggravate the hot-gas ingestion problem due to the reduction in shielding of the inlets and the probable large volumes of the fountain flow.

The hovering ground effect of a model configuration having either a single row of jets down the fuselage centerline or a rectangular array of jets in the fuselage, as indicated on the model sketch, are compared in figure 13. The model as shown in the sketch at the top of figure 13 had a low wing with an aspect ratio of 5.8, a taper ratio of 0.32, and a quarter-chord sweep of 28.2°. The data were run in a recent investigation at the Langley Research Center and the results are as yet unpublished. The incremental lift due to ground is ratioed to the thrust and plotted against ground height expressed in effective jet diameters. The beneficial effect of the rectangular array is shown by a comparison of the data for the single row of jets with the clustered jet arrangement. An additional benefit can be realized by canting the nozzles outboard from the vertical through 10°. This effect is similar to an increase in jet spacing shown in figure 12 since canting the engines increases the spacing of the jet impingement on the ground. The effect of canting the engines on the hot-gas reingestion is unknown at this time, but indications are that engine canting will have an unfavorable effect.

Although the general trends of the effects of interference of multijets in the presence of the ground have been illustrated to some extent in figures 12 and 13, it should be emphasized that only the trends are known. The results of many different multijet investigations have been documented and have indicated that the magnitude of the lift interference due to ground effect in hovering flight is dependent on the model configuration as well as the jet-exit arrangement. Therefore, in spite of the fact that these two sets of test data seem to show consistent trends, attempts to correlate the effect of ground on the interference lift has not as yet produced the desired results.

Transition interference.- The aerodynamic interference effects experienced in the transition speed regime between hovering and conventional flight has been the subject of a number of investigations summarized in reference 10. A large part of the research effort on jet VTOL configurations has been the investigation of the forces and moments induced on the aircraft by interaction of the vertical jets with the free-stream airflow during transition flight. As is illustrated in figure 14, during transition flight, the jets issuing from an aircraft are swept rearward by the free-stream flow and are rapidly rolled up in a pair of vortices. These rolled-up vortices and the vorticity represented by the velocity change across the boundary of the jet induce suction pressures and a downwash on adjacent surfaces on the aircraft.

The results of an investigation of the aerodynamic interference effects during transition flight on this particular five-jet VTOL model (fig. 15) have been discussed briefly in reference 10. A typical set of interference data are shown in figure 15. The incremental interference lift due to forward flight ratioed to thrust is plotted as a function of the effective free stream to jet-exit velocity ratio representing flight from 0 or hovering flight to conventional flight speeds. For this configuration with all jets deflected down and operating, the expected suction pressures and downwash cause a loss in lift and a nose-up pitching moment that increase with speed during the transition from hovering to conventional flight. In an effort toward a better understanding of these transition characteristics, tests were run with the three front lift engines only operating. The results indicate that jets located in front of the wing result in an unfavorable lift loss. Similarly tests were made with the deflected cruise engines (rear jets) only operating and the results indicate that the lift interference is favorable. The results of this investigation and others which have been made recently indicate that the loss in lift due to interference during transition can be minimized with proper location of the lift jets with respect to the wing. The pitching-moment trim resulting from engine location also shows that proper engine location will minimize the interference effects.

In order to explore this effect of jet position more systematically, a generalized study of jet positions several wing-chord lengths ahead to several chord lengths behind an unswept wing was initiated at the Langley Research Center. In this investigation, an aspect-ratio-6, unswept, untapered, wing-fuselage model equipped with a 30-percent chord slotted Fowler flap was used. Two jets, one on either side of the fuselage, were positioned spanwise at about the 25 percent wing station and at the various longitudinal and vertical positions shown by the plus marks in figure 16. The jets were mounted independently of the wing so that only the aerodynamic forces and interference effects were measured on the wing. The data show that with the exits on the wing-chord plane, considerable jet interference was experienced even with the jet as far as four chords ahead of the wing. Favorable interference effects, however, are encountered with the jets beneath and behind the 50-percent chord point of the wing and the interference effects are most favorable for positions closest to the flap. These results show general agreement then with the results for the five-jet model which have just been discussed and results reported previously by Williams in reference 11. These favorable interference increments are believed to be due to the action of the jet in helping the flap achieve its full lift potential. Another slightly different configuration with jets both in front of and behind the wing indicated an overall favorable interference lift effect, again indicating the importance of configuration geometry on the jet interference lift and moment characteristics.

CONCLUDING REMARKS

Hot-gas ingestion tests and tests concerning aerodynamic suck-down in ground effect and jet interference in transition have indicated the following:

1. The hot-gas ingestion problem depends upon the airplane configuration, particularly the position of the inlet relative to the nozzle exit arrangement and the relative position of the wing and other elements of the aircraft that could shield the inlets from the hot exhaust gases. The nozzle arrangements are an important parameter, in-line nozzles resulted in relatively low inlet temperatures whereas rectangular arrangements resulted in relatively high inlet temperatures.

2. Wind speed has a large effect on the magnitude of the inlet air temperatures. The maximum inlet air temperatures, in general, occurred for head winds between 0 and 20 knots, and the reingestion disappeared for most multijet nozzle arrangements for head winds above 30 knots.

3. Deflecting the engine's exhaust rearward and making rolling takeoff to stay ahead of the hot-gas field appeared to be one solution to the hot-gas reingestion probe.

4. The art of hot-gas ingestion is still in an exploratory stage. It is certainly not such that one could accurately predict the inlet air temperature rise for any particular configuration or operating condition. Only gross predictions of ingestion tendencies of new configurations could be made within the scope of the present available data. At the present time, therefore, it should be considered necessary in the development of a VTOL airplane, to make hot-gas ingestion tests of the particular configurations and operating conditions that are expected to be encountered.

5. The design principles that should be used to minimize aerodynamic interference effects, both in ground effect and during transition are in conflict with the design principles which should be employed to reduce the effects of hot-gas ingestion.

6. In the future, it is recommended that related and coordinated test programs, using identical configurations (not necessarily the same model) be established to investigate aerodynamic jet interference effects, both in ground effect and during transition, and the effects of hot-gas reingestion.

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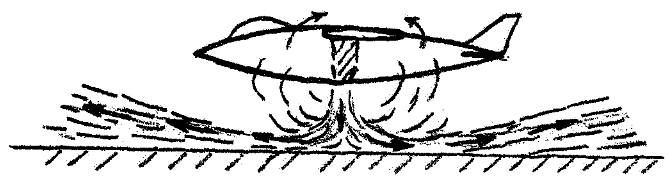
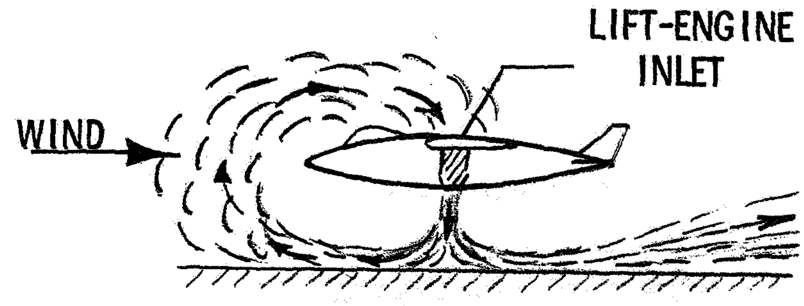
STILL AIR



SURFACE WINDS



REASONS FOR CONCERN

- THRUST LOSS
  - TEMPERATURE RISE OF 40°F CAUSES 15 % LOSS OF THRUST
- COMPRESSOR STALL
  - RAPID TEMPERATURE RISE
  - TEMPERATURE DISTRIBUTION

CAUSES

- BUOYANCY OF HOT EXHAUST
- SURFACE WINDS
- CONFIGURATION
  - EXHAUST AND INLET ARRANGEMENT

Figure 1.- Hot-gas reingestion.

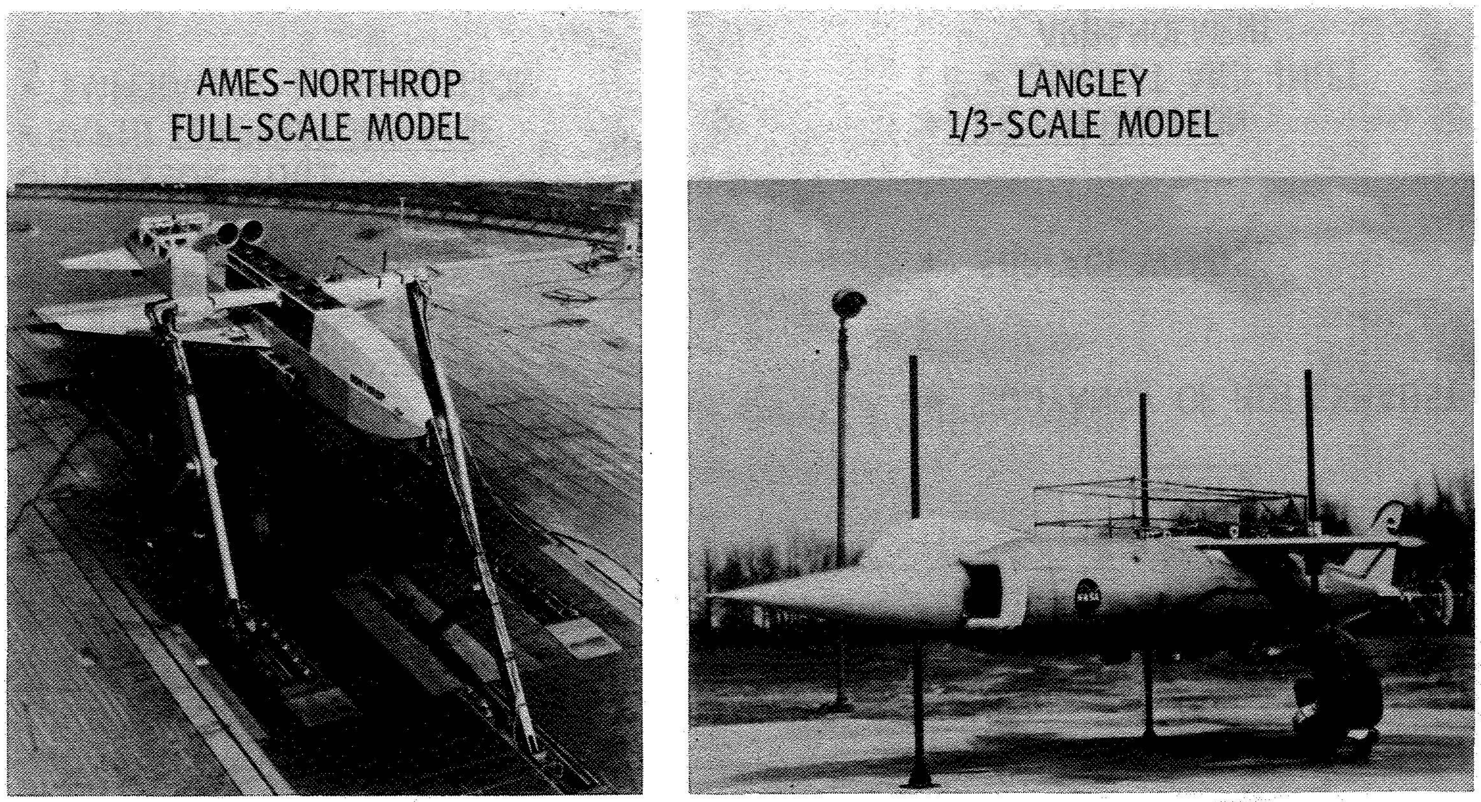


Figure 2.- Large-scale NASA models.

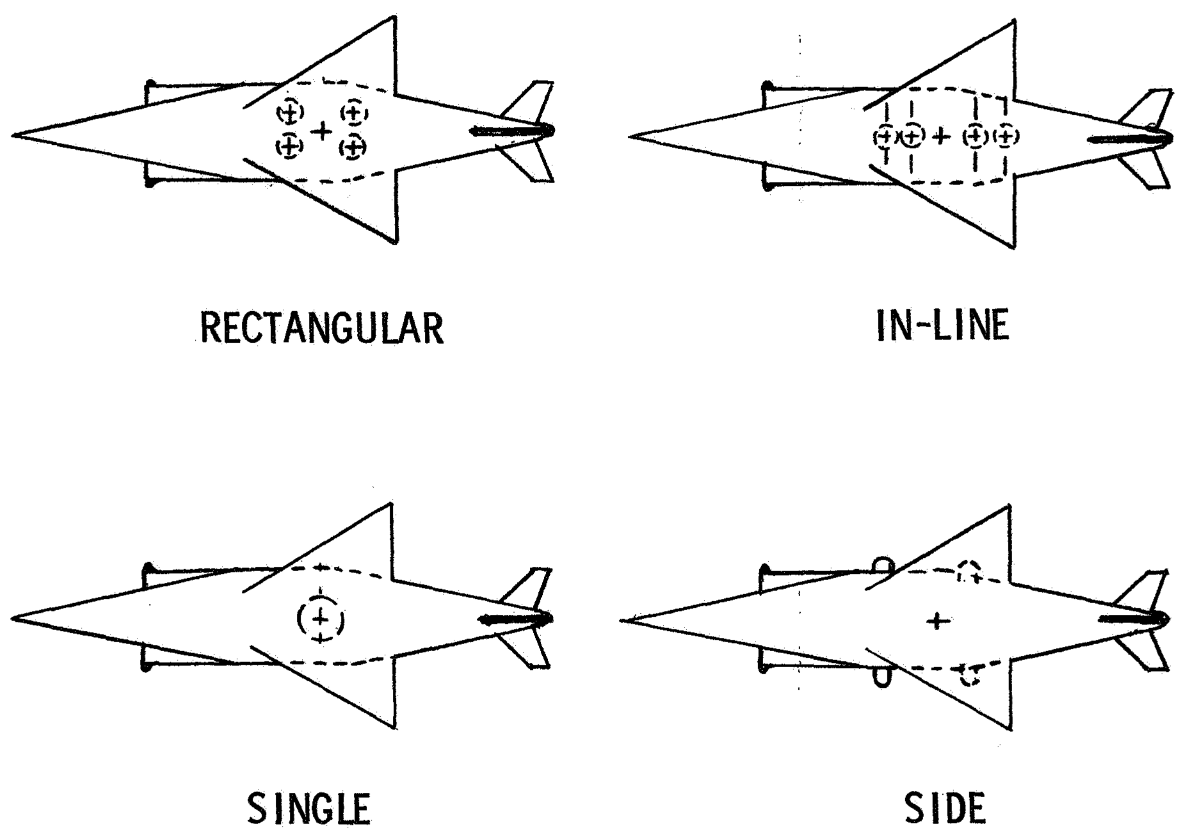


Figure 3.- Sketches of hot-gas ingestion model showing nozzle arrangement, high-delta wing, forward facing side inlets.

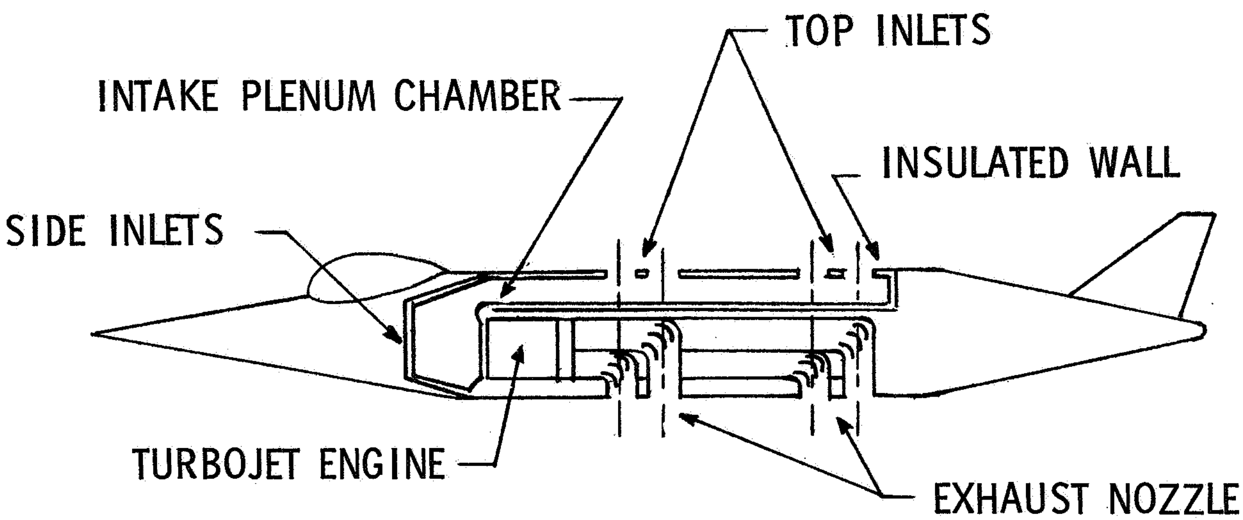


Figure 4.- Schematic arrangement of inlets, exhausts, and plenum chamber (in-line lift engine configuration illustrated).

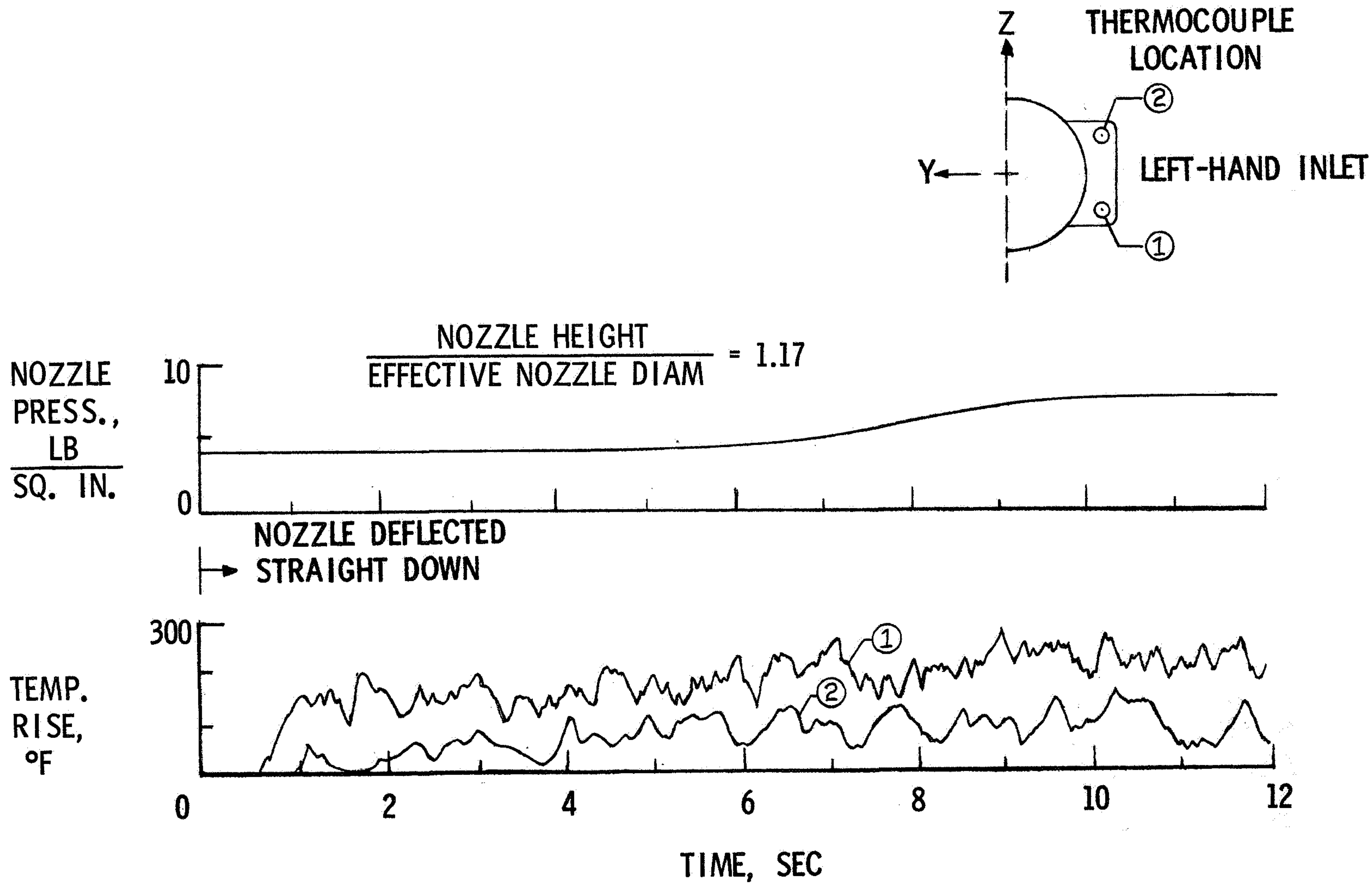


Figure 5.- Time history of inlet temperature rise and nozzle pressure, rectangular nozzle arrangement with side inlets.

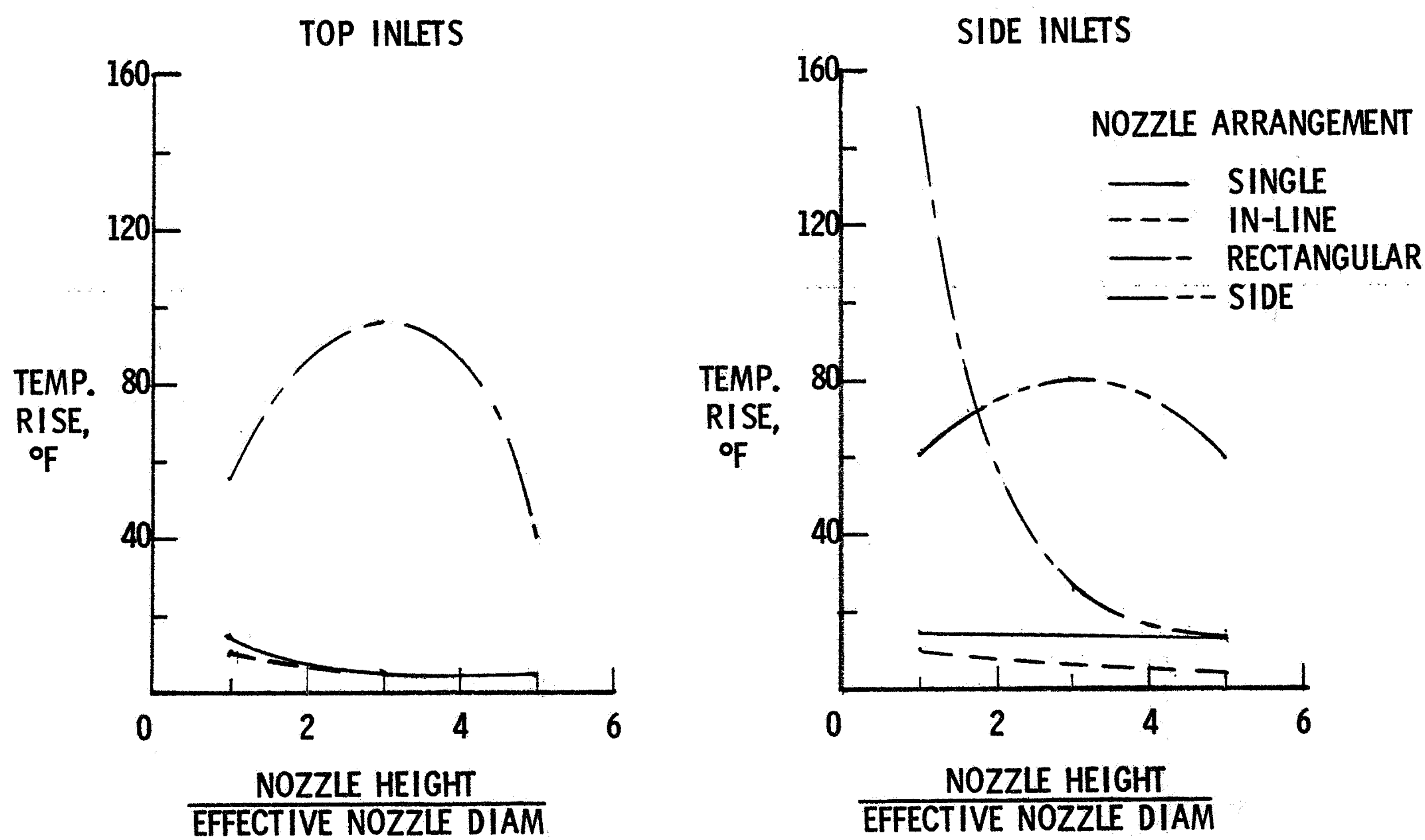


Figure 6.- Inlet air temperature rise in still air, high-delta wing.

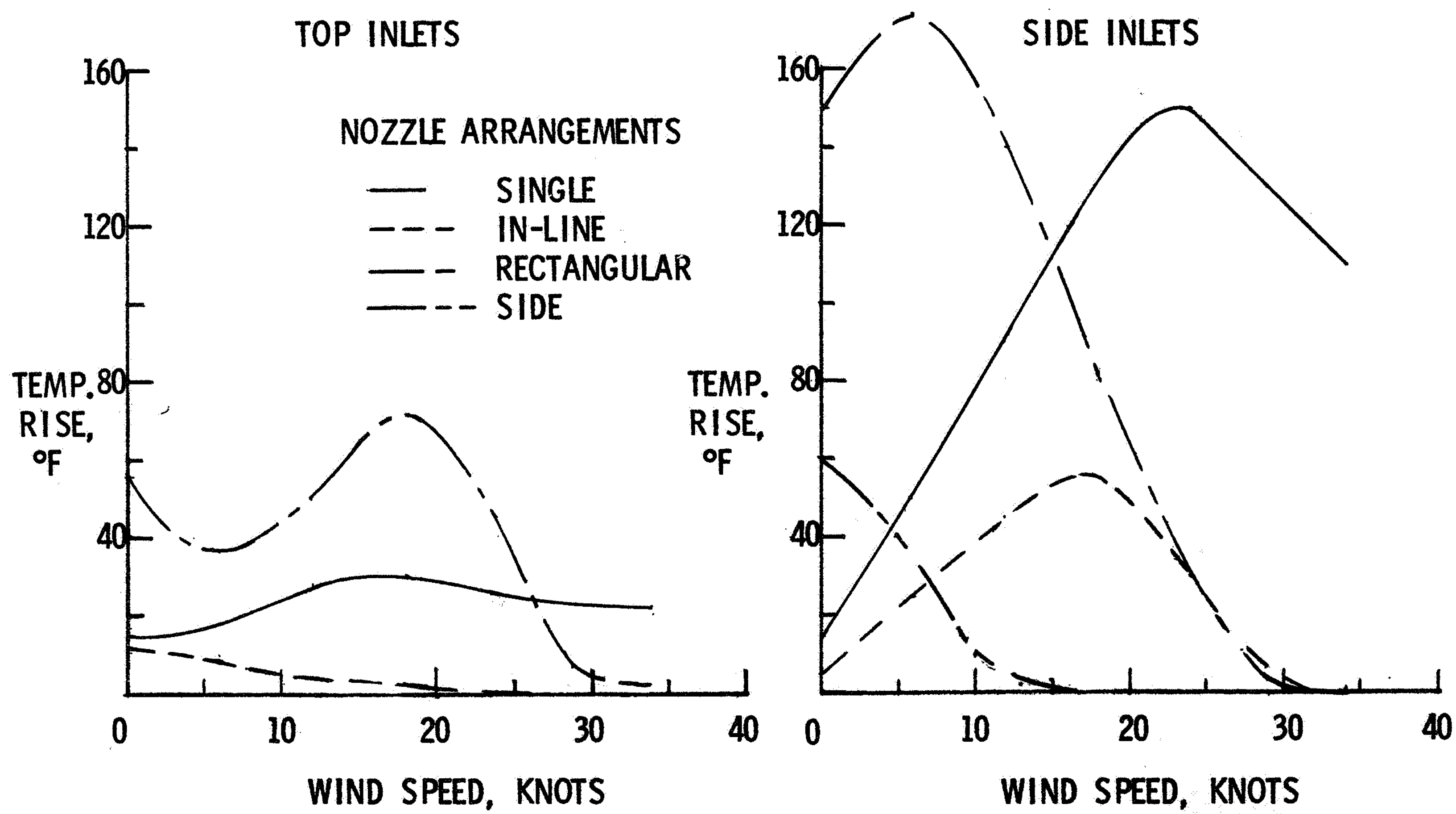


Figure 7.- Inlet temperature rise with wind; high-delta wing, $\frac{\text{Nozzle height}}{\text{Effective nozzle diam}} = 1.17$.

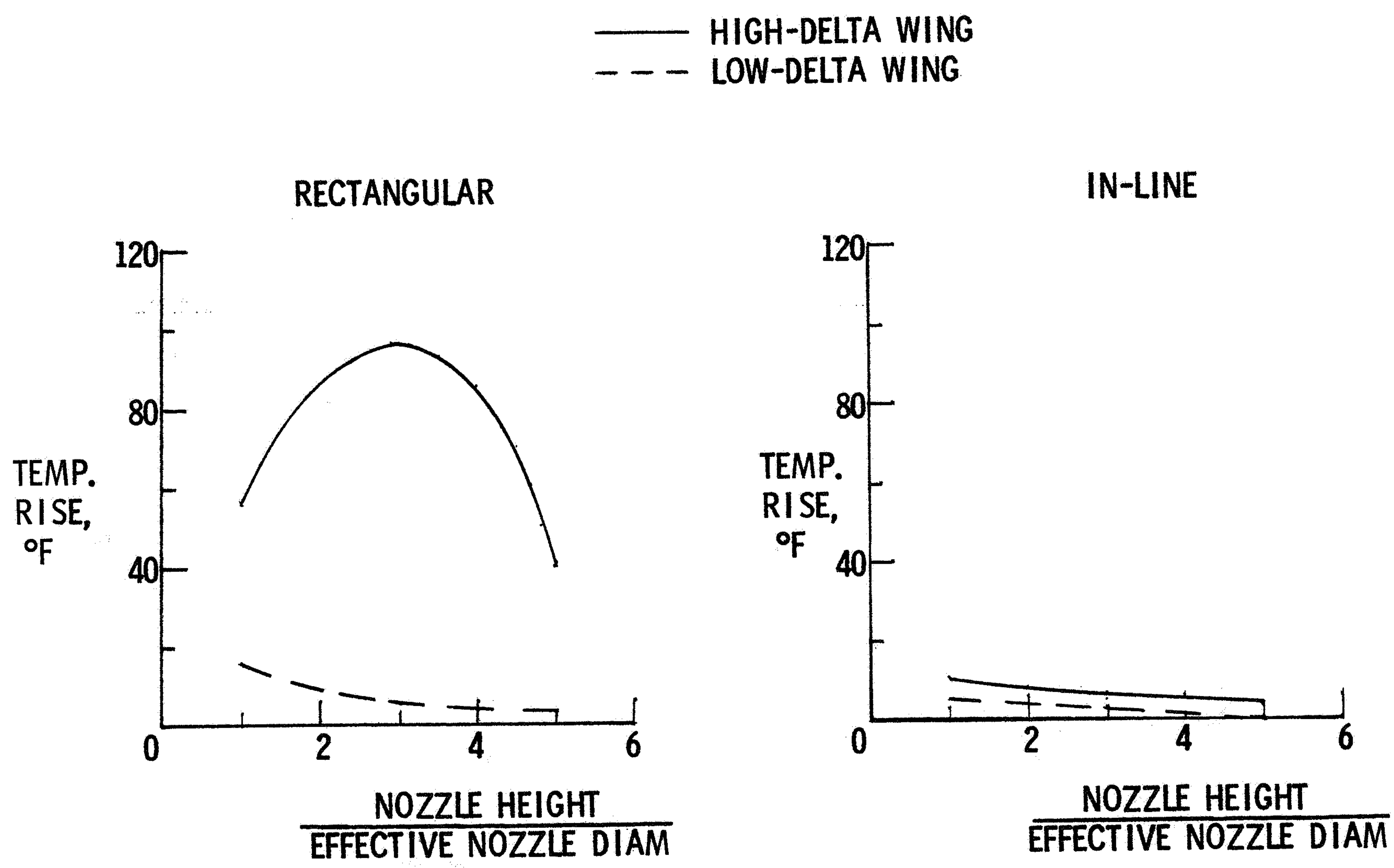


Figure 8.- Inlet air temperature rise in still air for rectangular and in-line nozzle arrangements with top inlets.

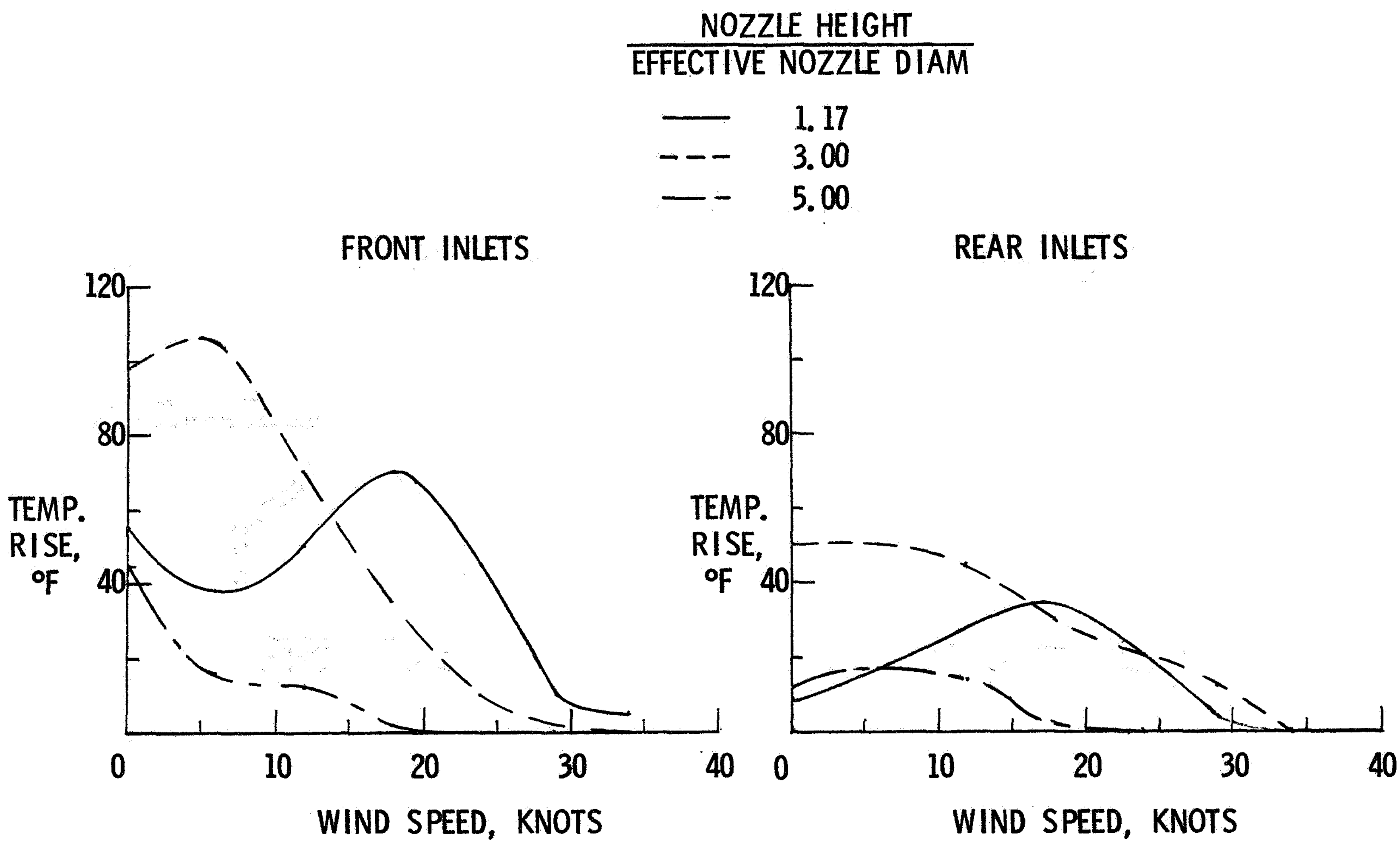


Figure 9.- Inlet air temperature rise with wind, rectangular nozzle arrangement with top inlets.

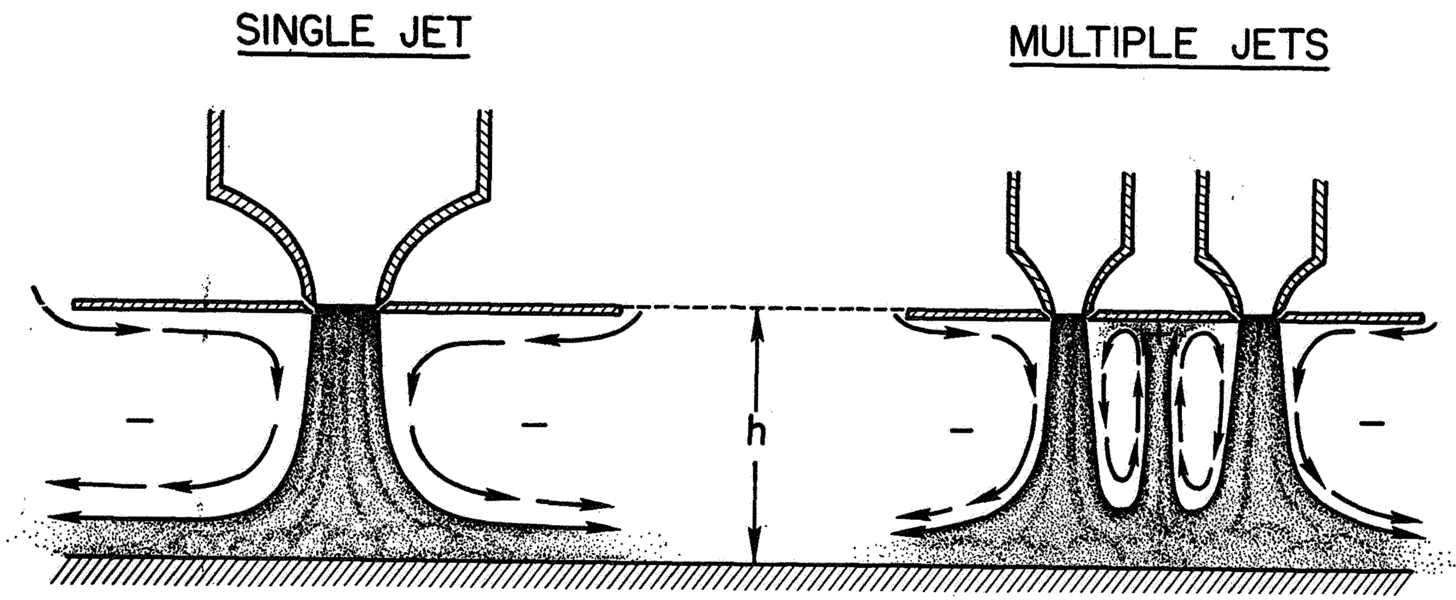


Figure 10.- Aerodynamic ground effects.

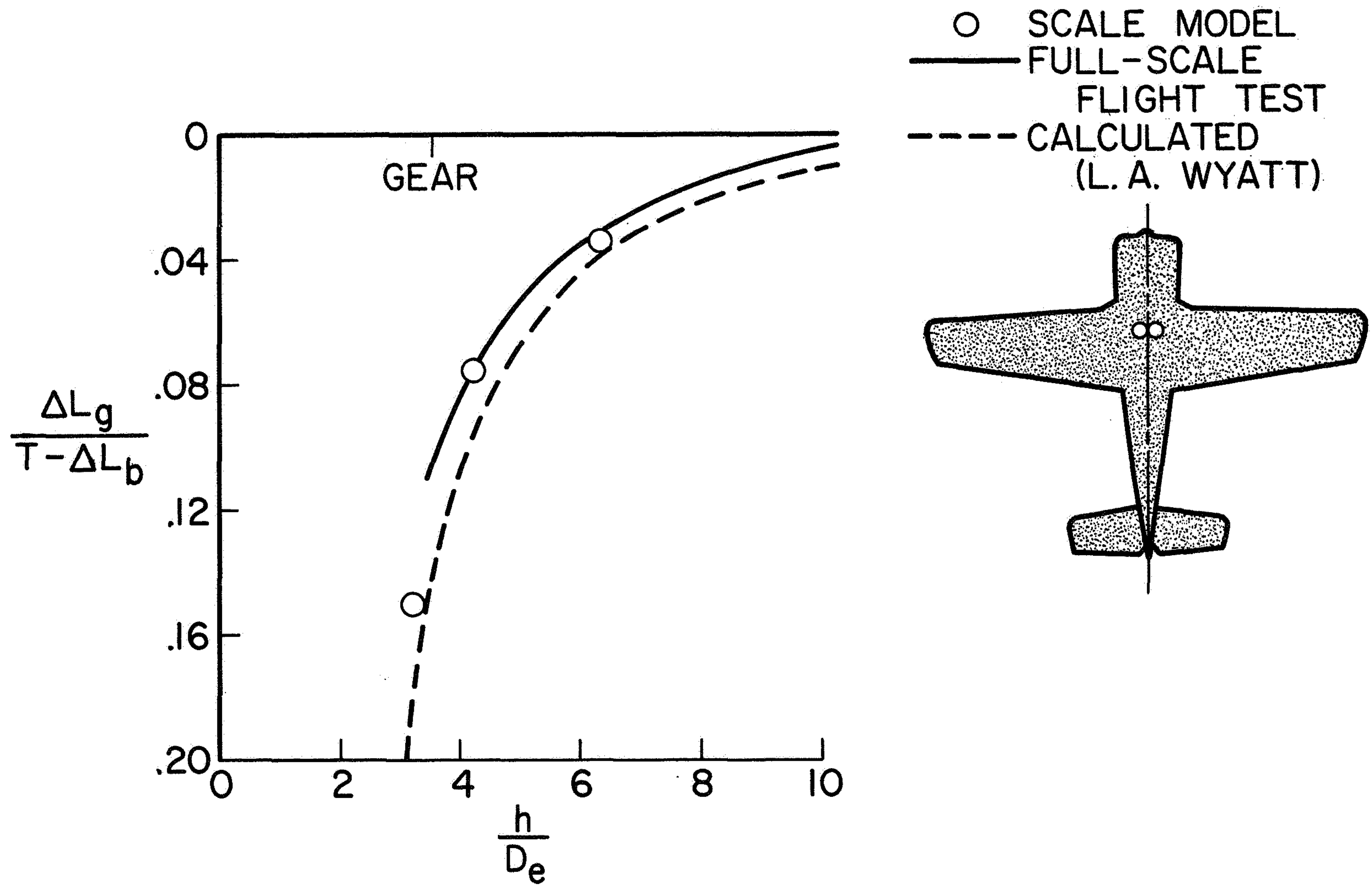


Figure 11.- Correlation of model with full-scale X-14A.

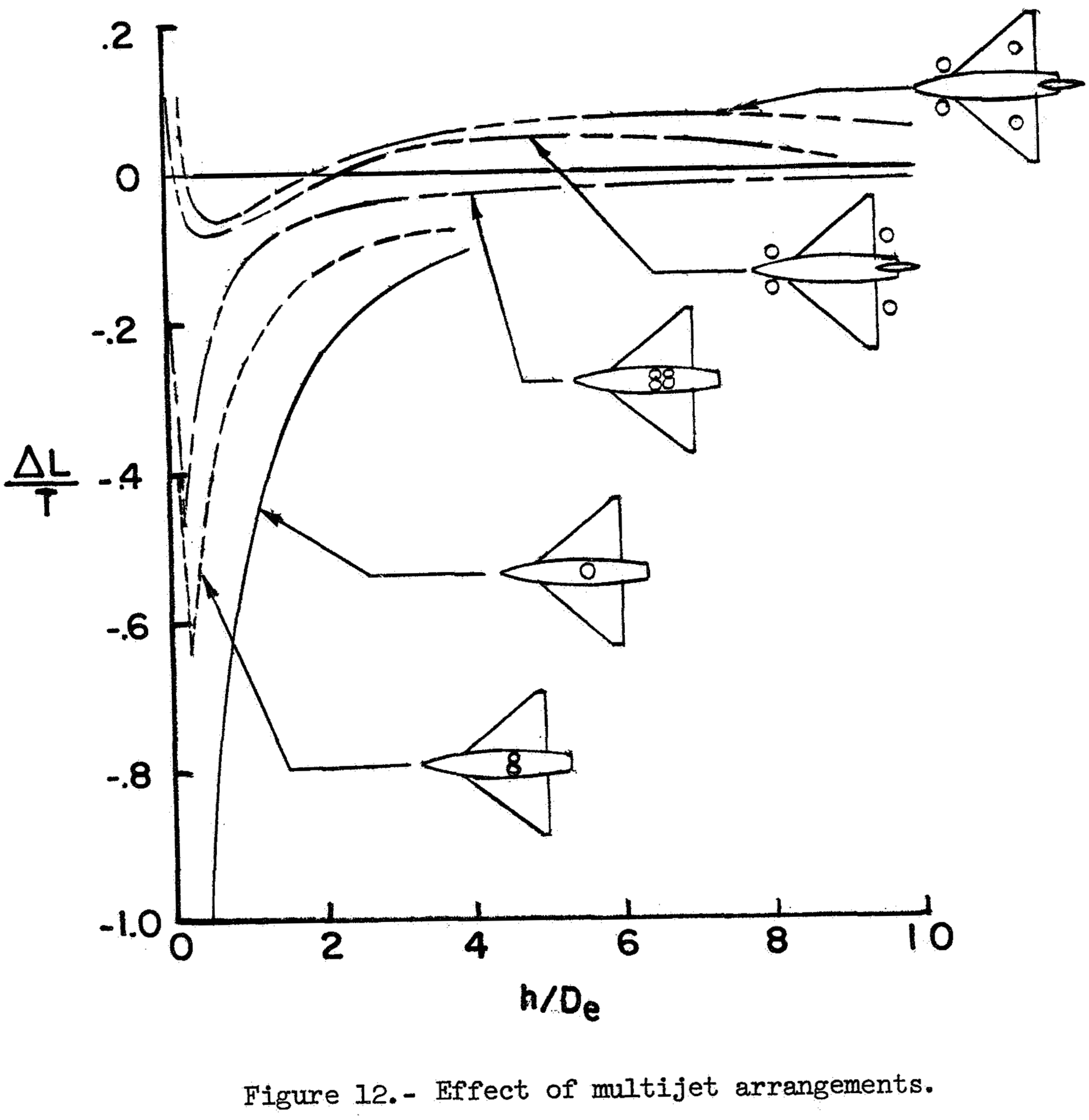


Figure 12.- Effect of multijet arrangements.

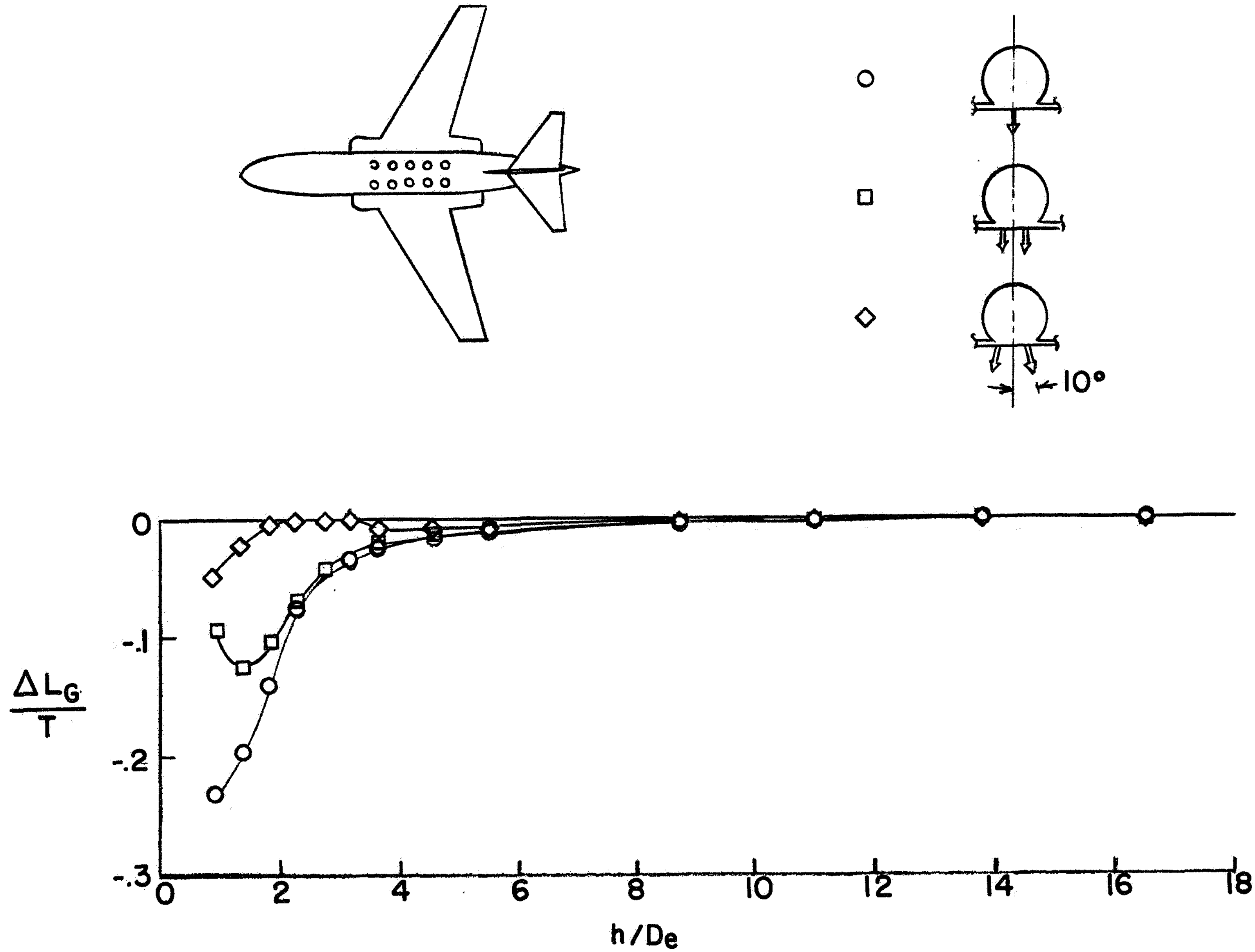


Figure 13.- Hovering ground effect.

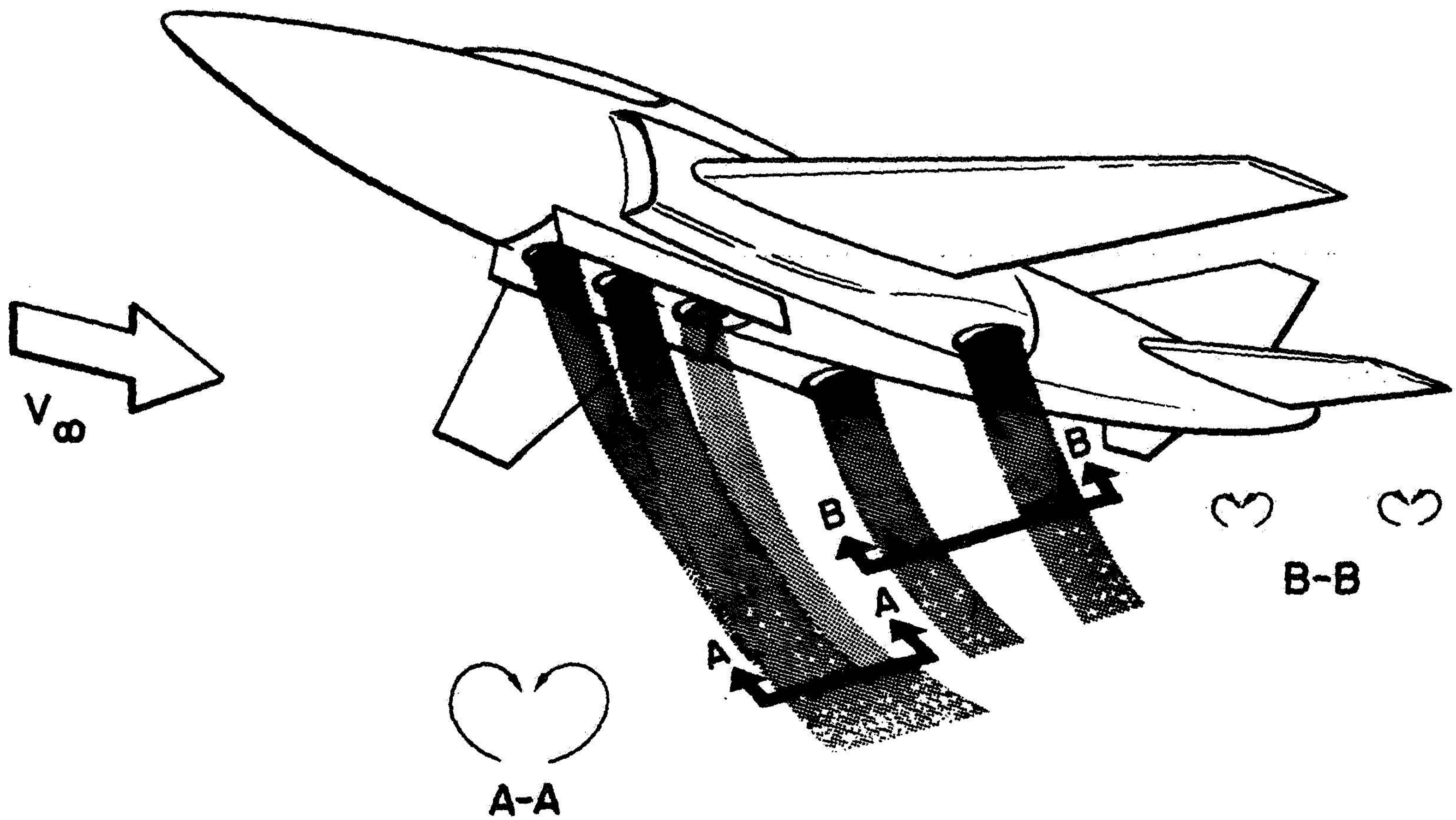


Figure 14.- Jet wakes in transition flight.

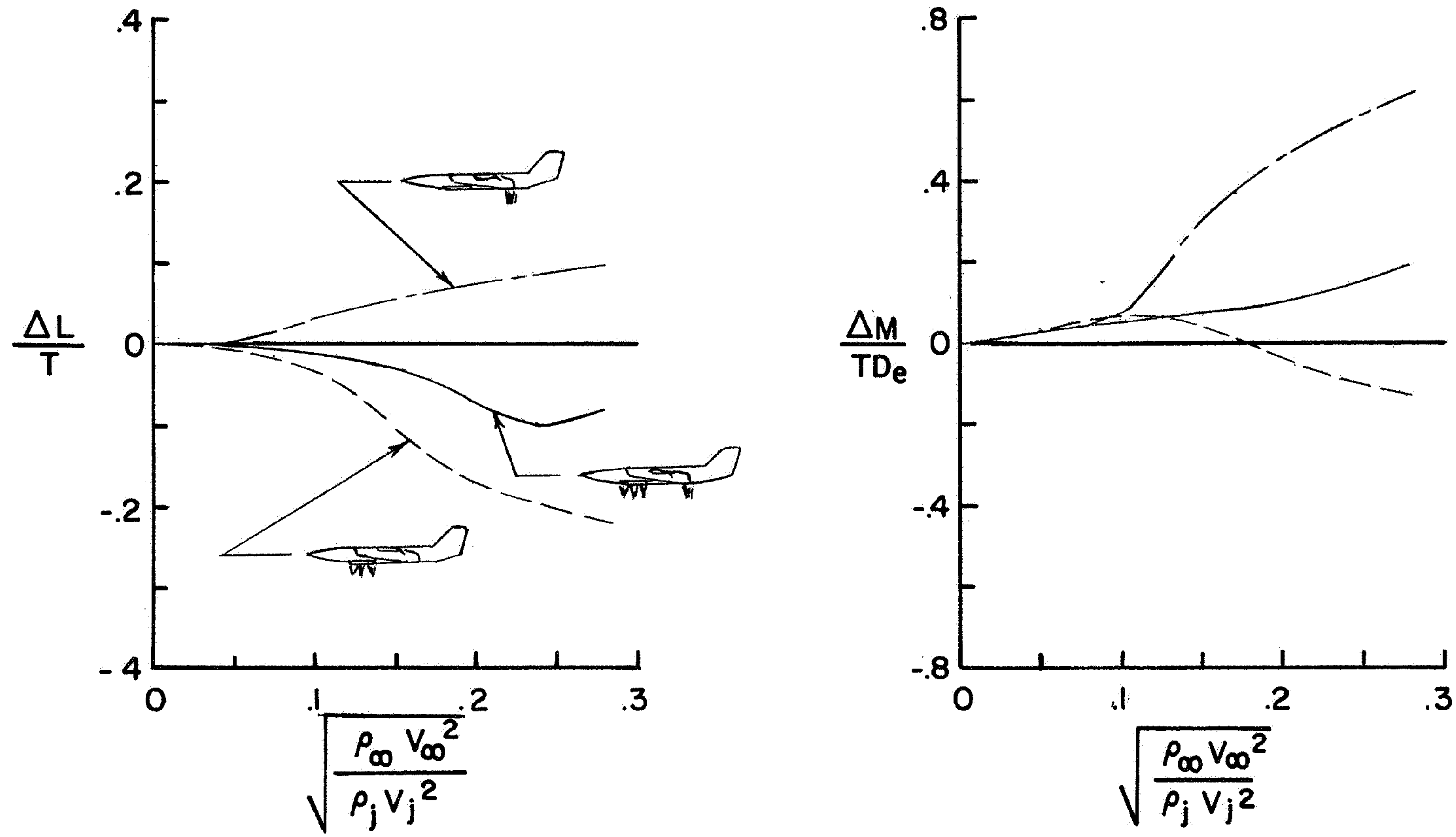


Figure 15.- Transition interference.

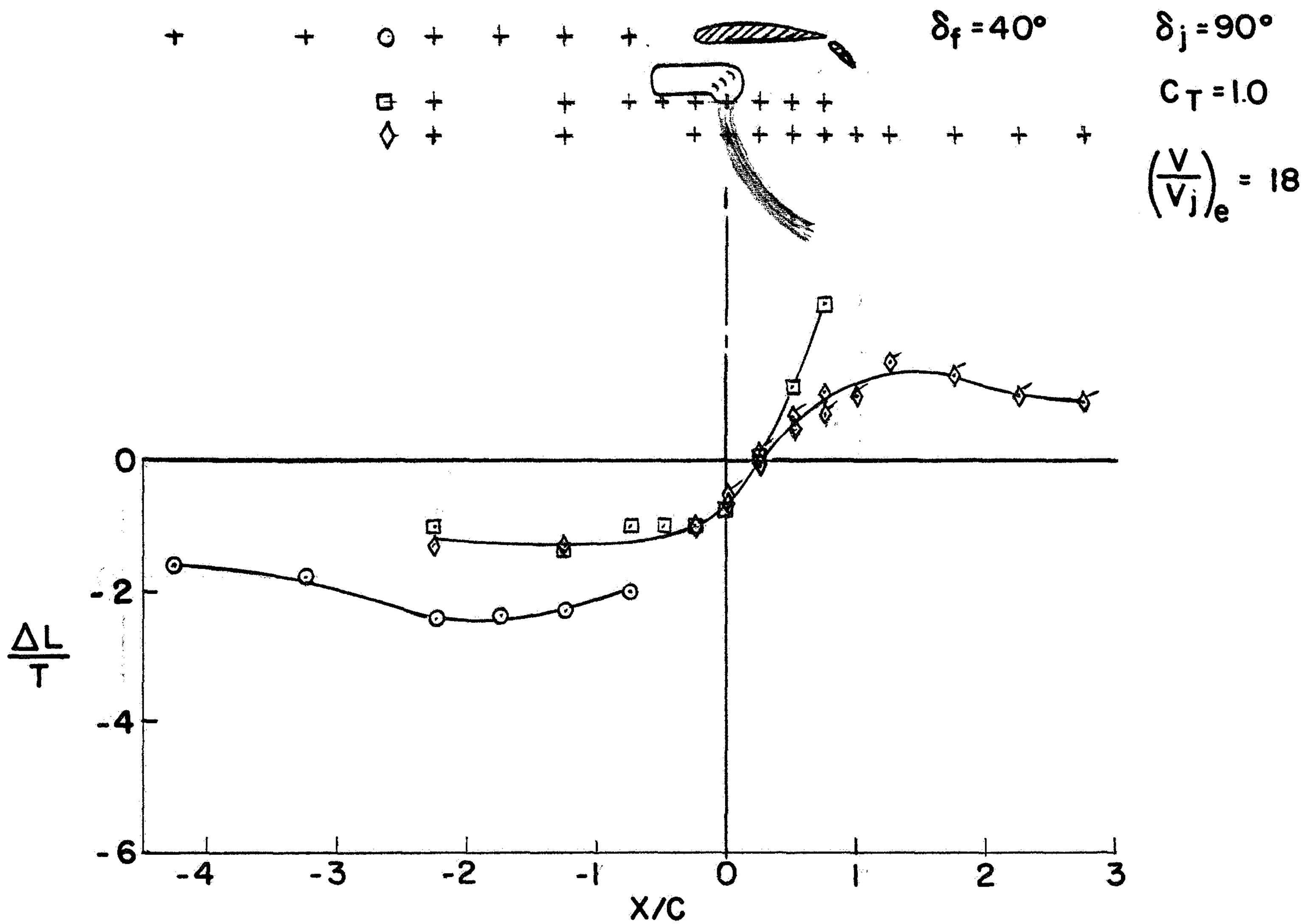


Figure 16.- Effect of jet position.

NASA-Langley, 1967