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THE REQUIREMENTS FOR AND EVOLUTION OF A TEST RIG
FOR EXHAUST GAS RECIRCULATION STUDIES OF
V/STOL AIRCRAFT

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1. INTRODUCTION

The dry Pegasus turbofan powered Harrier has been demonstrated to be an effective battle-field close-air-support subsonic aircraft and is currently in service with the RAF, USMC (AV-8A), the Spanish Navy (Matador) and the Royal Navy (Sea Harrier). Developments of the aircraft, notably the large wing Harrier and the AV-8B are respectively undergoing assessment by the RAF and flying in prototype form (YAV-8B) for possible procurement by the U.S. Marine Corps., U.S. Navy, U.S. Air Force and the RAF.

After a lull in activity following the cancellation of the P1154 increasing interest in the U.K. and U.S. in V/STOL aircraft having a supersonic capability, enhanced manoeuvrability and payload/range has led to renewed studies of single vectored thrust engines having augmented fan and/or core streams.

A characteristic feature of an engine having a four nozzle layout, operating in the VTOL, VSTOL and STOL modes, is that hot gas recirculation into the engine inlets can occur due to the creation of strong upwash fountains which form underneath the aircraft giving rise to 'near field' reingestion.

For the dry turbofan-engine installation hot gas ingestion has posed no problems as the fan exhaust is 'cool'. The fountain flow from the front nozzles effectively shields the inlet from the hot rear gases and appropriate VTOL, VSTOL and STOL operational techniques, exploiting the vectoring capability of the nozzles, have been developed either to eliminate or limit inlet total temperature rise to very low levels.

The risk of encountering reingestion problems is considerably greater with reheated exhaust streams where the much higher ingested gas temperatures may lead to severe thrust loss and engine surge.

Since the inception of the single vectored thrust engine layout, many fundamental theoretical model and full scale studies have been carried out in the U.K. - e.g. by N.G.T.E., B.Ae and R.R. and elsewhere, to identify and understand the recirculation flow mechanisms inherent in a four poster layout. These studies included the identification, by N.G.T.E., of scaling laws for model experiments to correctly simulate recirculation flow fields. The results of the early investigations identified the importance of aircraft dynamic motion as a parameter on which intake hot gas ingestion is dependent. In view of this Rolls Royce has developed an experimental technique, leading to the design and commissioning of a hot exhaust gas recirculation test facility, capable of simulating aircraft VSTOL manoeuvres close to the ground at model scale. This paper outlines the requirements for, and describes the evolution of, the facility. Some sample test results are presented for vectored thrust installations to illustrate the versatility of the facility for studying hot gas recirculation and developing solutions to the problem.

ABSTRACT

Following the successful evolution of a subsonic V/STOL combat aircraft, the Pegasus turbofan powered Harrier, increasing interest is being shown in V/STOL aircraft with supersonic capability. The thrust augmentation required for take-off and to reach supersonic speeds and high thrust for manoeuvring and combat may be achieved by reheating the fan and/or core exhaust streams. With reheated exhausts a critical installation issue, which is encountered for V/STOL aircraft manoeuvres close to the ground, is hot exhaust gas recirculation which may enter the engine inlets or cause severe aircraft structure heating.

To investigate these problems Rolls-Royce has developed a test rig for hot gas recirculation studies. This paper outlines the requirements for and evolution of the facility. Some sample test results are presented for vectored thrust installations, with illustrations of methods to avoid excessive hot gas recirculation.

3. CAUSES AND IMPLICATIONS OF HOT GAS RECIRCULATION

3.1 Causes

The single vectored thrust engine installation in the V.T.O.L. mode represents a four poster lift jet arrangement, as shown on Fig.1, which illustrates a number of ways by which exhaust flows might recirculate back to the engine intakes.

Possible mechanisms are:-

- (a) The separate lift jet flows meet on the ground causing up-flows or 'fountains' aligned horizontally and transversely beneath the aircraft.
- (b) The exhaust flows directed away from the central region bounded by the four poster planform travel outwards to recirculate on a longer time scale, and after much mixing with ambient air, driven by the effects of buoyancy and entrainment.
- (c) Some of the forward arc ground flow may be blown back to, or overtaken by, the inlets to be reingested if relative movement occurs between the aircraft and the ambient air mass.

These three possible modes of recirculation have been called 'near field' or 'fountain type', 'intermediate' or 'thrust reverser type' and 'far field' and are illustrated on Fig.2.

For aircraft vertical take-offs and landings, near field recirculation, consisting of longitudinal and transverse fountains, is the dominant mechanism. The hot gas route back to the inlets is short and direct with little opportunity for mixing to take place, and so the exhaust gas is ingested with minimal loss in temperature. A simple theoretical model was constructed to quantify the problem. It was assumed that the ground flow from each lift jet was initially radial and that a 'slice' of this flow from the two ground lift jets would reach the inlets. The size of this slice, in angular terms, was defined by a simple intuitive geometric projection back from the inlets. Having established a quantity for the gas ingested it was then a simple matter to perform a heat balance sum and calculate the resulting intake temperature rise.

Subsequently a variety of flow visualisation and measurement tests were carried out with laboratory models of a pair of front nozzles using air or water, and tracers such as helium gas, CO₂ particles, liquid dye, etc. These confirmed the importance of the forward jet longitudinal fountain in a 'four poster' recirculation system. Fig.3 shows an example of a water tank test with dye injected into the nozzle flows at two different points. This shows quite clearly that gas from the forward inboard quadrants of the nozzles flows very readily to the simulated inlet via the longitudinal fountain.

2. SYMBOLS

D	- Diameter
g	- Acceleration due to gravity
K_{123}	- Scaling constants
L	- Length
P	- Total pressure
p	- Static pressure
R	- Limit of radial extent of jet on ground
T	- Total temperature
$\Delta \bar{T}_{\text{INLET}}$	$\approx \bar{T}_{\text{Inlet}} - T_a$ where $\bar{T}$ = mean temperature at inlet plane
$\Delta T_{\text{FRONT NOZZLE}}$	$\approx T_{\text{FRONT NOZZLE}} - T_a$
TC_{120}	- Temperature distortion coefficient
τ	- Time ratio = $\frac{\text{time full scale}}{\text{time model}}$
V	- Velocity

SUFFICES

a	- ambient
I	- Inlet entry plane
J	- Nozzle exit plane
W	- Free stream or wind

Extensive tests both at model scale and on the P1127/Harrier carried out both by Rolls Royce and British Aerospace have provided many opportunities to examine the validity of the theoretical model predictions and simple water tank results for the dry engine Pegasus installation. Good agreement has been obtained confirming our understanding of the near field recirculation processes during VTOL manoeuvres.

It is also evident from Fig.3 that exhaust gases from the nozzles can flow directly forwards along the ground. Fundamental studies were carried out at NGTE (Refs.1 and 2 refer) to measure the forward penetration of the ground jet from a single nozzle, directed vertically on to the ground, under the action of a range of headwinds. Flow visualisation results clearly showed that the gas cloud formed can flow back, by a 'thrust reverser' type recirculation mechanism, into the region of the inlets of a V/STOL aircraft operating under headwind or during rolling take-off or landing manoeuvres.

3.2 Implications

3.2.1 Thrust Loss

Theoretical and experimental studies both at model and full scale have indicated that as much as 15-20% of the flow leaving the front nozzles on the existing Pegasus installation could return to the intake during certain stages of VTOL operations. As stated earlier the high level of recirculation does not present a problem since the engine is a turbofan and the front nozzle exhaust gas temperature relative to ambient is low (100°C , 210°F) and 20% of the front nozzle flow represents only 10% approximately of the total intake flow. Thus the maximum mean intake temperature rise does not, at worst, exceed 11°C , (20°F) or 11% of the front nozzle temperature rise during VTOL manoeuvres and generally the intake temperature rise is much less than this. There is also a temperature distortion, the maximum local values being approximately 2.0 to 2.5 times the mean value.

When the thrust of a vectored thrust engine is boosted by burning in the fan exhaust, Plenum Chamber Burning (P.C.B.), the temperature of the front nozzle flow is raised by an order of magnitude. If the same 20% of the front nozzle flow were again reingested and the exhaust gas temperature is, say, 1000°C (1800°F) then the mean intake temperature rise would be, in the worst case, over 100°C (180°F). This would imply peak local temperatures of over 200°C (390°F) and, even assuming that the engine could run under the associated flow distortion conditions, the thrust loss would be prohibitive. Fig. 4 shows that the thrust increase by augmentation would be more than offset by the loss of thrust due to hot gas recirculation, assuming a uniformly distributed inlet temperature rise.

Clearly the viability of the P.C.B. augmented vectored thrust V/STOL aircraft concept depends critically on the development of techniques to reduce hot gas recirculation effects to an acceptable level. In this respect the aim at Rolls-Royce has been to achieve inlet temperature rise and distortion effects in the augmented installation which are no worse than for the dry Pegasus in Harrier (AV-8A). This has meant reducing the amount of hot gas which can be allowed to recirculate by a factor of 10, approximately, for a PCB temperature of 1100°C giving a peak target value of mean $\bar{T}_{\text{inlet}}/T_{\text{nozzle}}$ no greater than 1%.

This target is taken to apply both for VSTOL operations where near field recirculation is dominant and also for USTOL manoeuvres where 'thrust reverser' type ingestion may be the prime source of intake hot gas reingestion.

3.2.2 Airframe Heating

For VTOL operations close to the ground the near field recirculation flow paths generated by the longitudinal and transverse fountains can produce exhaust jet impingement regions on the aircraft structure, notably the underfuselage region (Fig 2). VTOL flight tests and model results on the VAK 191B, for example, have indicated that peak gas temperatures adjacent to the aircraft structure occur between the rear nozzles amounting to about 120°C (248°F) or about 20% of the rear nozzle gauge temperature. The aircraft structure is subjected to this peak temperature for a limited duration only during a typical dynamic manoeuvre and, even making no allowances for gas/metal heat transfer effects, this level is well within the structure limit of the airframe.

With the augmented thrust engine, when the temperature of the front nozzle flow is, say, 1000°C (1800°F) the likelihood of aircraft structural damage during VTOL manoeuvres is very real. An extension of the VAK 191B data on the basis of a scaling factor, based on jet excess temperatures, indicates peak undersurface gas temperatures of the order of 200°C (390°F). This extrapolation is probably optimistic in that with the dry engine some mixing may take place between the cold front and hot rear jets. However, with the PCB front nozzle engine both front and rear jets are hot giving little chance for the dominant front nozzle temperature to be significantly reduced by mixing.

3.2.3 Deck Heating

During VTOL manoeuvres in ground proximity the ground surface is subjected to the direct effects of the exhaust jets. At very low heights there is little opportunity for jet temperature decay due to mixing with entrained cold air. Peak ground surface temperatures attained are a function of the residence time - i.e. the time the surface is subjected to the hot gas stream and to the variation in gas temperature close to the ground as the aircraft is either lifting off the surface during take-off or approaching the surface during landing.

The risk of surface damage also depends on the nature of the surface and experimental studies have been undertaken to assess the temperature resistance of different materials.

Harrier experience with a dry Pegasus and other V/STOL aircraft such as VAK 191B, Mirage IIIV, VJ101-X1, utilising lift engines or lift/cruise engine combinations with maximum jet temperatures of approximately 600°C have shown that VTO and V.L. are only feasible from specially prepared surfaces such as steel sheets, water cured concrete, etc., or by the use of grids or deflectors. The problem can, however, be greatly reduced and successful solutions obtained by the use of rolling take-offs and landings and, in particular, by thrust vectoring to reduce residence time.

4. TEST RIG REQUIREMENTS

The requirements of a test facility for the acquisition of model scale experimental data. can, depending upon the scope of the experimental objectives, embrace a range of different types of reingestion test facilities. Alternatives range from a simple fixed-height model static test rig suitable for fundamental studies of concepts to, at the other extreme, a sophisticated model able to 'fly' through sophisticated manoeuvres for pre-flight research and development work.

Requirements, based on the need to provide data on the potential problem areas described in the previous section, which are generally applicable to V/STOL hot gas ingestion testing, are listed below:-

- . A large tunnel working section - this is to allow for the large crosswise flow components (e.g. lift jets, spreading ground flows, buoyant upflows), for any model movement (e.g. accelerating/decelerating or steady vertical motion), and adequate model size.

- . Tunnel airflow and ancillary air supplies sufficient to provide correctly-scaled and variable free-stream velocity inlet and exhaust flows - this is to ensure that the powerplant flows recirculate and mix in as realistic a manner as possible.

- . Representative aircraft model shaping - this depends on the nature of the test but the detailed shaping of an aircraft can influence the recirculation flow paths, hence planform shape and major features, particularly on the under surfaces, should be simulated, where appropriate.

- . An adequate simulation of the ground beneath the aircraft.

- . Techniques for starting the flows in a realistic manner-particularly where transient reingestion phenomena are being studied. Alternatives include rotatable nozzles, removable deflector ducts, or ground trap doors.

. Instrumentation - This depends on the sophistication of the test and its objectives. For example, temperature instrumentation may range from grids or probes with fast response for mean temperature recordings to very fast response individual probe rakes for comprehensive analysis of engine compressor face maximum/minimum time dependent temperature distortion.

. Data acquisition and processing systems capable of coping with large quantities of information.

In addition, it is desirable to be able to purge hot gas away from the tunnel working section so that cold ambient conditions can be quickly re-established between tests.

5. RIG DEVELOPMENT

Although the requirements detailed in the previous section point to the need for a sophisticated test rig having a number of variable features a large amount of useful work has been carried out on rigs simplified in one way or another to meet limited objectives and to minimise capital expenditure and operating costs.

This section traces the studies carried out and briefly describes the test facilities designed to meet progressively more demanding objectives posed by the need to develop techniques to solve the recirculation problem.

5.1 Half-Model Testing - Fixed Height

Following the identification and understanding of the flow mechanisms associated with intake hot gas ingestion for a PCB augmented vectored thrust powerplant, work to determine methods for limiting recirculation to very low levels was carried out, initially at fixed height conditions.

An existing wind tunnel of 6' x 4' (1.8 m. x 1.2 m.) working section, originally designed to carry out low speed tests on half-models of vectored thrust fighter aircraft, was modified to accommodate a half model based on a P1127 aircraft configuration (Fig.5). The tunnel size permitted a reasonably large model scale (1/9th to 1/6th) to be used and the half-model technique greatly simplified the mechanical problems of mounting the model, rotating the nozzles, and supplying hot exhaust gas and inlet suction. The rotating nozzle system provided a representative method of setting up required hot jet conditions, with provision for adequate heating of the supply piping with the nozzles set aft and the tunnel run to purge the gas from the working section. When equilibrium conditions were reached the nozzles could then be rotated to simulate full scale aircraft operation.

The results of the studies enabled a number of concepts to be evaluated, including the effectiveness of various deflector shields and directed air jets or curtains designed to divert the fountain flows away from the engine inlets.

The technique, although it provided valuable insights into methods of fountain containment, suffered from a major drawback in that the flow field was not adequately simulated. Half-model tests against a tunnel wall constrains the fountains thereby inhibiting beneficial mixing of the hot jets with cool surrounding air, and introduces a spurious boundary layer under forward speed conditions. The limitations are shown on Fig. 6 which compares the half-model test results with complete model and full scale aircraft data from N.G.T.E. and N.A.S.A. test programmes. The half-model approach also precludes testing under crosswind conditions.

5.2 Complete Aircraft Models - Fixed Height

To avoid the limitations of the half model system, the rig was modified to accommodate a complete model. The working section size limited the full model to about 1/30th scale - difficult for model manufacture (Fig. 7). The system, however, provided a capability for alternative fixed heights and aircraft attitude and yaw. Rotatable nozzles were again fitted to permit correct setting up of airflow conditions for aircraft take-off and landing.

This rig was used to carry out studies to examine fountain flows in more detail with jet flows correctly simulated. The facility was also employed to investigate a new technique, jet convergence, discussed later in this paper, whereby the exhaust jet fountain is prevented from forming and restricting the hot gas to spread only along the ground.

The rig has provided information from which it was possible to define the minimum speed an aircraft should have at a given height for the avoidance of reverser-type (or mid-field) ingestion. Data was gathered to define delay times at a fixed height for a range of headwinds before the onset of intake temperature rise.

5.3 Moving Model

Although the fixed-height model provided useful insights into the build up of hot gas recirculation paths, including information on the effects of forward speed, the model/rig still had a serious deficiency: the working section was too small for tests with a reasonable scale 'whole' aircraft model which could be moved up and down to simulate aircraft jet-borne ascents and descents. The importance of vertical motion can be recognised by noting that, in the extreme, an aircraft might ascend or descend within the time it takes for reingestion to take place and for the engine to respond. It was decided that a new test facility was required to enable this important issue to be studied.

6. RIG DESIGN CONCEPT

6.1 Choice of Facility

The 6' x 4' (1.8m x 1.2m) tunnel was located in a large test cell 70' (21.3m.) long x 22' (6.7 m.) wide x 12' (3.7 m.) high, capable of accommodating a wide range of scale-model test rigs. On examination it was decided that two main options were available:-

- a) A whole aircraft model, mounted and supplied from above, suspended from a carriage with vertical travel only, located in a new, larger wind tunnel working section.
- b) A whole aircraft model, mounted and supplied from a carriage with both horizontal and vertical travel, such that it could be 'flown' through simulated V/STOL manoeuvres (no wind tunnel required).

The advantages in each case were as follows:-

Option a)

1. Relatively simple carriage and supply system.
2. Used minimum clear space.
3. Could use existing tunnel drive.
4. Could simulate atmospheric, or moving ship, wind effects.
5. Easy to purge hot air from test cell

Option b)

1. Most realistic simulation of jet-borne take-off and landing manoeuvre trajectories.
2. Maximum freedom from cell wall interference effects.

The disadvantages, on the other hand, were:-

Option a)

1. Tunnel floor boundary layer had to be tolerated or removed when simulating aircraft forward speed.
2. Prone to tunnel wall interference.

Option b)

1. Relatively complex carriage and model supply system.
2. Required maximum clear space.
3. Wind effects not easily simulated
4. Hot air purging slightly more difficult.

The need for an easily-operated, flexible, reliable, rig, was judged to outweigh the complexity implicit in option b). Consequently the wind tunnel option a) was chosen.

Fig. 8 shows the layout of the facility. A scale model investigation of the flows into, and within, the cell were carried out, and this showed that the existing tunnel could be left in place and that only a large bell-mouthed opening was required at the upstream end of the cell to provide a large open jet working section with the desired flow characteristics.

6.2 Model and Flow Scaling

During the early sixties thoughts were directed towards the procurement of test rigs for the study of recirculation flow paths produced by V/STOL aircraft in operation close to the ground. It was realised that rig limitations would require model size, airflow absolute pressures, velocities and temperatures to be different to those at full scale. Accordingly fundamental studies were undertaken in the National Gas Turbine Establishment, (Refs. 1 and 3) to develop techniques to relate model and full scale flow properties so that recirculatory flows were reproduced as realistically as possible. Experiments were carried out to study the exhaust flow characteristics of a heated jet directed vertically downwards at static conditions and under the influence of forward speed. Jet pressures, temperatures and velocities were varied for different nozzle heights above the ground and the results enabled scaling laws to be developed to relate model-scale tests to the full-scale conditions of the dry Pegasus powered P1127. These scaling laws, which have been adopted for all vectored thrust hot gas recirculation tests are summarised below:-

- a) Airframe inlet and exhaust linear dimensions to be geometrically similar:-

$$\frac{L_{\text{Model}}}{L_{\text{Full Scale}}} = K_1$$

- b) A constant ratio of model to full scale momentum (or dynamic pressure) should be maintained for all jets, intake flows and wind:-

$$\frac{(P_J - P_W)_{\text{model}}}{(P_J - P_W)_{\text{Full scale}}} = \frac{(P_1 - P_1)_m}{(P_1 - P_1)_f} = \frac{(P_W - P_W)_m}{(P_W - P_W)_f} = K_2$$

- c) A constant ratio of model to full scale efflux temperature rise above ambient should be maintained for all lift jets:-

$$\frac{(T_J - T_W)_{\text{model}}}{(T_J - T_W)_{\text{full scale}}} = K_3$$

- d) The ratio of gas buoyancy to momentum forces should be the same for the model as at full scale:-

$$\left(\frac{(T_J - T_W) D_J}{(P_J - P_W) T_J} \right)_{\text{model}} = \left(\frac{(T_J - T_W) D_J}{(P_J - P_W) T_J} \right)_{\text{full scale}}$$

- e) The recirculation time ratio, model to full scale, can be different from unity and is determined by the geometric and dynamic head scaling:-

$$T = \tau_{\text{full scale}} / \tau_{\text{model}} = \left(\frac{D/(P_J - P_W)^{1/2}}{D/(P_J - P_W)^{1/2}} \right) f = K_1 \times K_2$$

Where J refers to jet flow, I refers to inlet flow and W refers to the free stream or wind flow.

It can be seen that the linear scale and momentum relationships a) and b), when combined, give rise to the time scale T. The buoyancy/momentum relationship is derived from the N.G.T.E. correlation which is reproduced on Fig. 9. This curve illustrates that the position on the ground where the hot ground jet separates correlates well with a parameter which relates the jet momentum, excess temperature and temperature ratio, for a range of jet nozzle sizes, heights above the ground, and jet temperature.

By satisfying K_2 and K_3 , the momentum and excess temperature relationships, it is also possible, ideally, to satisfy the buoyancy criteria d). This can be achieved for a configuration where all nozzles operate at the same temperature, however, in some cases, e.g. for the Pegasus engine, different front and rear jet conditions exist and the buoyancy/momentum and efflux temperature relationships cannot be satisfied for both jets. A compromise has to be made. In general, since 'near and mid-field' recirculation (fountain ingestion) tends to dominate the hot gas reingestion problem it is usual to satisfy the excess temperature scaling (c) and accept incorrect buoyancy scaling as buoyancy is dominant mainly in the far field.

Full scale tests carried out to investigate hot gas recirculation effects on the P1127 aircraft (Ref. 4) yielded data to compare with data from models designed and tested to the above scaling laws. Sample results are shown on Fig.10 illustrating that good agreement was obtained. It should be noted that the close correspondence between model and full scale results was achieved under dynamic aircraft and model operating conditions.

6.3 Tunnel Working Section

When applying the above scaling laws to the sizing of the tunnel working section a number of other important constraints had to be taken into account.

. The available drive system permitted tunnel speeds up to 170 ft./sec. (52m/sec.) in a 15 ft² (1.4 m²) working section.

. The rig was required to simulate V/STOL aircraft manoeuvres in jet borne flight close to the ground - i.e. in a range 0-50 ft. (0-15m) full-scale.

. The model needed to be as large as possible for ease of manufacture, reliability, and to enable multi-point inlet temperature distortion instrumentation to be incorporated.

. The recirculation time was to be not less than about 1/5th of the full scale value to avoid problems with the model and carriage actuation arrangements and with transient temperature sensor response.

. The tunnel working section speeds needed to be high enough to minimise spurious draughts or wind gust effects.

. The maximum nozzle temperature needed to be limited to a value of about 500°C (930°F).

Application of the scaling laws enables the variation in time ratio, jet dynamic head, alternative model sizes, and model jet temperatures for simulation of a chosen full scale V/STOL aircraft powerplant to be examined. Results are shown on Figures 11 a) and b) for conditions representative of a Pegasus engine, dry and with P.C.B., respectively. The geometric scales selected (1/15th and 1/30th) give model aircraft wing spans of about 2' (0.6m) and 1' (0.3m) respectively. The larger scale represents the maximum practical model size requiring a vertical travel of about 4' (1.2m) which with an aircraft wing span of 2' (0.6m) requires a tunnel working section of the order of 12' x 7' (3.7m x 2.1m) - this being about the largest practical size to fit in the existing building.

To maximise the accuracy of the rig test data it is desirable to raise jet dynamic heads as far as possible so that jet velocities and tunnel speeds are kept as high as possible. With this in mind, examination of Fig. 11 b) for a fan/PCB exhaust jet at typical lift conditions gives a temperature limited point shown with a time₂ ratio of 3₂. The jet dynamic head for this point is 0.9 lbs./in² (6.2 KN/m²) compared to a full scale value of 22 lbs./in² (142KN/m²). By momentum scaling this specifies a tunnel speed 1/5th of full scale. With the available drive system the maximum speed available with a 12' x 7' (3.7m x 2.1m) working section is about 35 ft./sec. (11m/sec) - implying a full scale aircraft speed of 175 ft./sec. (53m/sec) - about 100 Kts. This was considered adequate to cover the likely V/STOL aircraft speed range. A 12' x 7' (3.7m x 2.1m) section was therefore selected for the new tunnel. The facility is able to accommodate V/STOL fighter models up to 1/5th scale and, by suitable flow scaling, able to simulate full scale flight speeds up to about 100 Kts. without too great a demand on instrumentation response times.

A simple open jet working section formed by the tunnel entry doors was selected (Fig. 12). This had two advantages:-

. The open-jet working section gives negligible side-wall interference, the total cell width at the model station being 22' (6.7m).

. The entry doors can be partially closed to raise the velocity if necessary.

An additional advantage of the arrangement is that the tunnel floor is a simple steel table which can be easily adapted to simulate any ground or ship landing platform on site.

6.4 Carriage Design

Fig. 13 shows the model carriage and supply system adopted. A simple vertical strut protruding through the tunnel working section ceiling was chosen because it permits the model to be yawed easily - the whole assembly is arranged to rotate on a turntable. Further, this arrangement also allows all the model supply equipment, (particularly the jet flow heater), to be located outside the test cell but with a minimum length of connecting pipes running to the model. The strut is mounted so that it can move up and down and there is also provision for it to be rotated for different model yaw angles. The vertical motion is powered by an electronically controlled hydraulic system. This has been designed to permit a range of aircraft ascent accelerations and descent velocities to be simulated; there is also a delay facility to allow the motion to be started a finite time after some initial trigger event (generally nozzle rotation). The required sequence of events is pre-selected and occurs automatically once it is initiated. The ascent and descent rates which can be set up are:-

	Model Carriage	Typical Full Scale Equivalent
Ascent Acceleration, 'g'	0.03 - 0.18	0.05 - 0.3
Descent Velocity, ft/sec (m/sec)	0.4 - 3.0 (0.1) - (0.9)	2 - 15 (0.6) - (4.5)

The model can also be locked at fixed heights and a control is fitted to permit fine variations of model height to be achieved close to the ground.

A separate function of the support stand is to carry the model supply ducts. This has been designed to accommodate as wide a variety of test configurations as possible. In principle it could be replaced, along with parts of the external supply system, if necessary. Nominal design capacities of the existing plant (not including the present carriage stand) are as follows:

Inlet	A single line capable of sucking up to 3 lbs/sec. (1.4Kg/sec)
Exhaust	A single line supplied at up to Wmax. = 3lbs/sec/ (1.4Kg/sec) Tmax. = 500°C (930°F) Pmax. = 50 p.s.i.a. (345 Kn/m ²)

With the present carriage designed for 1/15th scale P.C.B. Pegasus - powered aircraft models, the low jet pressures and airflow requirements have enabled a single pressure supply line to be used for the nozzle supply with a draw-off pipe from this supply feeding the primary line of an ejector system, the secondary flow being the model intake suction supply.

Fig. 14 shows a typical model assembly attached to the carriage strut. and Fig. 15 illustrates the complete installation in the test rig.

6.5 Rig Starting and Purging

One other important rig design topic is the development of satisfactory techniques to set up the various flows and the intended V/STOL manoeuvre in as realistic a manner as possible, without any premature heating of the air in the vicinity of the model. Two significant problems affecting this were:-

- . The time taken to set the nozzle air heater to the required conditions.

- . The time taken to heat up the connecting pipes so that the air reaches the nozzles at the required temperature with minimum heat loss.

The solution adopted was to allow the heater to discharge to an overboard 'dump' or 'bypass' while conditions were being set up and to use rotatable nozzles on the model which discharge the flow aft; to be carried away by the tunnel airflow, while the connecting pipes warmed up. When this was achieved the nozzles could be rotated downwards and the particular aircraft manoeuvre initiated. This technique was considered to be a simple and realistic simulation of a vectored thrust type of powerplant. Other types of powerplant have not been represented, but a similar 'aft discharge' technique, or a collector system - maybe in conjunction with a 'trap door' could be devised to deal with any of these. In fact, a number of alternative systems have been devised by other experimenters using rigs which provide model vertical motion.

Static air tests, i.e. vertical manoeuvres, presented a slight problem in that there was little air flow available to purge away the hot air used to heat the pipes. However, it was found that once the pipes had been heated in the way described, the lagging kept them hot and so VTOL tests could be carried out after a series of STOL tests with no difficulty. Purging the tunnel between tests is simply a matter of allowing it to flow on for about a minute after each run.

7. SEQUENCE OF OPERATION

The operating procedures for the simulation of a typical V/STOL aircraft manoeuvre are as follows:-

- . The model nozzles are set aft
- . With the bypass valve open the combustor is lit and adjusted to give the required flow and temperature
- . The intake suction flow is set to the required rate
- . The bypass valve is closed to direct air to the nozzles
- . The connecting pipes and model parts are allowed to warm up until the required nozzle temperature is reached and maintained

- . The data recorder is switched on (analogue or digital system)
- . The nozzles are rotated to vertical or the chosen angle - this automatically initiates model ascent or descent after a delay time, if selected
- . At the end of the manoeuvre the nozzles are returned aft and recording is stopped
- . The tunnel is run for about a minute to purge hot gas from the cell

A typical intake temperature trace is shown on Fig. 16.

8. MODEL INLET TEMPERATURE MEASUREMENT SYSTEMS

Two temperature recording systems have been evolved for the measurement of inlet temperature rise in the small scale V/STOL models tested in the rig to date:-

- . An analogue system for recording mean intake temperature rise due to hot gas ingestion - the results being continually recorded on a U.V. recorder
- . A digital system for recording local intake temperature rise using a multiple array of rapid response thermocouples.

The two systems are shown on Fig. 17 and have been evolved to resolve temperature changes of the order of $\pm 0.5^{\circ}\text{C}$

System 1

The analogue system was developed for the purpose of assessing the ability of a given arrangement to minimise inlet hot gas reingestion. For this limited objective, the measurement of mean intake temperature rise was considered adequate, thereby avoiding the need for point temperature measurement. To meet such a requirement resistance thermometry was chosen for a number of reasons:-

- . It avoids the manufacturing difficulties associated with the very small thermocouple junctions
- . Instead of temperature measurements at a number of points requiring individual thermocouples, the mean temperature along a chord is measured which permits large economies in number of sensors. For a given coverage density, on a square mesh, the number of resistance thermometers required is the square root of the number of thermocouple junctions. For bifurcated side-inlet configurations, typical of P1127/Harrier, it was estimated that approximately 36 thermocouples would be required to cover one half inlet so that about six resistance elements would be needed. However, to simplify sensor manufacture, it was decided to employ a single grid of resistance elements at a plane downstream of the simulated engine face (Fig. 17a). Ten elements were considered adequate and the design finally adopted was to carry each wire across the duct twice in an interlaced pattern, providing, effectively, 20 wire coverage to give some redundancy in case of wire breakages due to foreign object impingement.

- . Tungsten wire could be used-which is approximately 10 times as strong as typical thermocouple materials thereby significantly reducing the likelihood of wire breakage - a problem common to thin wire thermocouples.
- . In order to follow the temperature rise transients anticipated sufficiently closely, the measuring system was required to have a time constant of the order of 10^{-2} secs. This, for the time ratio of 3 of the 1/15th scale model gives an equivalent full scale time constant of about 30 milliseconds. Heat transfer considerations for a step change in temperature suggest that this necessitates a measuring element diameter of the order of 0.05 m.m. at the air velocities present in a typical 1/15th scale model intake duct of about 210 ft./sec. (65m/sec).
- . The sensor finally chosen was a resistance thermometer consisting of 20 tungsten wires of (0.002 in.) (0.05 m.m.) dia. (See Fig. 17a). The thermometer was fitted in a single bridge circuit, the out of balance voltage resulting from changes in thermometer resistance being recorded on a 12-channel galvanometer recorder.
- . The instrument was calibrated using a heated distilled water bath to determine a temperature coefficient, defined as galvanometer trace deflection per degree per unit wire length, taking the wire length for steady-state calibration as the total length between anchor pins. The effective calibration constant for transients was then obtained by multiplying this coefficient by the exposed wire length.

System 2

The system devised for recording local intake temperature incorporates 36 rapid response, miniature thermocouples (Fig. 17b), and provides a means of rapid sampling of a number of points at a model intake delivery plane to pick up the localised and short duration hot streaks which characterise near-field recirculation. Measurements of local temperatures are essential for determining time-dependent spatial temperature distributions in the intake. Temperature distortion data forms a critical portion of the overall information required to assess engine performance under hot gas reingestion conditions. Engine operation is related not only to mean intake temperature rise - which is manifest as a loss in available thrust, but also on the temperature distortion profile which affects thrust and which could cause surge. Associated work on engine surge response has provided a higher order thrust loss model and correlations between compressor and engine-face temperature distortion and loss of surge margin which, in the present content, are used to evaluate hot gas ingestion data requisition needs.

In order to follow the rapid changes in temperature distributions characterised by near field hot gas recirculation it was essential to employ instruments having time constants less than 10^{-2} seconds - short times at full scale being further reduced by model time-ratio scaling requirements. The probes finally chosen were DISA type 55A52 resistance thermometers which have 5 micron thick tungsten sensor wires. These probes, having a time constant of about 0.5 milliseconds, are capable of following temperature variations at frequencies up to 300 Hz in a (210 ft./sec.) 65m/sec/ air stream velocity. Equivalent full scale time constant and cut off frequencies are 1.5 milliseconds and 100 Hz respectively.

Initial studies investigated DISA probes having 1-micron thick platinum sensor wires. The use of these probes would have meant less heat conduction loss via the wire support prongs and hence less chance of measurement error. Also, the higher wire resistance of the probes, giving higher voltage for a given temperature rise, would have meant less amplification and so a higher overall response rate from the digital handling equipment, allowing a higher scanning rate to be used. The higher wire resistance would also have meant less likelihood of encountering spurious effects due to lead and contact resistances. The cut-off frequency of the 1-micron sensors was 3.5 KHz.

Initial tests indicated that the 1-micron sensors would have too high a breakage rate during tests. Five micron sensors were selected as these gave a considerable increase in strength due to both the material change, from platinum to tungsten, giving about a 3 times increase in tensile strength, and a 25 times increase in cross sectional area, and the response rate was judged adequate.

Analogue recording of the output from the DISA probes - e.g. on a U.V. galvanometer recorder, was not attractive for a number of reasons including the requirement of separate channels for each sensor. Accordingly, a multiplexed digital system was designed which alternately switches the various sensor readings at high speed on to a single channel. An analogue/digital converter is used to convert the analogue output from the multiplexer/amplifier to a digitised signal which is then recorded on magnetic tape. (Fig 17b). The tape output is then read on to a computer and software analysis programmes are used to give a printed data output.

The type of equipment chosen gave a sampling rate of 50 per second per tapping. This was considered to be quite adequate for the anticipated intake temperature transients.

Check tests were carried out on the 1/15th scale model to determine temperature fluctuations during simulated take-off and landing manoeuvres. Results, Fig. 18, indicated that the recording interval of 0.02 seconds model scale, equivalent to 0.06 seconds full scale, appeared to be short enough to follow the observed temperature fluctuations for a realistic take-off manoeuvre.

9. RIG OPERATING EXPERIENCE

During commissioning trials on the rig specific studies were carried out on the following items:-

. Model Carriage

Performance checks on the hydraulically-operated model carriage showed that the acceleration and velocity requirements were exceeded, that end of stroke safeguards were satisfactory, and that the control system was adequate for smooth ram travel.

. Model Services

Airflow supplies designed to give flows adequate for the models tested to date were satisfactorily achieved.

Required scaled nozzle temperatures and pressures were achieved and calibrations were obtained to relate nozzle line to bypass line conditions.

Tunnel calibrations showed that design conditions were met. Prevailing external wind strengths and directions pose no restrictions on tunnel useability although some limitations on tunnel low speed testing exist for rare external wind conditions. Studies are at present in hand to remove these limitations by fitting screens in the tunnel entry.

The turbulent or unsteady nature of recirculating exhaust flows means that the ingestion of hot gas streaks tends to be a variable phenomenon. As a consequence it has been found necessary to repeat each manoeuvre at least 3 times to obtain a reliable overall measure of the likelihood and magnitude of recirculation occurring. This does not noticeably affect the cost of testing because the time for each run is a matter of seconds, which is negligible compared with the total tunnel occupancy costs of a test programme.

10. SAMPLE RESULTS

10.1 Basic Data

The moving model rig has been used primarily to test the representative aircraft model shown on Fig.14. Tests over a wide range of carefully simulated jet borne ascents and descents, and a range of forward speeds have been carried out. The objective of the tests was to examine the effectiveness of a number of reingestion avoidance techniques over a realistic V/STOL aircraft take-off and landing manoeuvre envelope, and to identify any flight conditions where residual recirculation effects might prove to be prohibitive. The tests were carried out on the model using the analogue system of mean intake temperature rise measurement to define aircraft operating envelopes. This system is simpler and cheaper to operate, with a more rapid acquisition of model results. The model has also been tested using the local (digital) measurement system whereby peak local temperatures and temperature distortion contours and distortion coefficients can be obtained. This system of course requires considerably more sophistication and effort in its operation, requiring longer data processing.

Typical results for both systems are shown on Fig. 19. These results are for a nozzle configuration designed so that the jets merge at or above ground level, thereby suppressing the central hot gas fountain present with pairs of vertical jets.

Fig. 19a shows a typical trace of mean intake temperature rise as a function of aircraft height (and corresponding time) for a particular fixed acceleration take-off manoeuvre. From such traces it is possible to plot charts, as shown on Fig. 19a, displaying the highest value of mean inlet temperature rise encountered in any given manoeuvre (defined by ascent acceleration and relative wind speed). Similar traces can be produced for typical fixed-velocity landing manoeuvres.

The above data can also be obtained from the multipoint measurement system. As shown on Fig. 19b, traces of peak local and peak mean overall temperature variation with aircraft height and time are produced. Again, a typical take-off condition is presented, and similar data can be produced for typical fixed velocity landing manoeuvres. Engine face transient temperature distortion plots can also be constructed, see Fig. 19b, from which temperature distortion coefficients, for any chosen segment, can be calculated using the computer programmes, available.

10.2 Application of Results

From the data shown on Fig. 19, and other similar curves for different nozzle angles and wind directions, predictions can be made of the likely intake temperature rise and compressor face temperature distortion due to hot gas ingestion during any take off and landing manoeuvre. Provided the aircraft characteristics are sufficiently well known, so that the relationship between speed, nozzle angle, and ground roll can be defined, the variation of intake temperature during the manoeuvre can be predicted. The maximum value for each take-off run or landing can then be plotted as a function of the ground speed. Fig.20 shows an example for an aircraft powered by an augmented vectored thrust engine where the intake temperature rise due to hot gas ingestion is less than the target level set for all take-off and landing manoeuvres except in the case of very short take-off runs. Under these particular conditions, the combination of nozzle angle and forward speed can produce a significant amount of intermediate, or thrust reverser, recirculation. It will be noted that a purely vertical take-off is acceptable and it is possible to avoid the high levels of intake temperature rise for the very short ground runs by the selection of suitable operational procedures.

It should be noted that although the measurements of intake temperature rise indicate that acceptably low levels of hot gas recirculation can be achieved, there are other factors to be taken into account in the assessment of aircraft overall performance close to the ground. The total weight that can be lifted vertically will be reduced by other losses which are incurred as a result of achieving low recirculations levels. These affects are outside the scope of this paper but include:-

1. The loss of thrust due to the inwardly angled jets
2. Elimination of the longitudinal fountain created between the front jets of the normal four poster without nozzle convergence. Losing this fountain reduces favourable lift effects near the ground.
3. The elimination of the fountain, without excess convergence angles, may require a longer undercarriage than could other-wise be used so there may be a weight penalty or a retracted-undercarriage stowage problem.

The reingestion facility provides a means for establishing the hot gas reingestion data necessary to provide for trade studies.

10.3 Relevance of the Moving Model Technique

It was postulated, during early work concerning the need for a moving model rig, that fixed-height data might give pessimistic intake hot gas ingestion levels in that the model would, in reality, take-off or land before hot gas recirculation patterns were fully established. Typical results for the 1/15th scale model tested both at a fixed aircraft height of about 8', and under simulated take-off and landing conditions are shown on Fig. 21. The time slice for the fixed-height data is about 5 seconds, (full scale), which is within the time interval normally taken for an aircraft to complete a VTO or V.L. The results show that simulation of the actual manoeuvre produces significantly lower levels of mean intake temperature rise thereby confirming the requirement for a moving model test facility.

11 CONCLUDING REMARKS

The moving rig has been successfully developed at Rolls-Royce to permit accurate simulation of aircraft manoeuvres close to the ground. The limitations of fixed-height testing have been exposed.

Model tests using the moving-model rig have shown that a potential problem of the single augmented vectored thrust engined V/STOL aircraft - that of hot gas recirculation - may be avoided, provided the appropriate features are incorporated in the installation

Further applications of the rig for use in the V/STOL field can be readily identified-including studies of deck obstructions for operation from ships, operation near buildings e.g. hangers, aircraft underfuselage temperature and ground footprint measurements.

The rig has been employed in five major test programmes, following commissioning trials at the end of 1974. During this period in excess of 3,500 runs (embracing live ascents and descents) have been achieved.

REFERENCES

1. M. Cox & W.A. Abbott Studies of the flow fields created by single vertical jets directed down-wards upon a horizontal surface. N.G.T.E. Memo. No.M390 October, 1964
2. W.A. Abbott Studies of flow fields created by vertical and inclined jets when stationary or moving over a horizontal surface. N.G.T.E. Memo. No. M.391 October, 1964
3. E.D.G. Kemp Studies of Exhaust Gas Recirculation for VTOL Aircraft. A.I.A.A. Paper No. 67-439
4. A.W.R. Allcock & W.A. Abbott Full Scale and Model Studies of Exhaust Ingestion on the Hawker-Siddeley P1127 with special reference to the scaling laws. Unpublished M.O.D. (PE) Material

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FOUR POSTER LIFT JET ARRANGEMENT
FLOW PATTERN

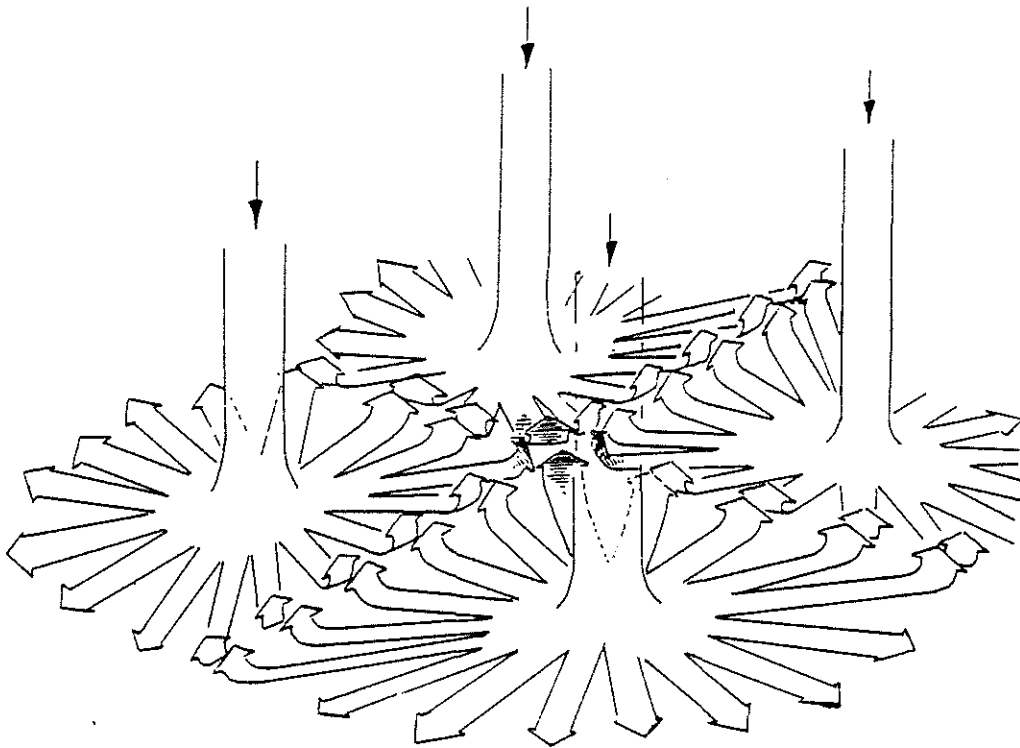


Figure 1

4-POSTER PEGASUS HOT GAS
RECIRCULATION MECHANISMS

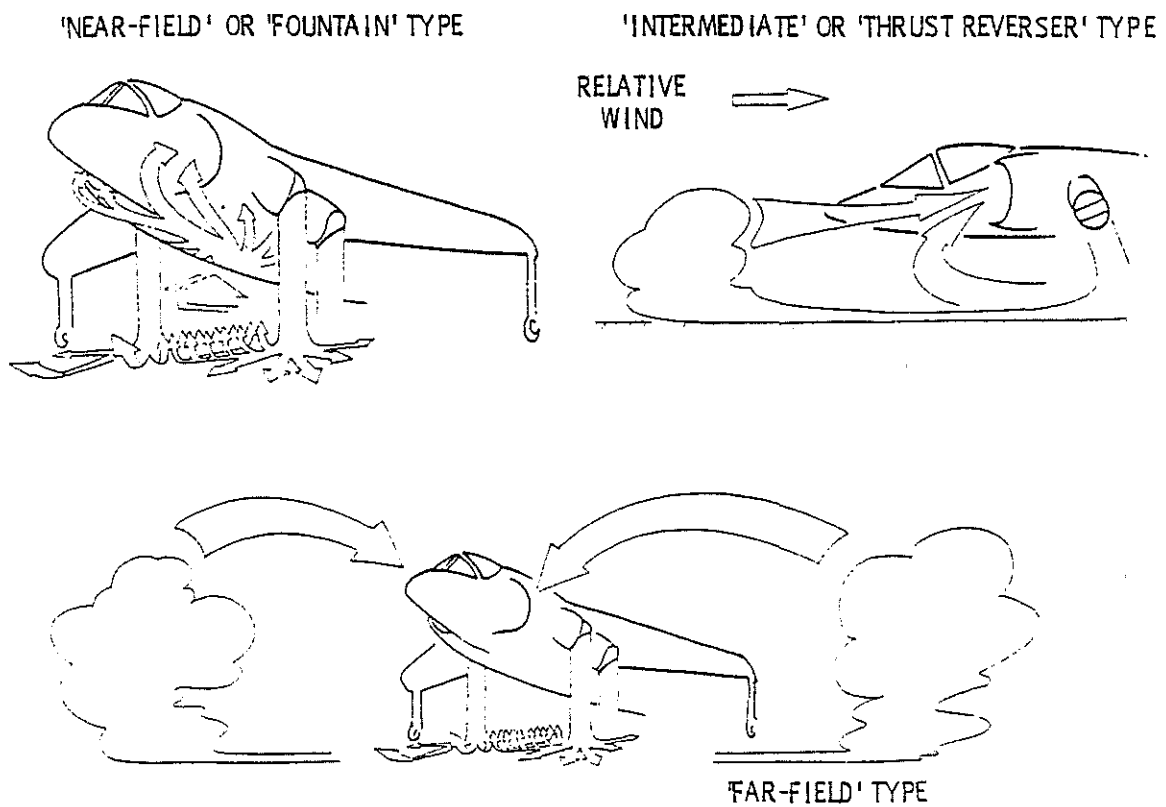


Figure 2

WATER FLOW SIMULATION OF FOUNTAIN TYPE RECIRCULATION

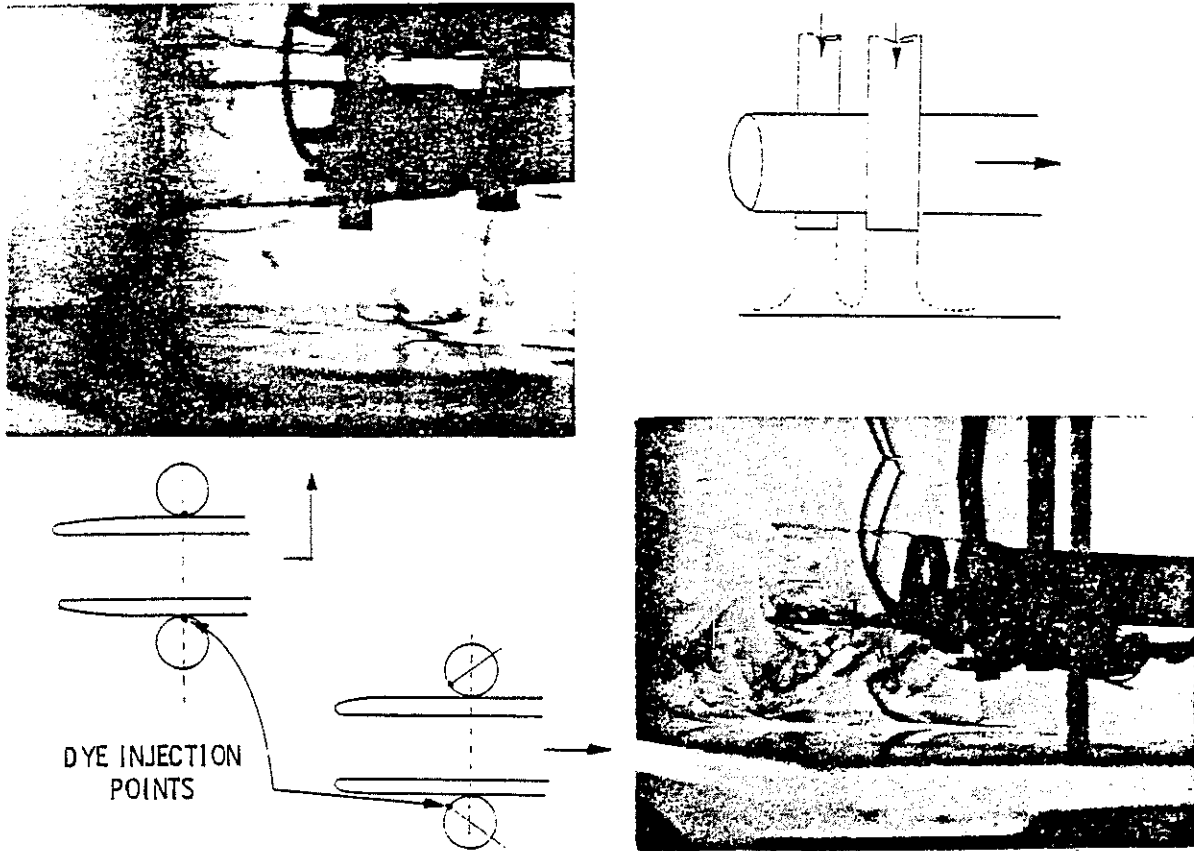


Figure 3

THRUST LOSS DUE TO HOT GAS REINGESTION ASSUMING UNIFORM INLET TEMPERATURE

$$\text{TEMPERATURE RISE} = \frac{\Delta \bar{T}_{\text{INLET}}}{\Delta T_{\text{FRONT NOZZLE}}} \%$$

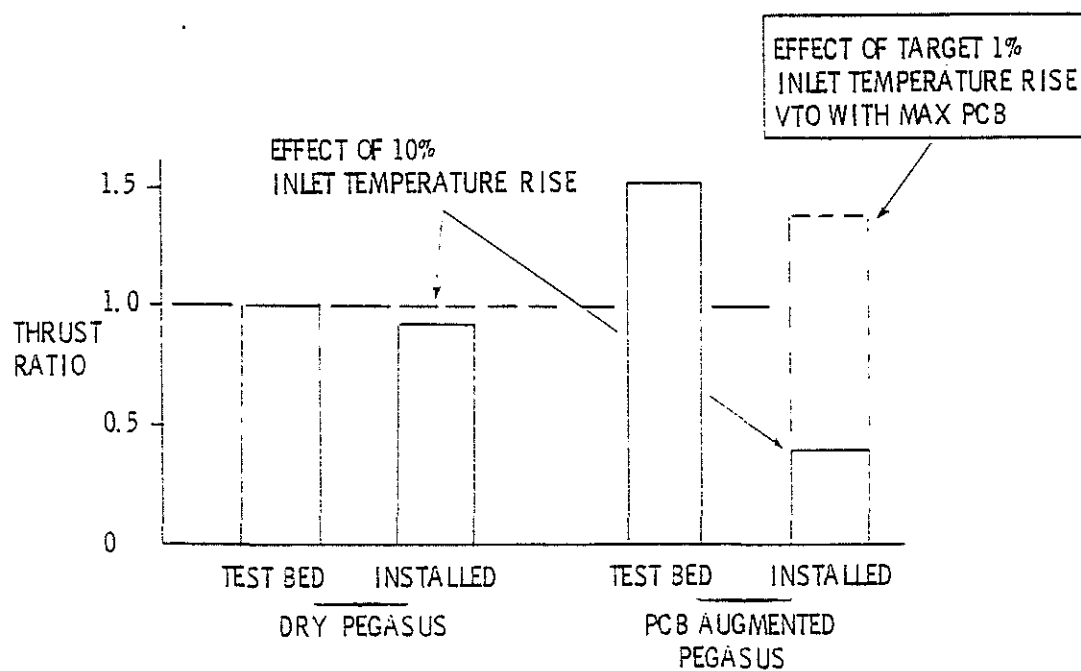


Figure 4

HALF-MODEL INSTALLATION

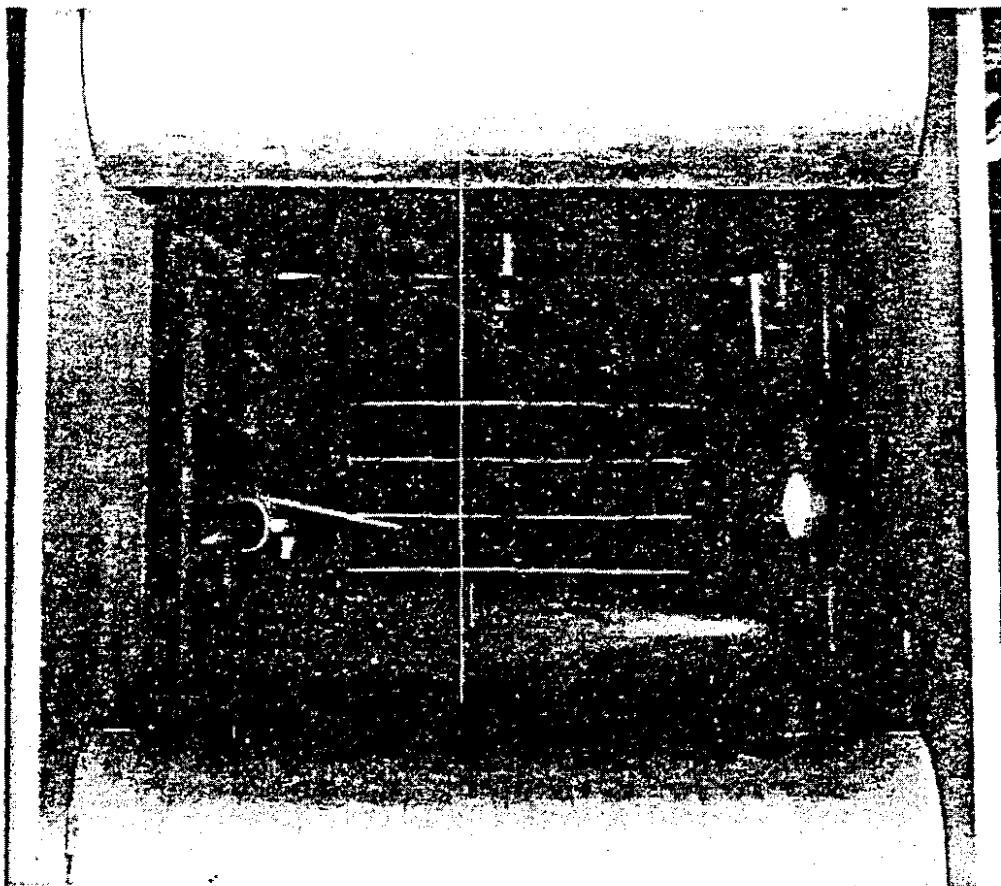


Figure 5

REINGESTION TESTING WHOLE VERSUS HALF MODELS

HARRIER - TYPE LIFT-JET ARRANGEMENT

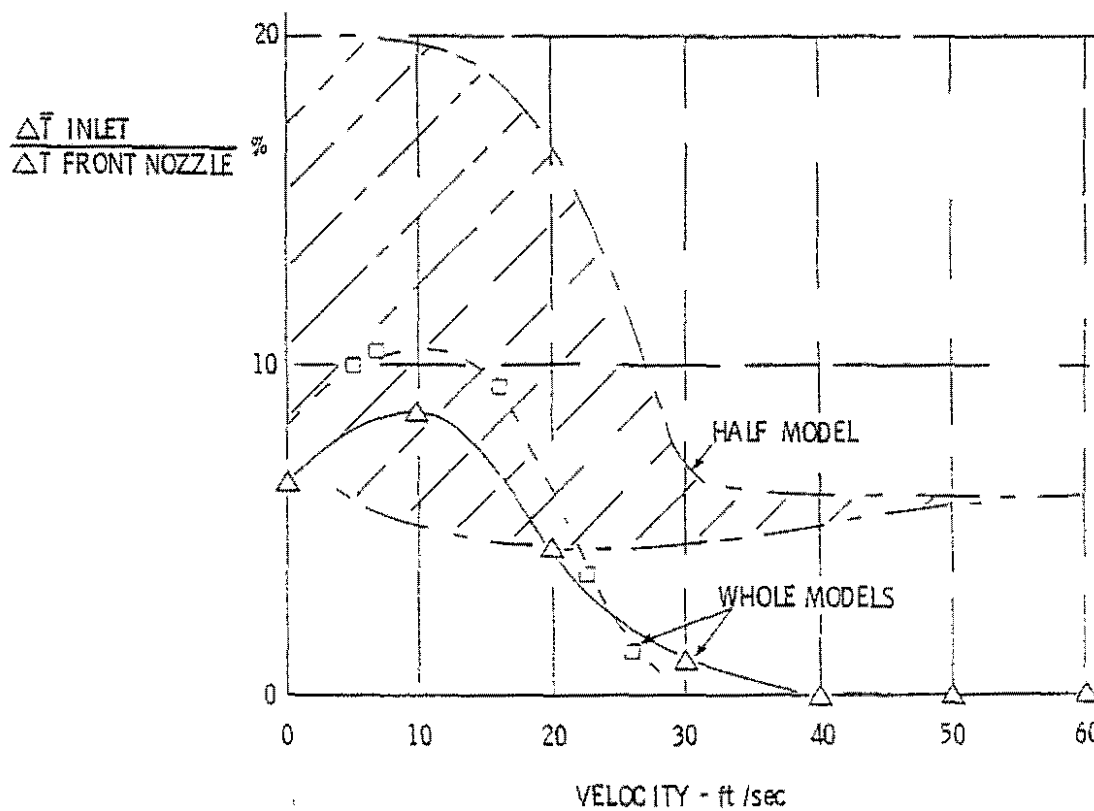


Figure 6

1/30TH SCALE WHOLE MODEL IN THE REINGESTION TUNNEL

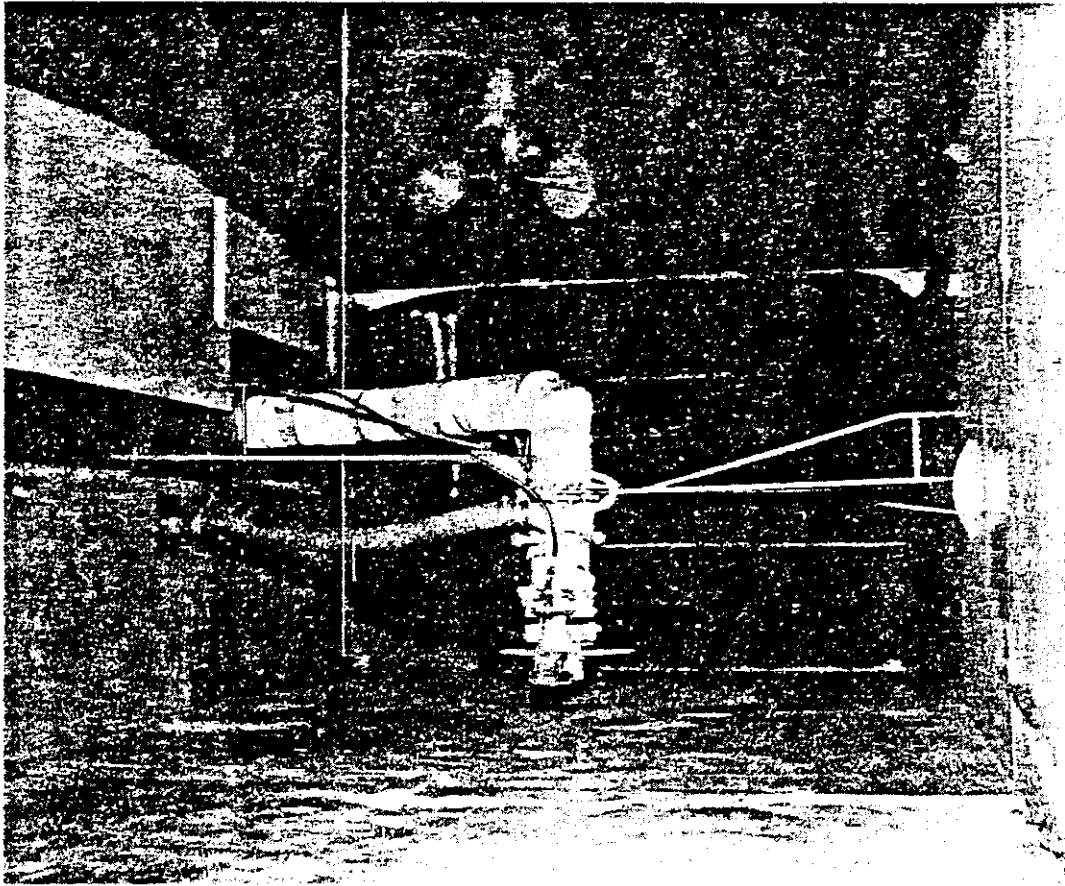


Figure 7

ROLLS-ROYCE BRISTOL REINGESTION TEST FACILITY

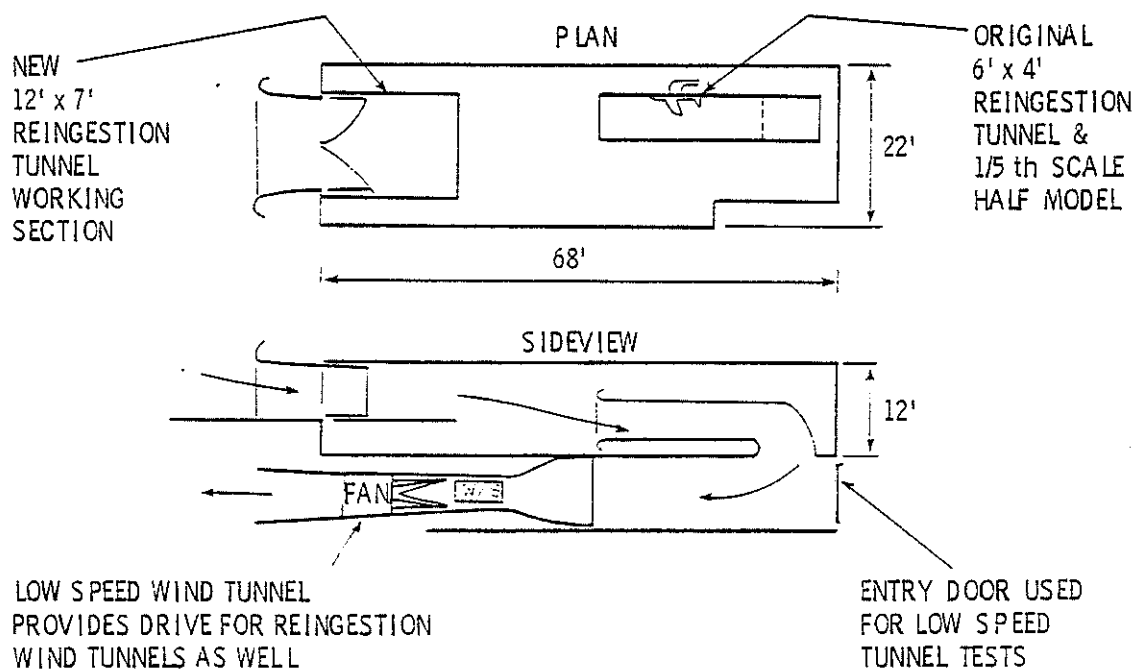


Figure 8

BUOYANCY / MOMENTUM CORRELATION

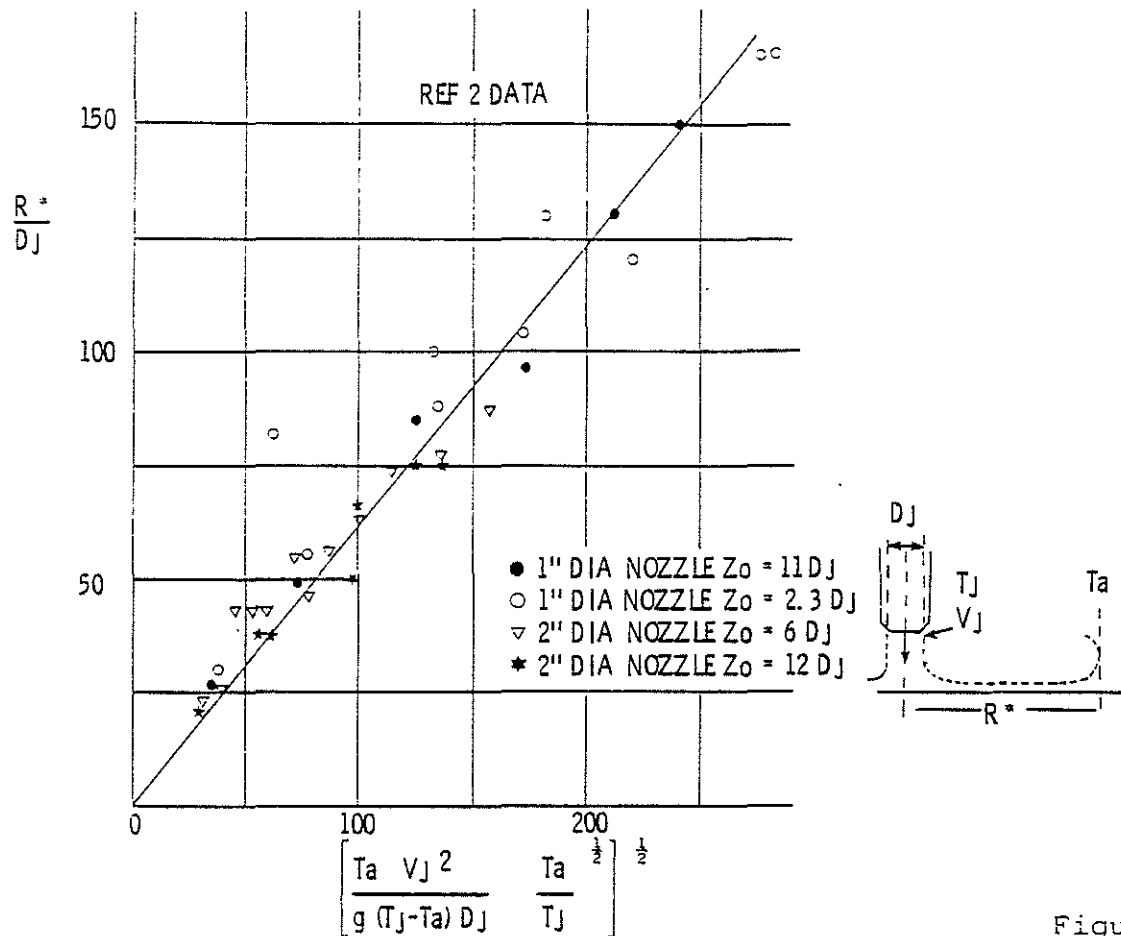


Figure 9

COMPARISON OF MODEL AND FULL-SCALE RECIRCULATION TEST RESULTS (P1127 AIRCRAFT)

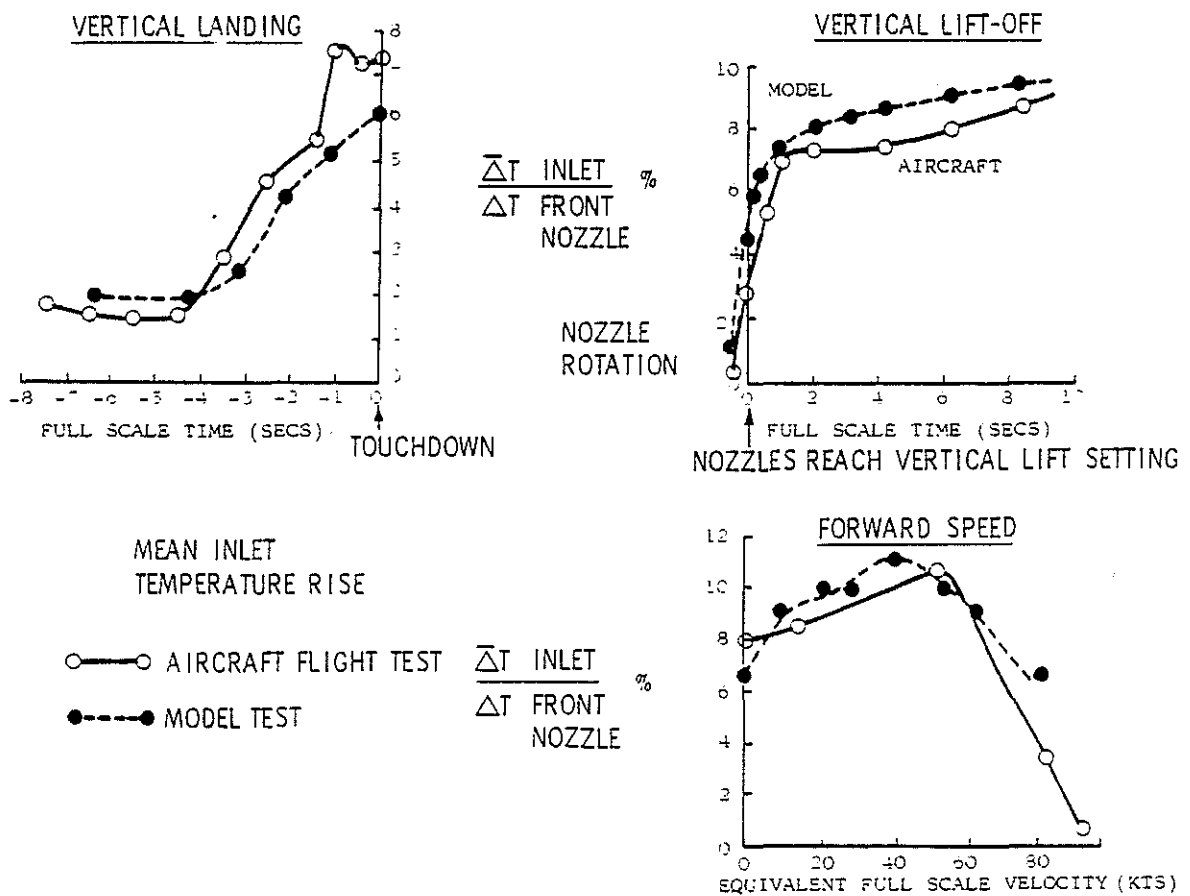


Figure 10

MODEL SCALING REQUIREMENTS

APPROX MODEL JET TO SIMULATE HOT AND COLD FULL SCALE JETS @ 2.5 : 1 PR

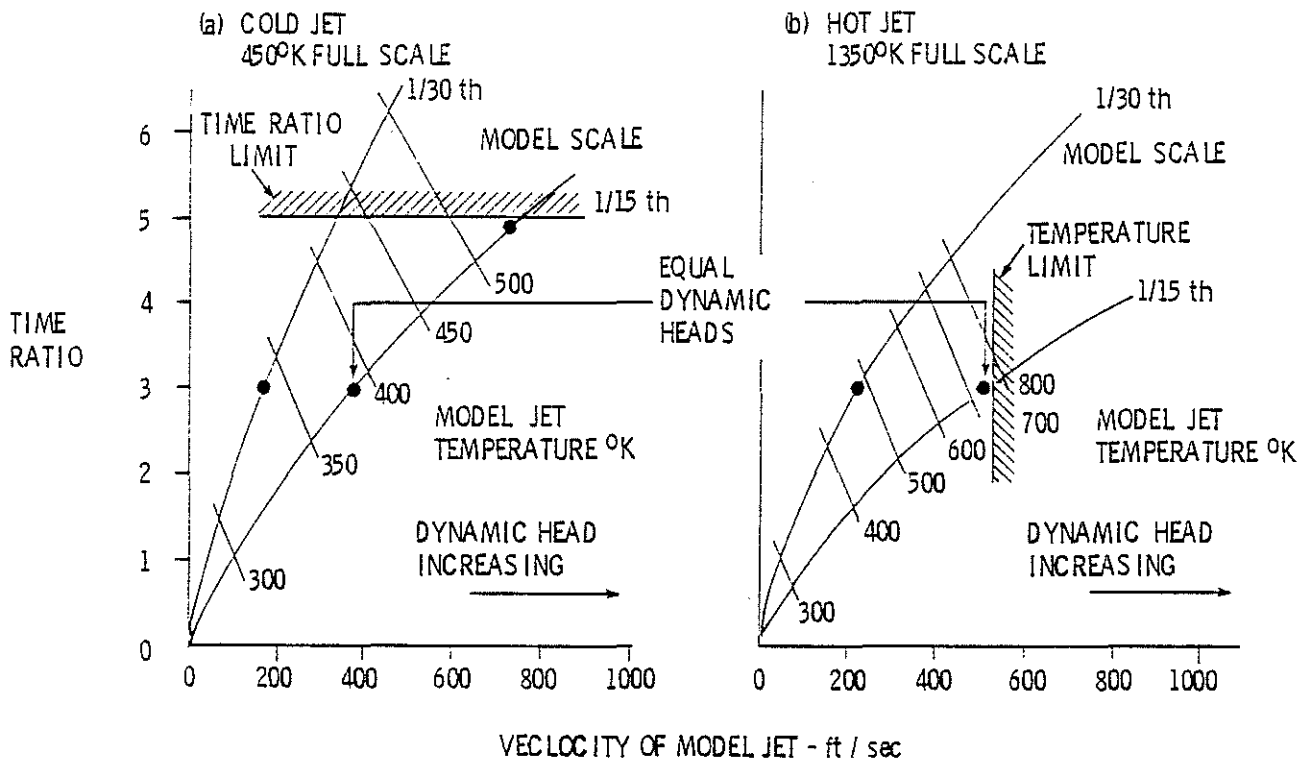


Figure 11

REINGESTION TUNNEL - WORKING SECTION

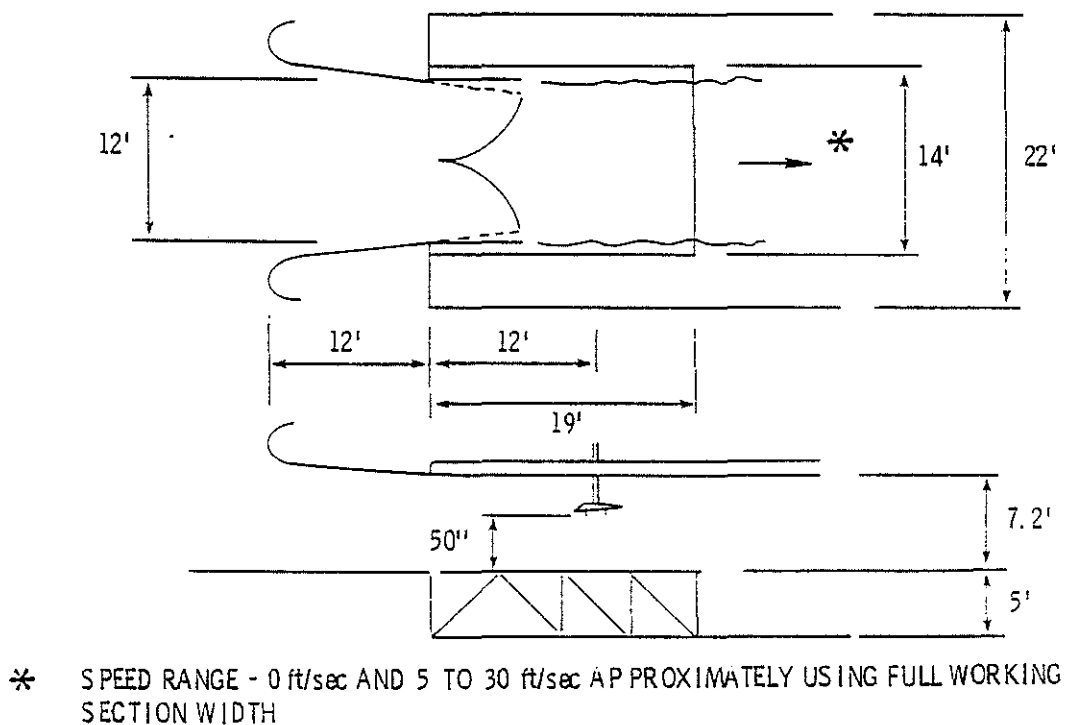


Figure 12

REINGESTION TUNNEL - MODEL CARRIAGE

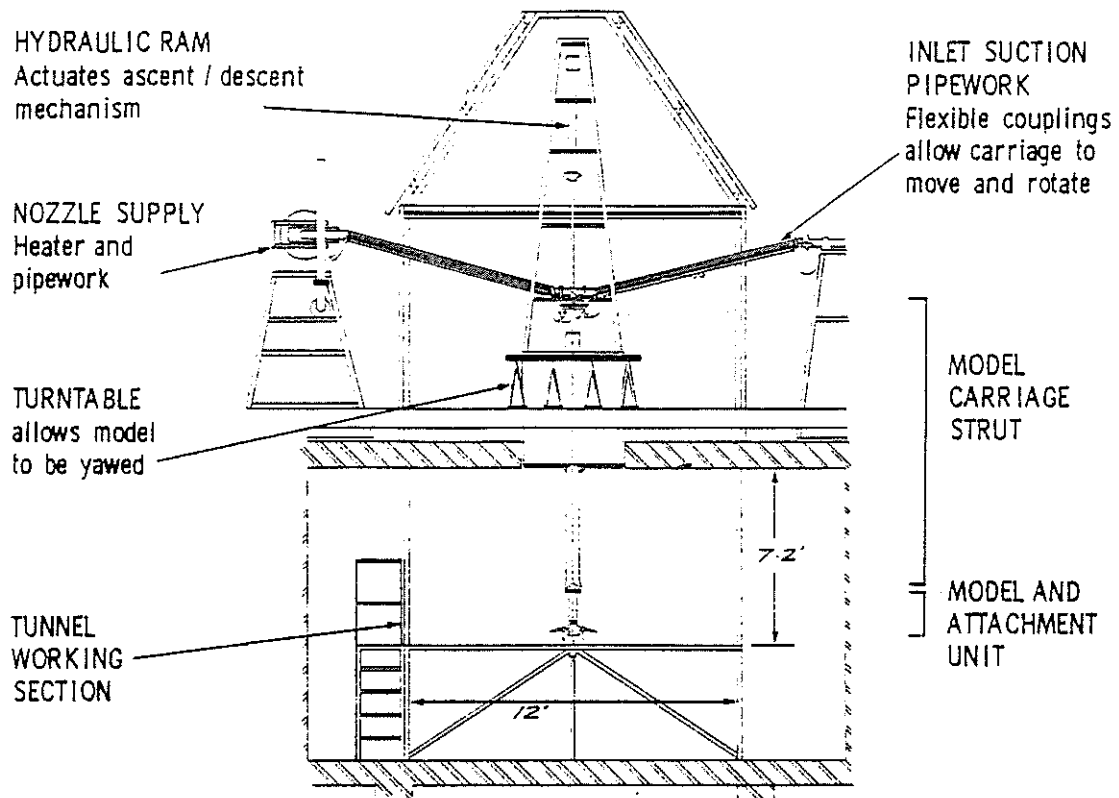


Figure 13

ROLLS-ROYCE 1/15 th SCALE TEST MODEL

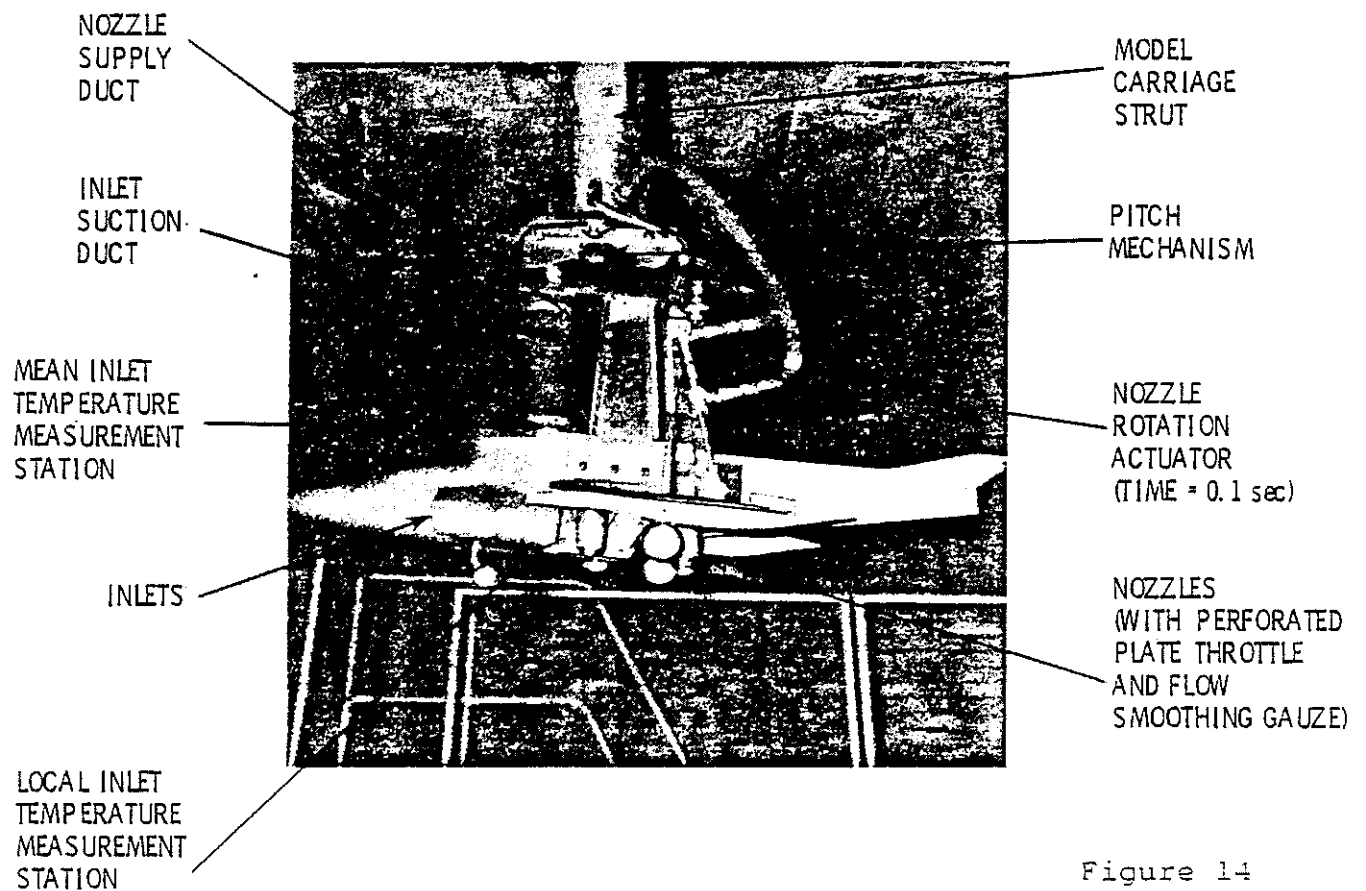


Figure 14

VISTOL WIND TUNNEL

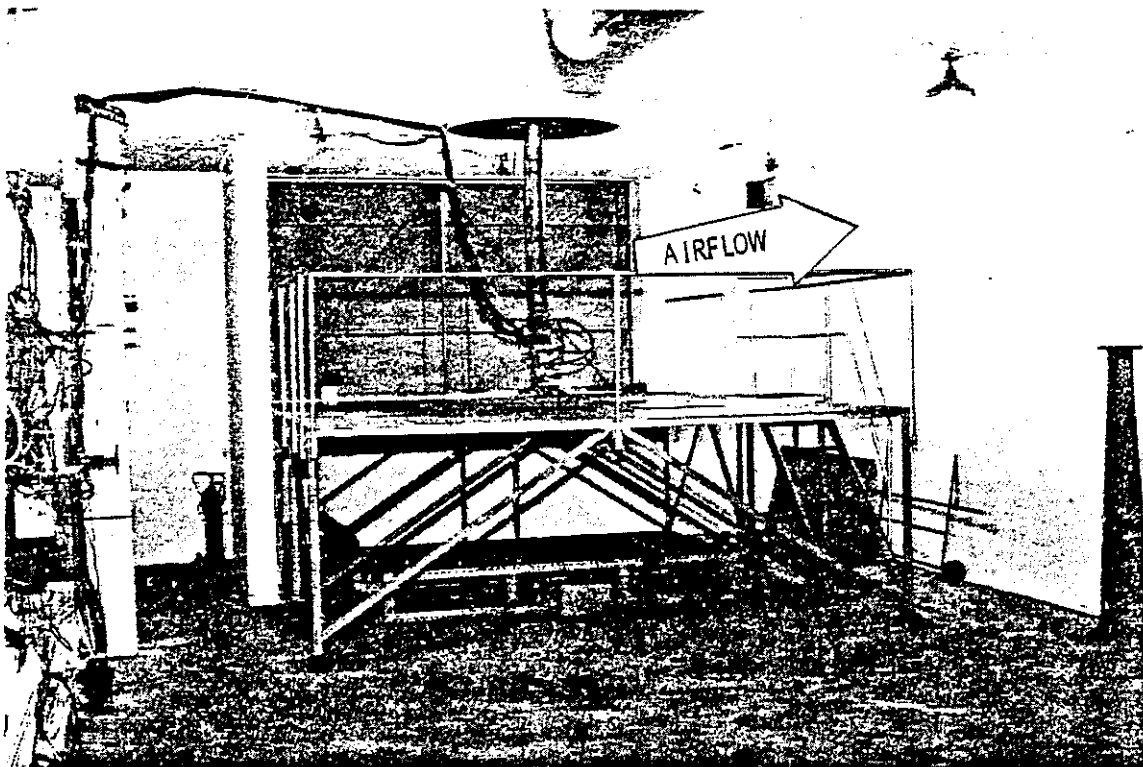


Figure 15

TYPICAL TRACE SHOWING TEST RUN EVENTS

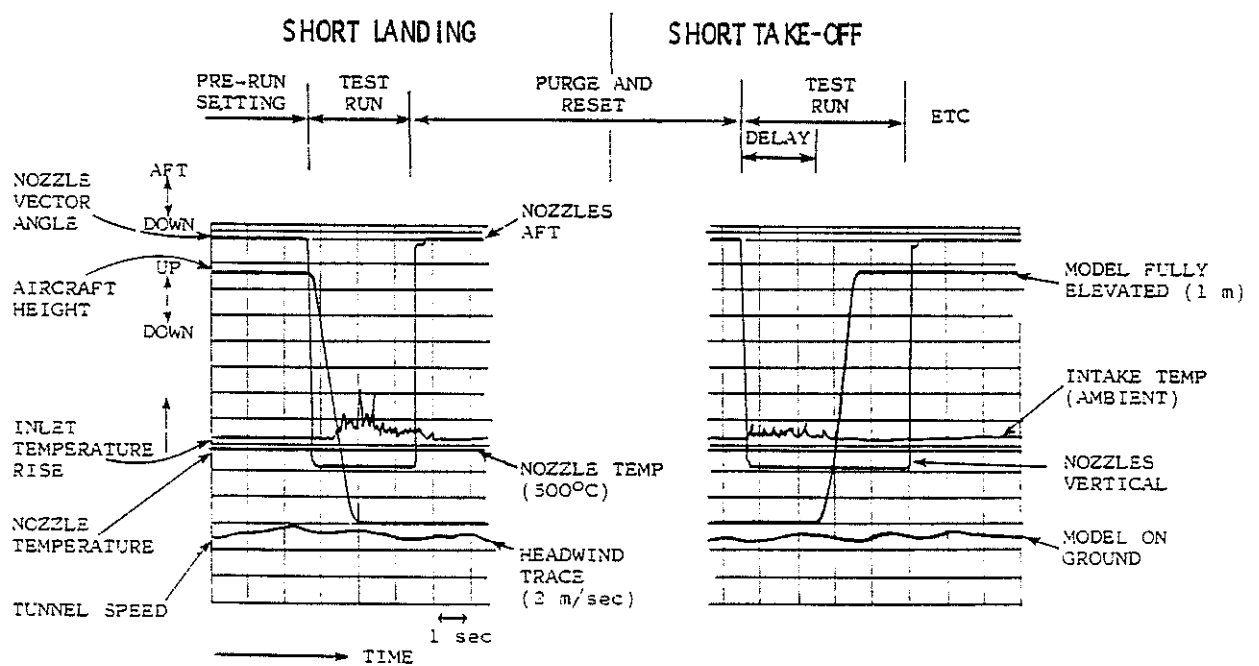
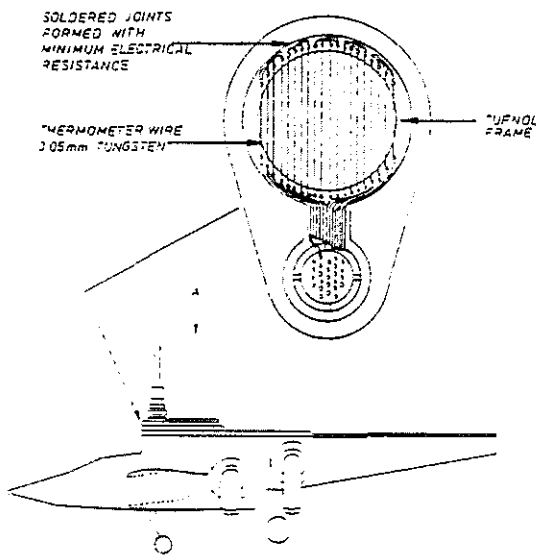
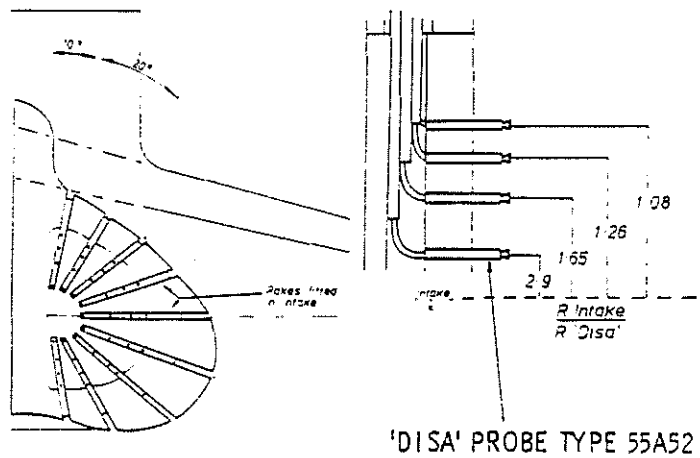
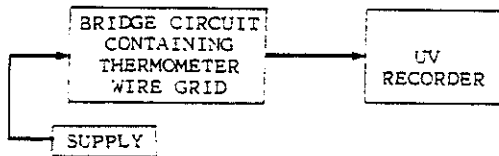


Figure 16

INLET TEMPERATURE INSTRUMENTATION



INTAKE TEMPERATURE MEASURING GRID



'DISA' SENSOR RAKES FITTED TO TEST MODEL

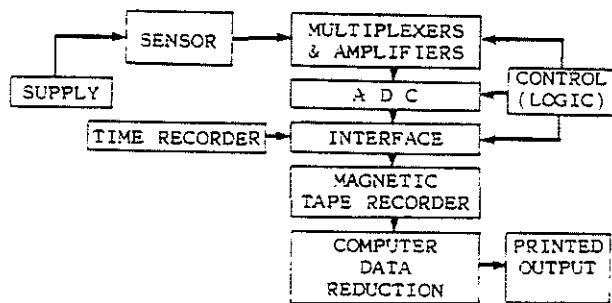


Figure 17

TYPICAL TIME HISTORY OF TEMPERATURE RISE

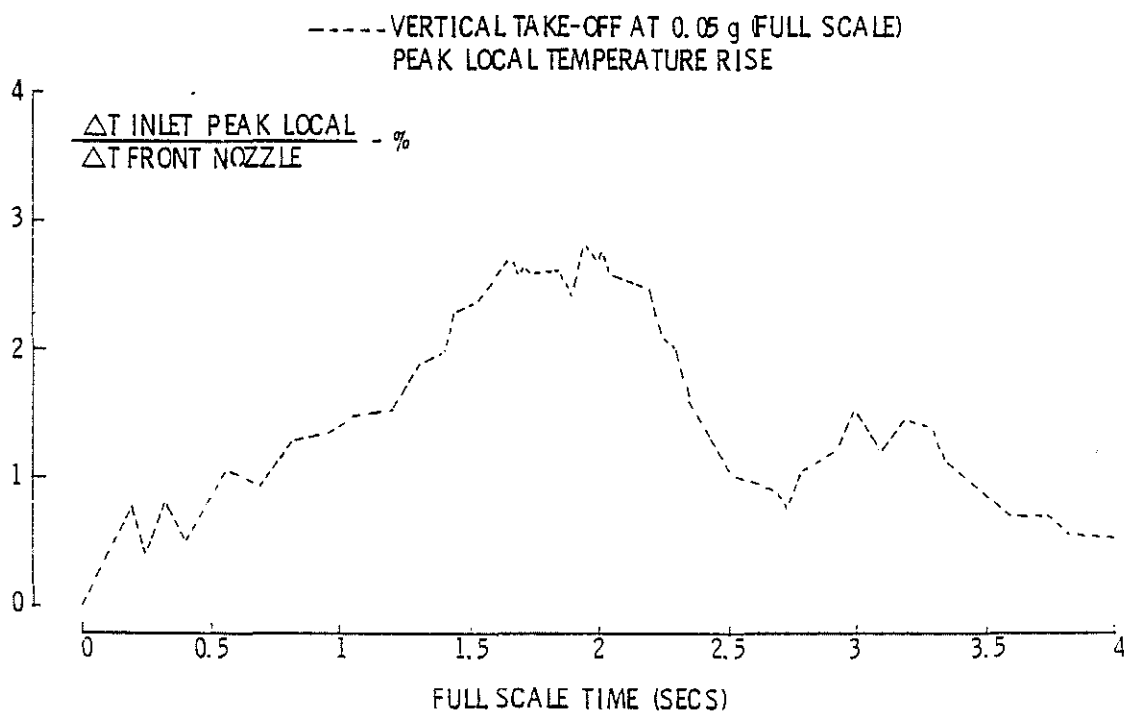


Figure 18

SOME TYPICAL TAKE-OFF RESULTS

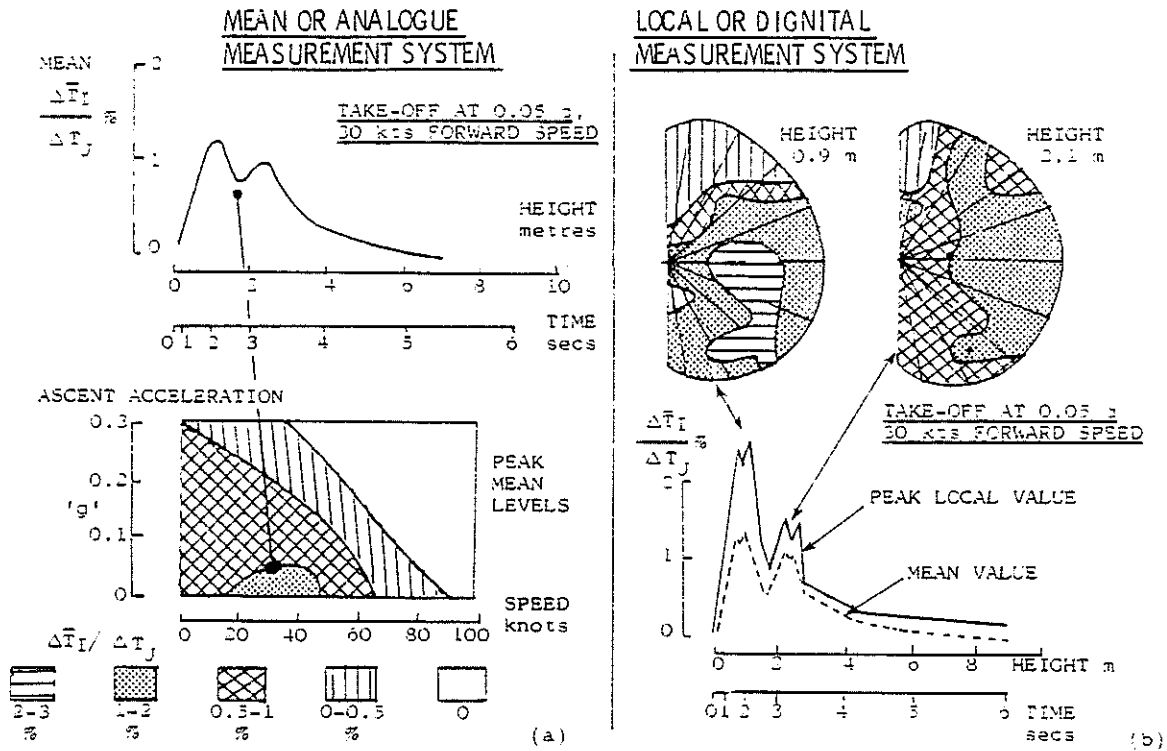


Figure 19

CONVERGED LIFT JETS TYPICAL V/STOL MANOEUVRES PEAK MEAN INLET TEMPERATURE RISE AND DISTORTION LEVELS

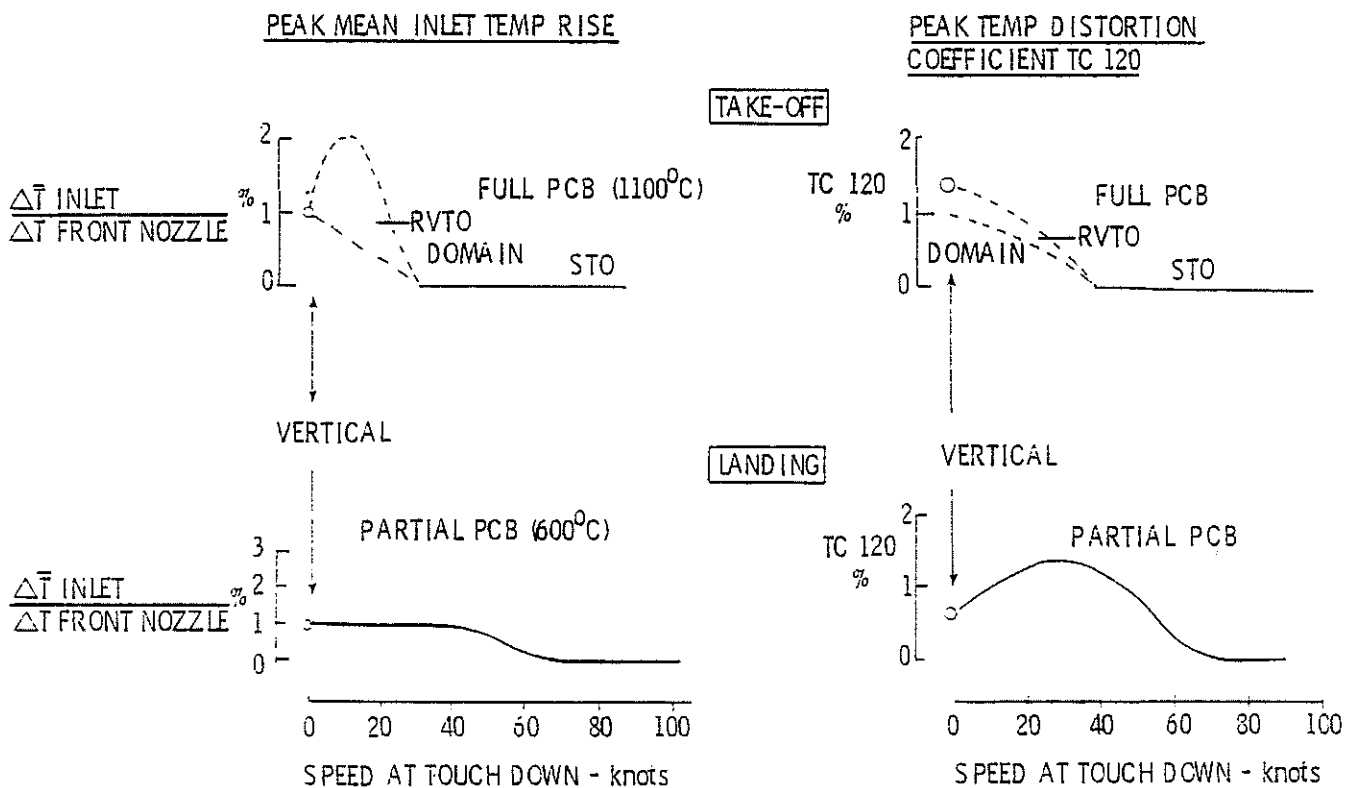


Figure 20

COMPARISON BETWEEN PROLONGED HOVER AND MOVING
MODEL TESTS

VARIATION OF PEAK MEAN INTAKE TEMPERATURE RISE
WITH HEADWIND

FULLY CONVERGED NOZZLES

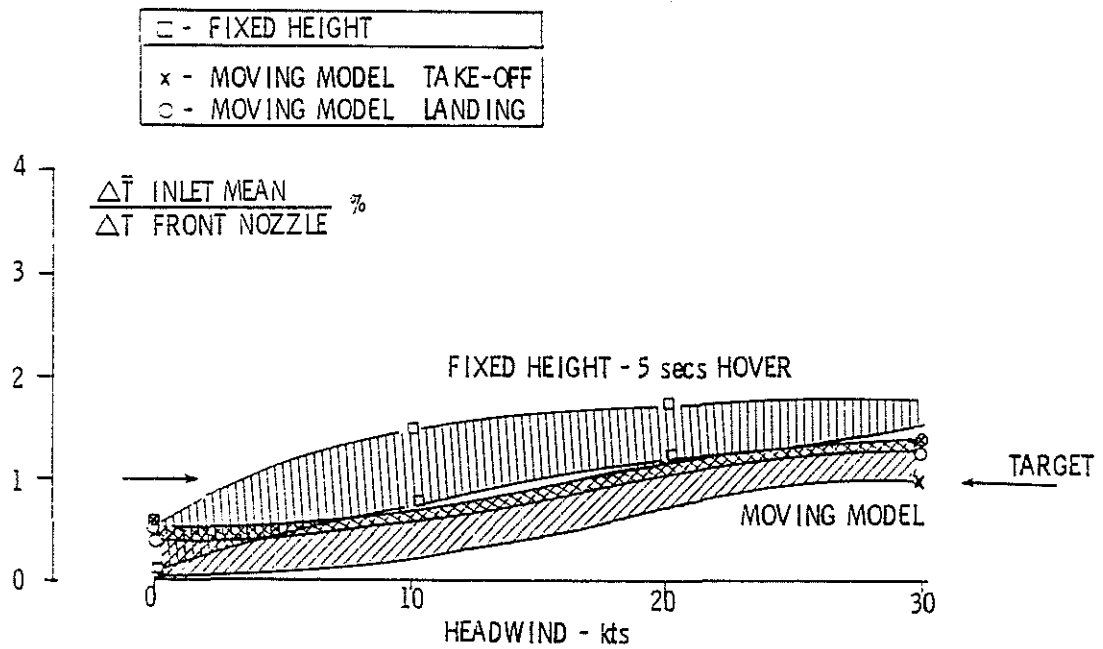


Figure 21