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MELBOURNE, VICTORIA

Aero Propulsion Technical Memorandum 458

AERODYNAMIC MODEL TESTS OF EXHAUST AUGMENTORS FOR F/A-18 ENGINE RUN-UP FACILITY AT RAAF WILLIAMTOWN - SUMMARY REPORT (U)

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S.A. Fisher and A.M. Abdel-Fattah

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SUMMARY

Model tests of the air cooled exhaust augmentors proposed for the F/A-18 engine ground run-up facilities at RAAF Williamtown were undertaken, to confirm satisfactory aerodynamic behaviour of the augmentor designs and to provide data for optimising certain aspects of the designs. The tests were carried out on 1/45 scale models, using an unheated air jet to represent the engine exhaust. Geometric features were identified which had important influence on augmentor duct flow symmetry and the cooling flow augmentation ratio.

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CONTENTS

1. Introduction

This report summarises the results of model tests of the proposed exhaust augmentors for both the 'installed' and 'uninstalled' engine run-up facilities being designed for the F/A-18 aircraft at RAAF Williamtown. The purpose of the tests was to provide data for optimising detailed aspects of the aerodynamic design of the two facilities. The scope of the tests was agreed with Australian Construction Services (ACS), and the work was undertaken in response to ACS Purchase Order No S21/89PD dated 23 November 1988.

2. Test Models and Instrumentation

The basic configuration and dimensions of the 'installed' model were based on drawings tabled at the project review meeting on 15 September 1988, reproduced in outline together with leading full scale dimensions in Figure 1. The secondary inlet dimensions were supplied by Challis and Associates on 6 October 1988, and primary augmentor tube dimensions were supplied on 11 November 1988.

The basic form of the 'uninstalled' model, which was constructed earlier, was based on a drawing dated 26 July 1988, reproduced in outline in Figure 2. Primary tube dimensions were not available, and were scaled from the drawing. The shape of the secondary inlet ducts was different from that which appeared on subsequent drawings, in that 'kinks' which were later added to the aft walls of the ducts, adjacent to the acoustic splitter trailing edges, were not included in the model.

Photographs of the two models are shown in Figure 3. The 'installed' model is seen in partly modified form, with bellmouth fairings on the secondary air inlets, while the 'uninstalled' model appears in original, unmodified form. Both models were 1/45 full scale, constructed mainly from timber and glass. In the vicinity of the air inlets, only those features thought to be directly relevant to the augmentor duct internal flow were represented on the models; the test bay structures, for example, were not included.

The engine exhaust jet was simulated with unheated air issuing from a convergent-divergent nozzle of correct geometrical scale. The nozzle blowing pressure was 340 kPa, providing a pressure ratio equal to that of the exhaust nozzle of the F404 engine operating in the full afterburner mode, so that the Mach number at the nozzle exit plane and the scaled jet momentum were both similar to the full scale jet. All tests were carried out with an arrangement representing single engine operation in full afterburner. The jet nozzle was positioned with its exit plane approximately 1.4 m (full scale)* upstream of the commencement of the parallel section of the primary augmentor tube.

Air velocity measurements were made in the exit planes of the main ducts using a traversing pitot-static tube aligned with the duct axis. The pressures were measured with strain gauge transducers and recorded on an X-Y plotter. In some cases measurements were also made further upstream in the ducts, but the results are not reported here. Likewise, wall static pressure distributions measured with

---

* All dimensions quoted in this document relate to the full scale facilities

flush tappings in the duct rooves are not included in this report. Flow visualisation with optical schlieren apparatus and wool tufts was also used in the investigation.

3. Interpretation of Test Results

Notwithstanding the correct geometric scale of the models, only loose simulation of the mixing flows in the full scale augmentor ducts was possible with the unheated air jet. The duct exit velocity distributions presented below therefore give only a qualitative indication of the behaviour of the flow in the full scale facilities.

A primary measure of augmentor effectiveness is the cooling flow augmentation ratio, defined as the ratio of the total entrained air mass flow to the jet mass flow. The values presented in this report are as calculated for the model tests with the unheated air jet. According to theory backed by empirical experience, taking account of differences in gas properties as well as temperature, the 'cold' augmentation ratios may be translated to the full scale, hot jet situation by multiplying by a factor of approximately two. This factor takes no account of differences, between model and full scale, of such effects as internal skin friction, but these would be expected to be of second order importance.

4. 'Installed' Model Tests

4.1 Jet Alignment

In the 'normal' test configuration for the 'installed' model, the jet was aligned to represent single installed engine operation. This is shown schematically in Figure 4. For investigative purposes some tests were also conducted with different jet alignments.

4.2 Effect of Augmentor Duct Roof Cutback

Initial tests indicated that the exhaust deflector ramp which appears in Figure 1 adversely affected the velocity distribution at the duct exit plane, and probably imposed unnecessarily high back-pressure on the duct. Figure 5 shows the nature of the modification which was investigated, in this case with the jet central and coaxial with the augmentor duct. Figure 6 shows the effect on the distribution of flow velocity at the duct exit plane indicated in Figure 5 (which was effectively moved 1.75 m upstream in terms of full scale dimensions) calculated from measurements with the traversing pitot-static pressure probe. In taking these measurements, as with all of the velocity measurements at the duct exit, it was recognised that there may have been a degree of misalignment of the flow relative to the probe, due to the influence of the deflector ramp. However, the designed tolerance of the probe to misalignment was such that this should not have had a substantial effect on the results.

Figure 6 shows that there was a marked improvement to the exit plane velocity distribution when the roof was shortened, as well as to the augmentation ratio calculated from the measured velocities which is also shown in the Figure. All subsequent results apply to the modified roof configuration.

4.3 Primary Augmentor Tube

Numerous tests were carried out to investigate the effect of the primary augmentor tube and to identify the optimum configuration. The results are presented here in essence only.

4.3.1 Lateral Flow Distribution

Figure 7 shows velocity profiles measured on the mid-height horizontal plane at the exit of the main augmentor duct, with 'normal' jet alignment, with a primary tube of 1.5 m x 2.4 m obround cross section and four different lengths. For all but the very shortest 'tube' (of length equal to the thickness of the wall in which the tube was mounted) the lateral location of the peak velocity at the main duct exit was displaced a significant distance from the projection of the nozzle centreline. This apparently resulted from lateral angular deflection of the jet in the primary tube, caused by interaction between the tube wall and the asymmetrically disposed jet. This effect is revealed in the schlieren photograph in Figure 8, showing the jet being deflected in its passage through an obround tube in isolation.

With the longer tubes the degree of jet core displacement observed in the main augmentor duct would pose an unacceptable risk of wall overheating in the full scale facility. On the other hand, jet/primary tube interaction is arguably favourable in the case of the 1.3 m length tube, since the jet core is deflected a small degree from the projection of the nozzle axis, so as to become approximately centralised at the main duct exit. Selection of this primary tube geometry for the full scale facility on the basis of this evidence would involve an implied assumption that the effect of jet/primary tube interaction is the same for the hot, full scale jet as with the cold, small scale jet. This is uncertain, although probably not a dangerous assumption.

The effect of increasing the cross-sectional width of an obround primary tube of length 3.1 m is shown in Figure 9. Some benefit is apparent, but jet/tube interaction remains substantial.

Lateral velocity profiles are shown in Figure 10 for two geometrically similar, relatively short primary tubes of different cross-sectional size. As might be expected, the degree of jet deflection increased when the cross-sectional size was reduced so as to bring the jet into closer proximity with the primary tube wall.

4.3.2 Adopted Configuration

If a primary augmentor tube is to be used, tube dimensions chosen on the basis of the above results could be as shown in Figure 11. Filling some of the airspace around the outside of the tube within the inlet enclosure, as shown in the Figure, should favourably reduce the scale of the recirculation associated with the separated flow in that region. This configuration was adopted for further investigation of the merits of using a primary tube, outlined below.

4.3.3 Augmentation Characteristics

Figure 12 compares the main duct exit velocity distribution measured in the presence of the adopted primary tube arrangement with that obtained when no tube was in place. The results shown actually apply to a configuration with secondary inlet bellmouth fairings added (see below), since it was only with this arrangement that full sets of data were available to make this comparison. The curves reproduce the benefit in lateral flow symmetry due to the short primary tube which was apparent in Figure 7 and mass flows calculated from the velocity distributions indicate a marginally superior augmentation ratio with the tube in place.

4.3.4 Sensitivity to Vertical Jet Misalignment

Further tests were carried out to determine whether the adopted primary tube arrangement would unreasonably exacerbate the effect of inadvertent vertical misalignment of the engine nozzle, due to jet/tube interaction similar to that observed in the horizontal plane.

Figure 13 compares velocity profiles on the vertical centreline at the main duct exit, measured with and without the primary tube in place. It should be noted that, for the 'no tube' configuration in particular, the centreline traverse plane did not coincide with the lateral location of maximum exit velocity (see Figure 12). Flow profiles are shown:

(a) for 'normal' jet alignment,

(b) with the jet horizontal but displaced downwards by 100 mm (full scale),

(c) with the nozzle displaced downwards by 100 mm and also tilted downwards by an amount (approximately 1 degree) which would apply had the 100 mm displacement been caused by rotation of the aircraft about its main undercarriage.

The effect of each level of misalignment on the centreline velocity profile was not significantly affected by having the short primary tube in place, and in each case approximated the effect which might have been qualitatively estimated on the basis of simple geometric projection of the jet nozzle axis.

4.4 Effect of Inlet Fairings

On the basic model it was observed by the use of tufts that gross flow separations occurred at the upstream edges of the secondary inlets, and also at the vertical corners where the secondary inlet ducts were integrated with the main augmentor duct. These flow features, shown diagrammatically in Figure 14(a), could be expected to increase the aerodynamic losses and reduce the augmentation ratio and, arguably, increase the tendency to internal flow asymmetry. Modifications investigated to improve these aspects were bellmouth fairings on the secondary inlets (Figure 14(b)) and fairing of the internal vertical corners (Figure 14(c)).

The results are shown in Figure 15. These tests were conducted with no primary tube in place and with 'normal' jet alignment, so all of the illustrated exit flow distributions feature the residual lateral asymmetry which was characteristic of this arrangement. The bellmouth fairings, which from visual observation clearly improved the qualitative nature of the flow in the inlet ducts, also significantly increased the maximum velocity registered near the centre of the main duct exit. There was also a compensating tendency towards reduced velocity near the side walls so that, on balance, there was only a modest improvement in augmentation ratio.

Adding the internal corner fairings further increased the augmentation ratio, presumably be reducing or eliminating the flow separation at those corners. It appears likely that the effect of the bellmouth fairings on the internal flow was such as to increase the tendency towards flow separation at the internal corners, so that the need for corner fairings went hand in hand with addition of the bellmouths. This apparent aerodynamic coupling between the effects of the two features may be worthy of further investigation.

5. 'Uninstalled' Model Tests

5.1 Flow Symmetry

In the 'uninstalled' facility the jet would be expected to be always aligned coaxially with both the primary tube and main augmentor duct. Notwithstanding this, early model tests with a primary augmentor tube 1.3 m (full scale) in diameter and 2.3 m long showed that:

(a) angular misalignment of up to 0.5^{0} caused flow asymmetry at the main duct exit similar to that which might be predicted by linear projection of the nozzle axis,

(b) the symmetry of the exit flow was much more sensitive to small lateral displacements of the nozzle from its correct coaxial location.

These observations were consistent with the more detailed quantitative measurements of similar effects in the 'installed' model described in Section 4.3 above. In view of this, and in order to minimise sensitivity to any inadvertent misalignment of the engine in the 'uninstalled' facility, it was thought to be logical to adopt a primary tube of corresponding proportions to that described in Section 4.3.2 above. A tube 1.3 m in diameter cut back to 1.2 m in length was used for most subsequent tests, the smaller diameter (relative to the 1.5 m vertical dimension adopted for the 'installed' model primary tube) being:

(a) preferred in order to reduce the entrained air flow through the primary tube and minimise the air velocities over the engine test stand

(b) probably tolerable in this basically coaxial facility.

The main duct exit flow distribution and augmentation ratio with this arrangement are shown in Figure 16(a).

5.2 Effect of Augmentor Duct Roof Cutback

Figures 16(a) and (b) show that, as with the 'installed' facility, the augmentation ratio in this model increased significantly when the exit plane was effectively moved 1.75 m (full scale) upstream by shortening the duct roof. The exit flow distribution also improved, although there remained a noticeable degree of flow distortion in the vertical plane. Flow surveys taken further upstream (not shown here) indicated that this residual distortion was still caused mainly by upstream influence of the exhaust deflector ramp, so there may be scope for even further reduction of the roof length if this is acceptable from the acoustic viewpoint.

5.3 Inlet Fairings

In this model, inlet bellmouths and fairing of the vertical corners at the entry to the square augmentor duct were added simultaneously. It was assumed that there would be a degree of aerodynamic coupling between the effects of these features, as was observed in the 'installed' model, although the presence of acoustic splitters in the secondary inlet ducts of this model may well have weakened this effect. The geometric nature of the modifications was similar to those applied to the 'installed' model, shown in Figure 14. Comparison of Figures 16(b) and 16(c) shows that the bellmouths and fairings further improved the augmentation ratio although, as might have been expected because of the acoustic splitters, by a lesser amount than was observed in the 'installed' model.

6. Conclusions

(a) The primary augmentor tube proposed in the original design of the 'installed' facility interacted with the asymmetrically positioned jet to cause substantial lateral flow asymmetry in the main augmentor duct.

(b) Increasing the width of the primary tube improved but did not correct the flow asymmetry.

(c) The flow asymmetry increased with reduced primary tube cross-sectional dimension and with increased primary tube length.

(d) A configuration with relatively short primary tube length was identified which, at least with an unheated jet at model scale, interacted favourably with the jet to yield a symmetrical main duct flow distribution, and which was tolerant of modest degrees of angular, lateral and vertical jet misalignment.

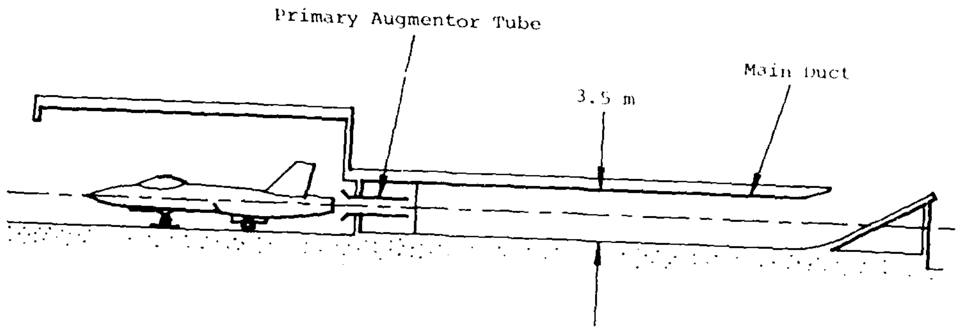
(e) A design with no primary augmentor tube at all would also be acceptable but marginally inferior aerodynamically.

(f) A proportionate reduction in length of the primary augmentor tube initially proposed in the 'uninstalled' facility should also provide improved tolerance to inadvertent jet misalignment in that facility.

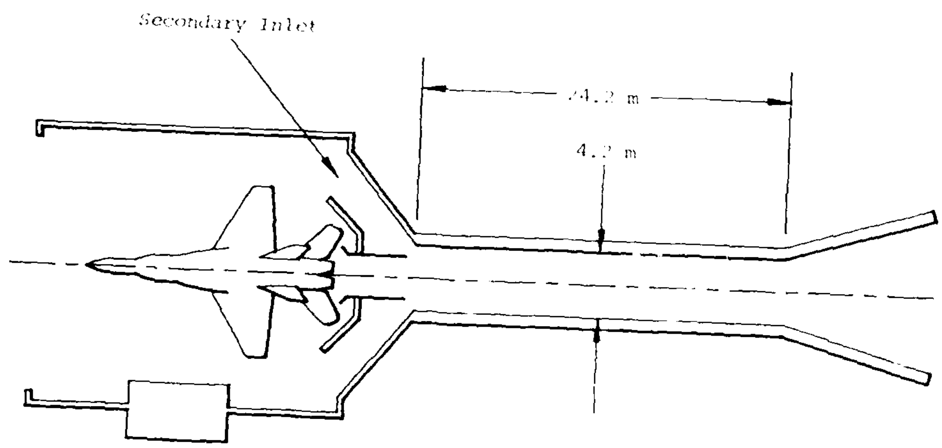
(g) Reducing the length of the main augmentor duct roof by 1.75 m (full scale), thus effectively moving the duct exit plane upstream by that distance, significantly improved the exit flow distributions and augmentation ratios in both the 'installed' and 'uninstalled' models. It appeared that further reduction in the roof length may well have been beneficial aerodynamically, at least in the 'uninstalled' model.

(h) Adding bellmouth fairings to the secondary inlets, and fairings to the vertical corners at the main augmentor duct entry, improved the quality of the inlet flow and the augmentation ratio in both models. Aerodynamic coupling between these features made the latter modification an important adjunct to the former, especially in the 'installed' model.

(i) The cooling flow augmentation ratio was measured to be in the range 5.5 - 6.0 in the 'installed' model and 4.5 - 5.0 in the 'uninstalled' model. These figures theoretically translate to approximately double these values for the full scale facilities, with a single engine operating in the full afterburner mode.



ELEVATION



PLAN

FIG. 1 INSTALLED ENGINE RUN-UP FACILITY

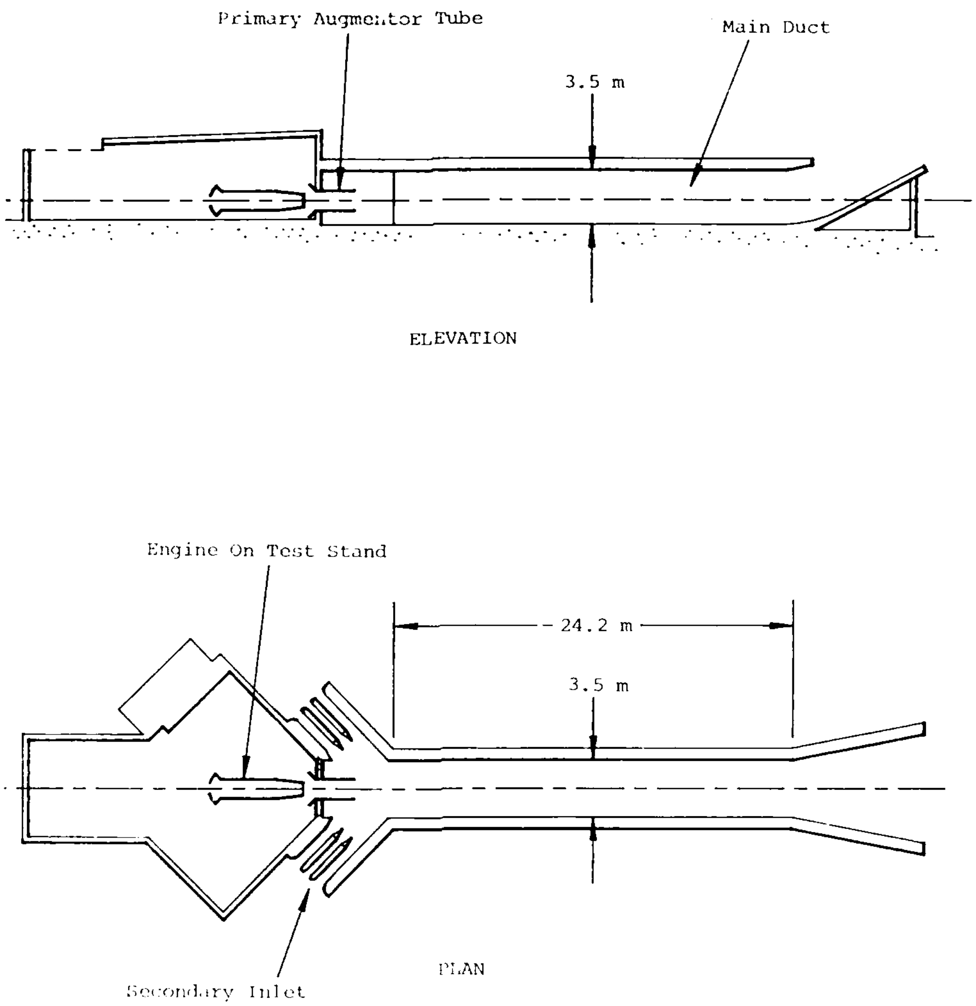
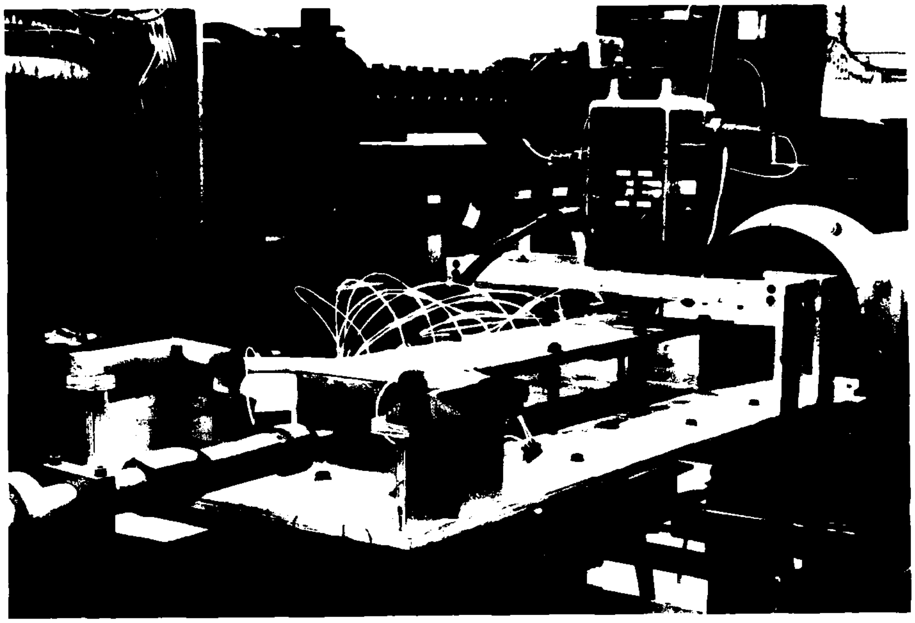
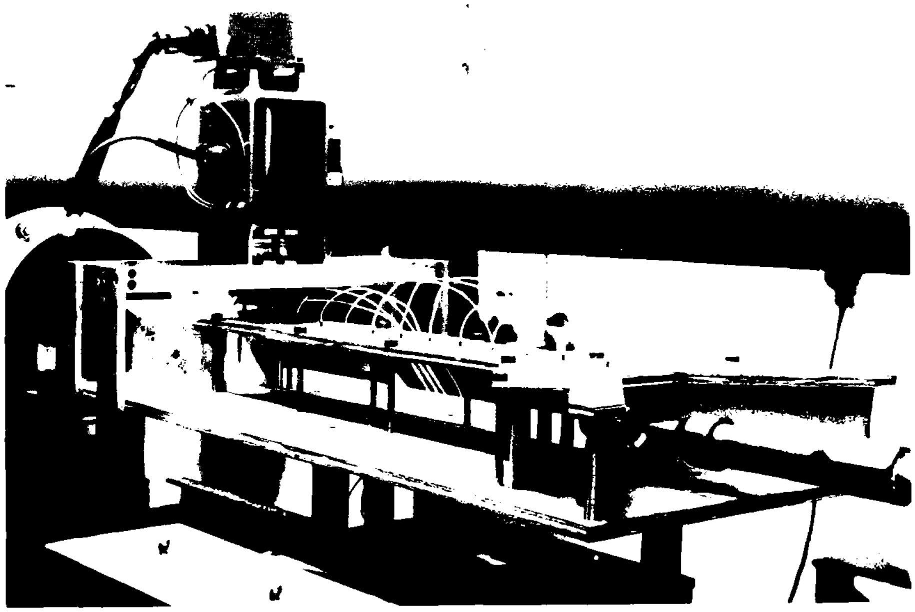


FIG. 2 UNINSTALLED ENGINE RUN-UP FACILITY



(a) 'INSTALLED' FACILITY



(b) 'UNINSTALLED' FACILITY

FIG. 3 PHOTOGRAPHS OF TEST MODELS

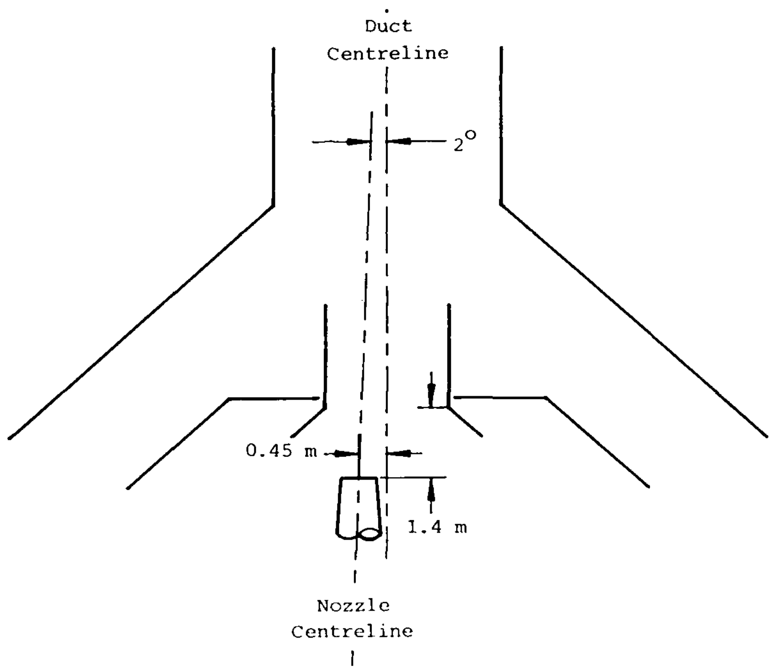


FIG. 4 JET ALIGNMENT IN 'INSTALLED' MODEL

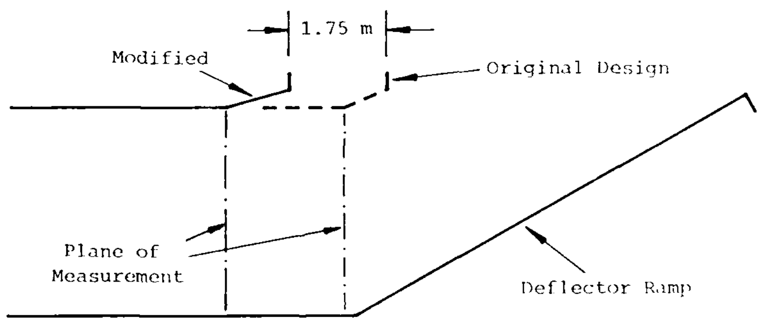
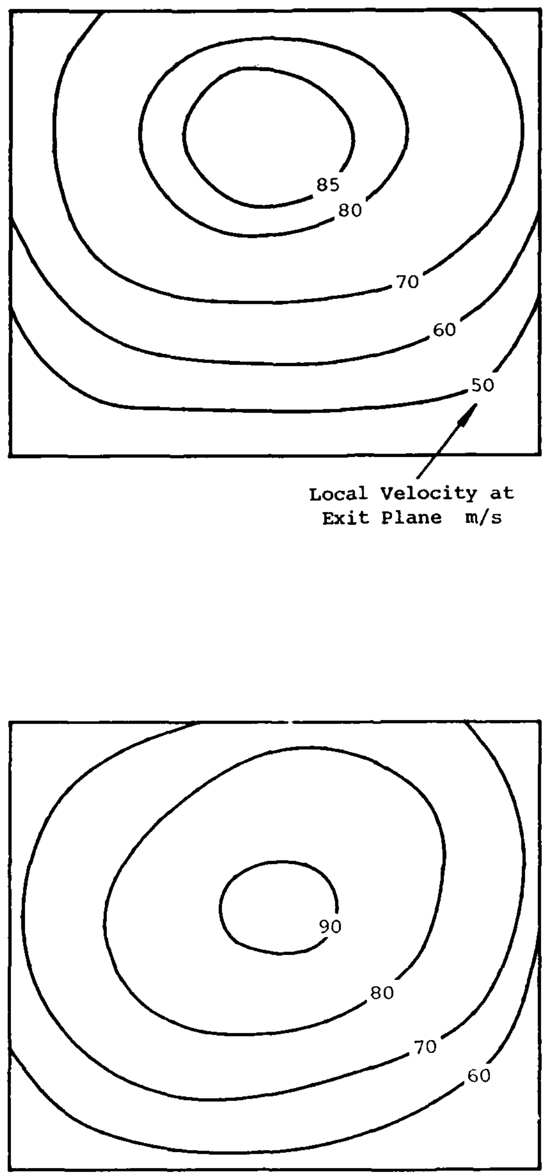


FIG. 5 MODIFICATION TO AUGMENTOR DUCT ROOF



ORIGINAL DESIGN

'Cold' augmentation
ratio = 5.04

MODIFIED ROOF

'Cold' Augmentation
Ratio = 5.67

FIG. 6 EFFECT OF ROOF MODIFICATION ON EXIT FLOW DISTRIBUTION - UNINSTALLED FACILITY

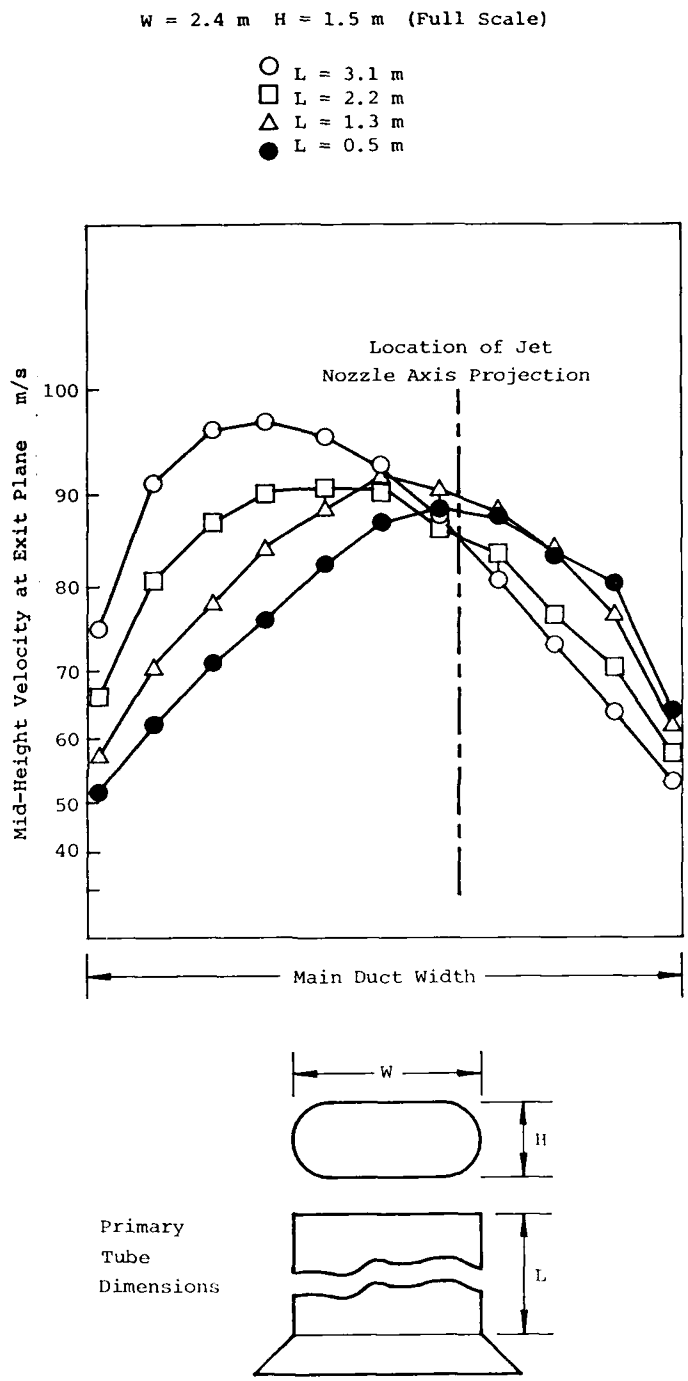


FIG. 7 EFFECT OF PRIMARY TUBE LENGTH ON LATERAL VELOCITY PROFILES - 'INSTALLED' FACILITY

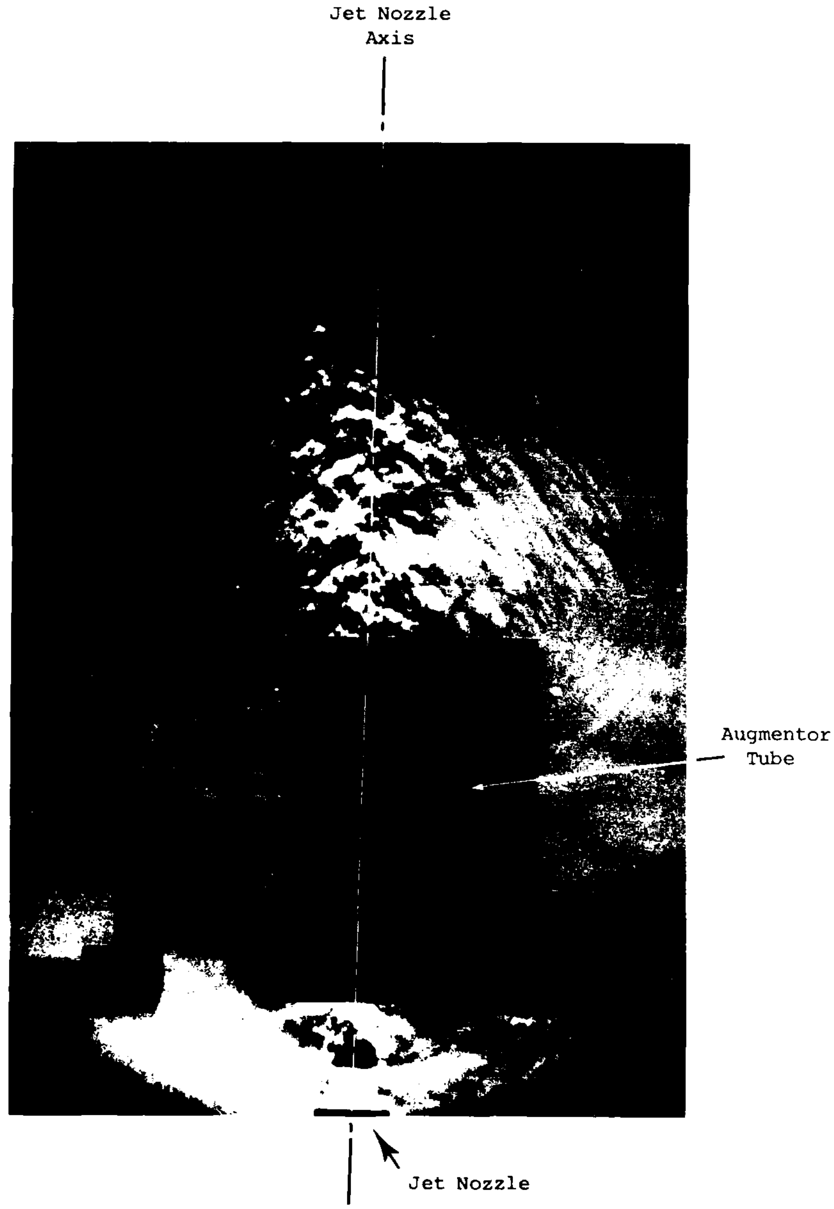
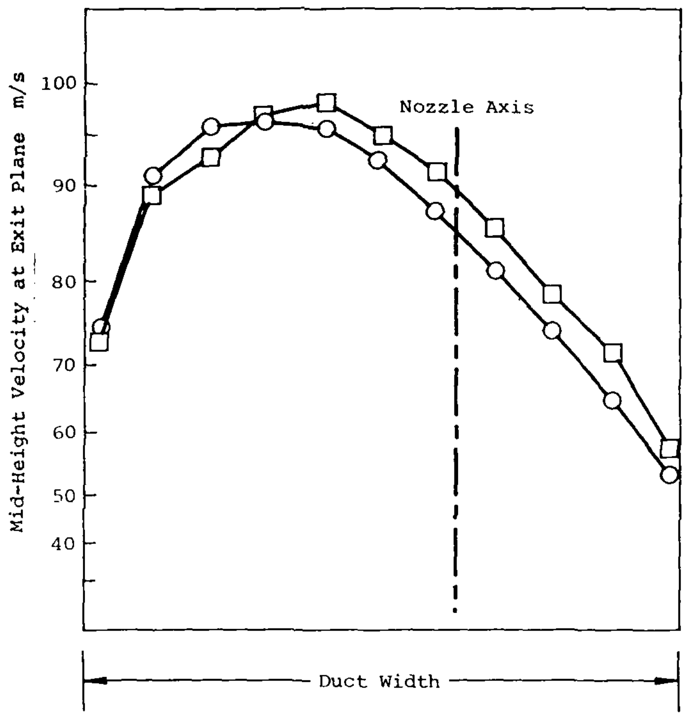


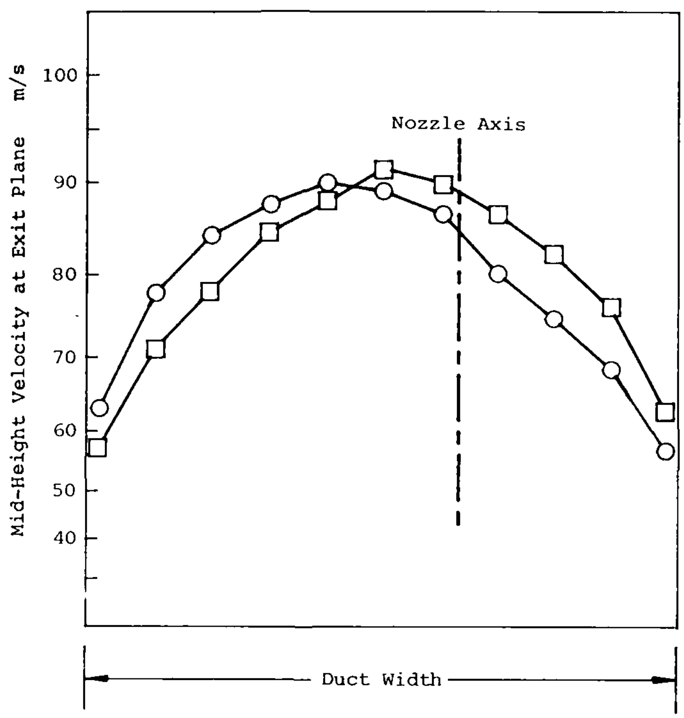
FIG. 8 SCHLIEREN PHOTOGRAPH OF JET WITH PRIMARY TUBE IN ISOLATION - 'INSTALLED' FACILITY



H = 1.5 m   L = 3.1 m   (See Fig. 7)

○ W = 2.4 m
□ W = 2.8 m

FIG. 9   EFFECT OF PRIMARY TUBE WIDTH - 'INSTALLED' FACILITY



	W	H	L	
○	2.2 m	1.3 m	1.1 m	(See Fig. 7)
□	2.4 m	1.5 m	1.3 m	

FIG. 10 EFFECT OF PRIMARY TUBE SCALE - 'INSTALLED' FACILITY

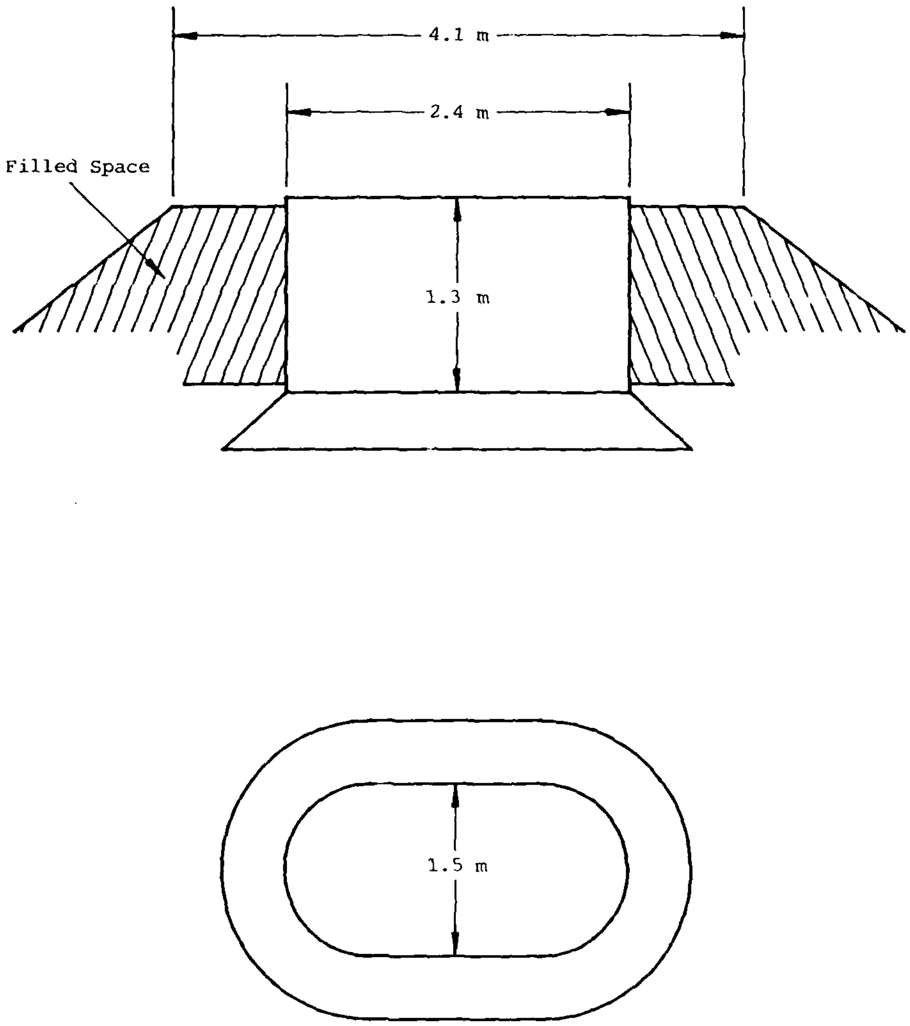
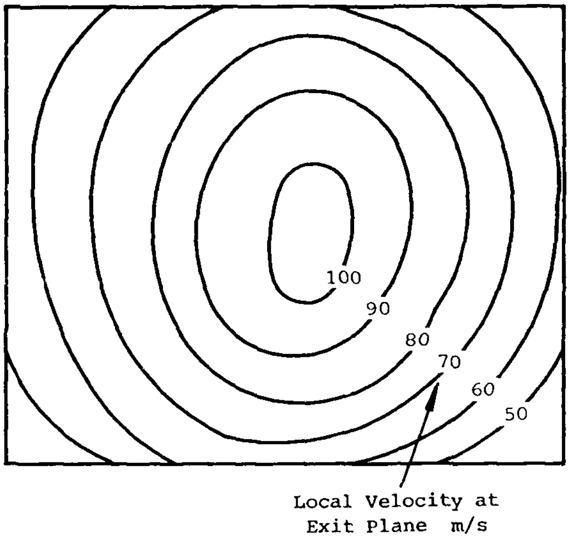
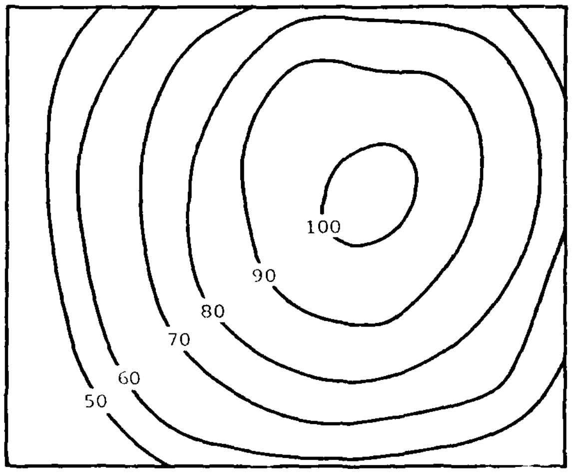


FIG. 11 ADOPTED PRIMARY TUBE ARRANGEMENT - 'INSTALLED' FACILITY



ADOPTED PRIMARY TUBE
L = 1.3 m H = 1.5 m
W = 2.4 m
(See Fig. 7)

'Cold' augmentation
ratio = 5.77



NO PRIMARY TUBE
L = 0.5 m H = 1.5 m
W = 2.4 m

'Cold' Augmentation
Ratio = 5.64

FIG. 12 EFFECT OF ADOPTED PRIMARY TUBE - 'INSTALLED' FACILITY

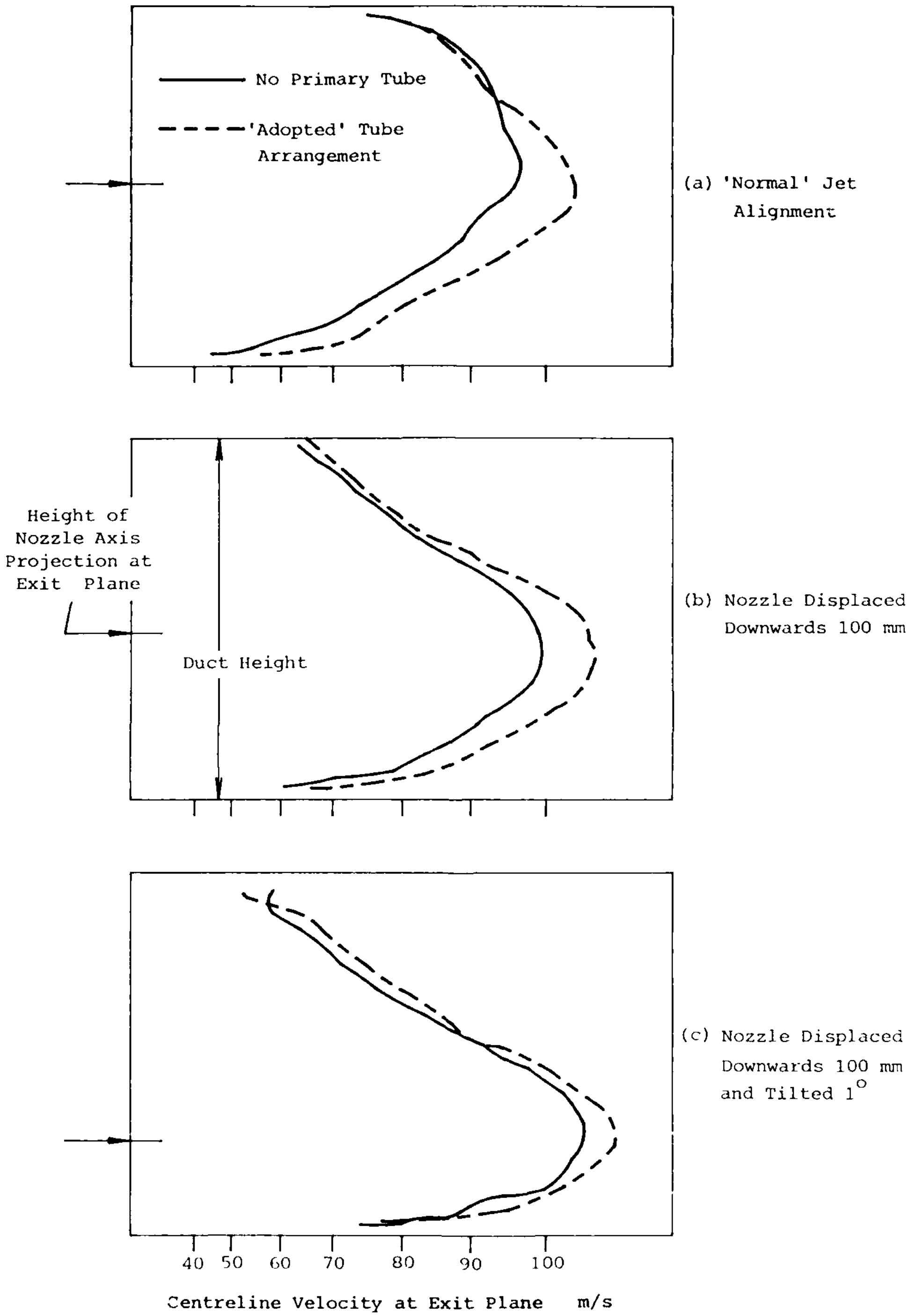
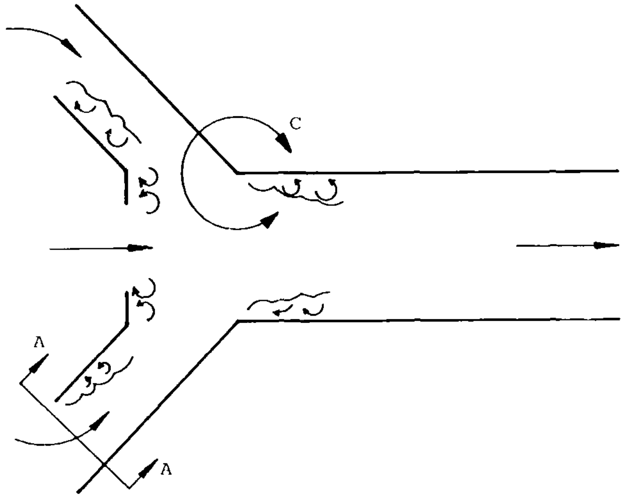
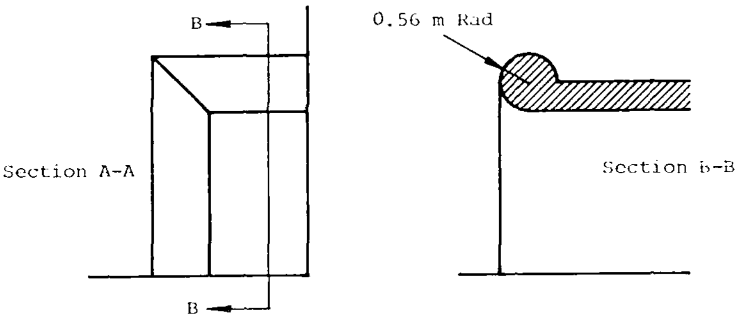


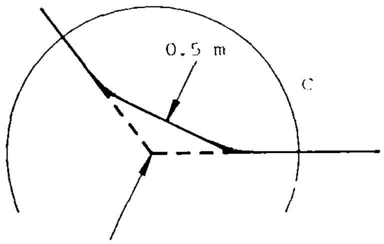
FIG. 13 EFFECT OF VERTICAL MISALIGNMENT - 'INSTALLED' FACILITY



(a) FLOW SEPARATIONS IN UNMODIFIED DESIGN

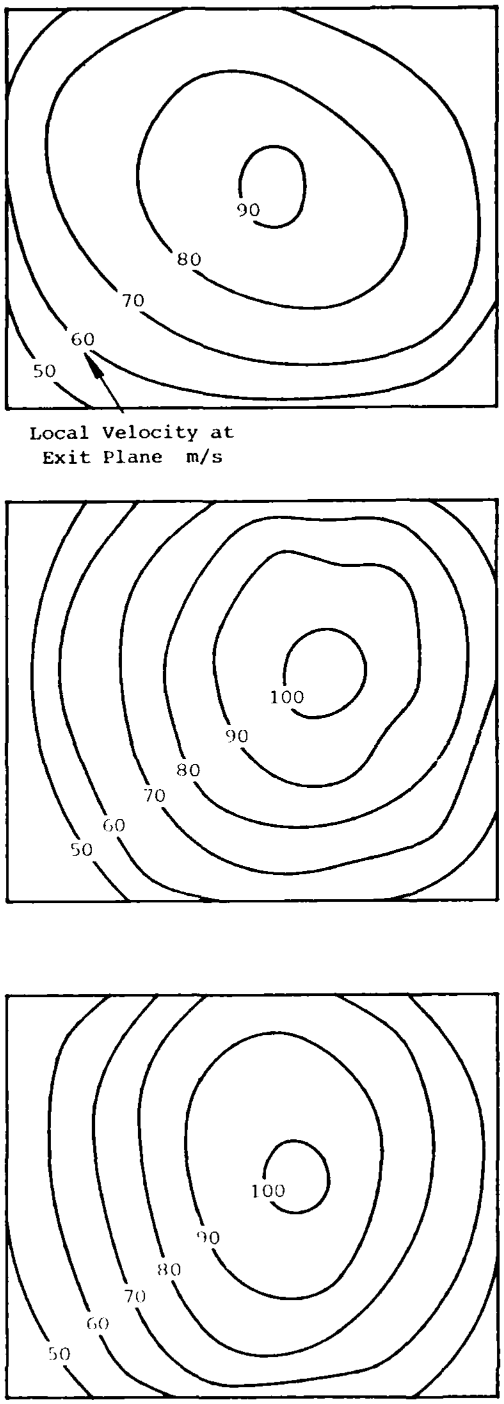


(b) BELLMOUTH FAIRINGS



(c) DUCT CORNER FAIRINGS

FIG. 14 INLET MODIFICATIONS - 'INSTALLED' FACILITY



NO FAIRINGS

'Cold' Augmentation Ratio = 5.52

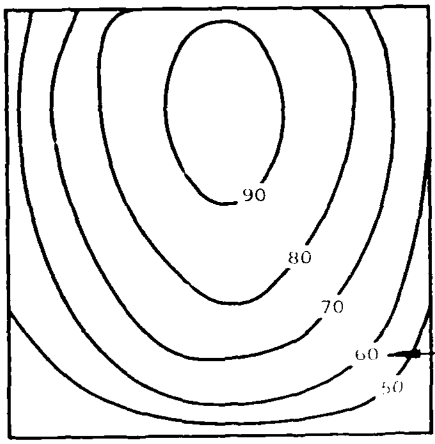
INLET BELLMOUTHS FITTED

'Cold' Augmentation Ratio = 5.64

INLET BELLMOUTHS AND FAIRED DUCT CORNERS

'Cold' Augmentation Ratio = 5.83

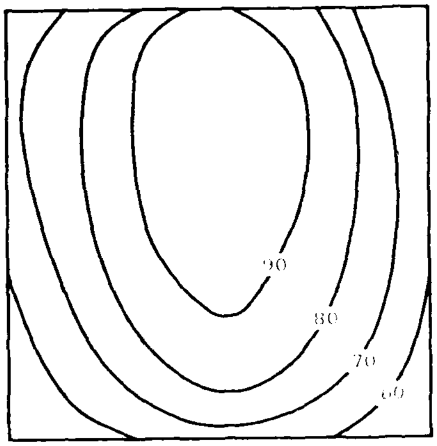
FIG. 15 EFFECT OF INLET MODIFICATIONS (NO PRIMARY TUBE) - 'INSTALLED' FACILITY



(a) SHORT PRIMARY TUBE

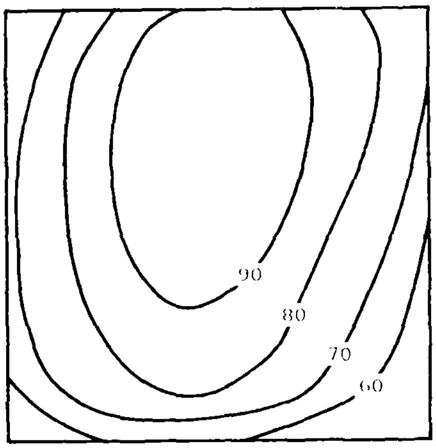
'Cold' Augmentation Ratio = 4.40

Local Velocity at Exit Plane m/s



(b) SHORTENED DUCT ROOF

'Cold' Augmentation Ratio = 4.88



(c) INLET BELLMOUTHS AND FAIRED DUCT CORNERS

'Cold' Augmentation Ratio = 4.97

FIG. 16 EFFECT OF MODIFICATIONS TO 'UNINSTALLED' MODEL

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Model tests of the air cooled exhaust augmentors proposed for the F/A-18 engine ground run-up facilities at RAAF Williamtown were undertaken, to confirm satisfactory aerodynamic behaviour of the augmentor designs and to provide data for optimising certain aspects of the designs. The tests were carried out on 1/45 scale models, using an unheated air jet to represent the engine exhaust. Geometric features were identified which had important influence on augmentor duct flow symmetry and the cooling flow augmentation ratio.

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