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Aerodynamic and Mechanical Tests of a Model of a Variable Mach Number Nozzle

By

Z.M. Jawor

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Aerodynamic and mechanical tests of a model of a variable Mach number nozzle

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Z. M. Jawor

SUMMARY

A model of a two-dimensional variable nozzle, of a type suitable for use in a free-jet Engine Test Facility, has been tested to determine the uniformity of flow in the Mach number range 1.6 to 3.0. The tests were made at about full-scale Reynolds numbers, the Mach number variations being deduced from measurements of the static pressure by wall tappings and traverses.

Only the initial build was tested over the full Mach number range and for this the Mach number variation in the test region lay between ±1½ and ±2 per cent. The effect of nozzle block pivot position was examined at the higher Mach numbers and it was found that the variation could be reduced to between ±1 and ±1½ per cent in the range 2.4 to 3.1.

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ILLUSTRATIONS

1.0 Introduction

The work described herein was carried out as part of a programme aimed at developing a nozzle configuration suitable for use in an Engine Test Facility for the free-jet testing of intakes and engines over the range of Mach numbers from 1.6 to 3.0. In this application a larger tolerance in the uniformity of Mach number in the working section can be permitted than is normally accepted for a supersonic wind tunnel, but mechanical simplicity is important in order to allow both reliability at elevated temperatures and rapid changes of Mach number for transient operation.

Earlier considerations of variable nozzles[1,2,3] showed that the two-dimensional semi-flexible nozzle having a single pivot and a single jack for each wall (Figure 1) offered a good compromise between aerodynamic performance and mechanical simplicity. Reference 1 describes a successful small model of this type having a 2 × 2 in. working section.

The present Memorandum describes tests on an intermediate scale 1 ft square nozzle, this being built to test the proposed mechanical arrangement for the full-scale design and to check the effects of change of scale and Reynolds number on the flow uniformity.

2.0 Test apparatus

2.1 Nozzle

The nozzle, which is shown in Figure 1, was of a semi-flexible configuration, the movable walls consisting of flexible plates of uniform thickness rigidly connected at their upstream ends to hinged throat blocks and constrained at the exit by a parallel linkage system. The flexible plates moved between parallel side walls. The outlet section measured 12.1 x 12.95 in. and remained constant throughout the speed range.

Variation of the Mach number in the working section was effected by rotating the nozzle blocks about the pivots shown in Figure 1. Operation of a single handwheel actuated a crank mechanism through gears to obtain this action. The position of the pivots in relation to the centre line of the nozzle could be varied by means of shims, as the previous experimental investigation had shown the pivot position to be an important parameter. All moving surfaces were provided with seals to prevent leakage of air to the regions behind the flexible plates. The flexible plates were of 0.295 in. thickness, machined overall from high tensile steel. The average clearance between the plates and the side walls was 0.024 in.

2.2 Rig layout

Air at high pressure was supplied to the nozzle from either an M.V. or G.E.C. plant compressor and exhausted to atmosphere through a transition piece, a constant area rectangular duct for stabilising the flow after the normal shock, a subsonic diffuser and a silencer. The cross-sectional area of the rectangular duct, which measured 12.1 × 16.0 in., was larger than the working section of the nozzle to allow the escape of leakage air from behind the flexible plates and to compensate for the blockage caused by the supports of the traversing probe. The increase in area took the form of a step at the nozzle exit.

The temperature of the air supply could be varied between 50 and 220°C whilst on the M.V. sets; when using the G.E.C. sets, however, the heat loss in the plant ducting prevented there being a useful temperature range.

For the higher Mach number range (2.4 to 3.1) the M.V. sets were used, while for the lower range (1.6 to 2.4) the larger G.E.C. sets were required in order to supply sufficient mass flow. Dry air was used for all the main aerodynamic calibrations.

2.3 Instrumentation

In order to determine the Mach number variation within the working section, 32 static pressure points were located in a half-diamond pattern on one side wall of the nozzle as indicated in Figures 1 and 2. The holes, of $\frac{3}{32}$ in. diameter, were connected to a bank of single-limb mercury manometers. In addition a static probe traversing axially measured the variation along the centre line of the nozzle. Four $\frac{1}{32}$ in. diameter sensing holes in the probe, positioned 90° apart, transmitted pressure to one limb of a U-tube filled with tetralin. The other limb was connected to a datum pressure tapping, marked P_2 in Figure 2. A pitot tube in the 30 in. supply duct recorded the total pressure at inlet to the nozzle. Static pressures were measured behind the flexible plates and, for the upper surface only, just downstream of the step. These pressures gave an indication of the efficiency of the seals.

3.0 Tests

The initial tests showed a tendency for the operating mechanism of the nozzle block to jam when an airstream temperature of 150°C was reached.

An improvement permitting an operating temperature of 170°C was attained by lagging the outside walls of the nozzle. However, this improvement was not enough to meet the operational requirement and the nozzle was stripped. The inspection revealed that the jamming was caused by the asbestos seals between the flexible plates and the side walls, the asbestos being insufficiently resilient to accommodate the changes of clearance resulting from differential expansion. The asbestos seals were therefore replaced by silicon rubber tubes of circular cross section, 4 mm o.d. and 1 mm wall thickness, lubricated with silicon rubber vacuum grease. Jamming was thereby cured, but a difficulty arose in retaining the seals in their slots. The asbestos seals and their retaining slots were of triangular cross section and, since re-machining of the highly stressed plates to give rectangular slots appeared undesirable, the new circular seals were glued into the existing slots with Hermetite. However, despite the glue, the seals tended to roll out of the slots and become nipped in the clearance space. The seals were therefore modified by inserting a 16 s.w.g. copper wire inside each silicon rubber tube. This configuration was satisfactory and remained unchanged until the end of the tests. A tadpole section seal would have fitted the existing slots better but the time and cost of manufacture appeared excessive.

The static pressure measured behind the flexible plates during the performance tests was on average only 0.16 in. of mercury higher than the corresponding static pressure downstream of the step at the nozzle exit, indicating that little leakage was occurring through the seals.

The initial tests provided a check on the mechanical operation of the nozzle, but gave only a rough indication of aerodynamic performance since the air drier was not then available and there may have been condensation shocks in the test section. At a Mach number of 3.0, for example, there could have been about 70°C of supercooling in the test section when running at the maximum inlet temperature of 220°C. The air drying plant became available for the later tests, which were therefore made at an inlet temperature of 50°C.

At each setting of the Mach number control (calibrated initially on the basis of area ratios) a full record was taken of the side wall static pressures and a traverse was made of the static pressure probe along the nozzle axis. For the first tests 0.250 in. shims were used at the nozzle pivots, corresponding to the best results from the 2 x 2 in. variable nozzle. Later the tests were extended to cover shim sizes varying between 0.048 and 0.700 in. but measurements were then confined to the higher Mach number range.

During the tests the static pressures downstream of the step at the nozzle exit were lower than the static pressures in the test region. The difference between the pressures varied from 3 lb/sq.in. at low Mach numbers to 1 lb/sq.in. at high Mach numbers. Attempts to run with the pressures equal were unsuccessful, apparently on account of instability in the diffuser.

4.0 Results and discussion

Summaries of the performance tests run with dry air at 50°C are presented in Figures 3, 4, 5 and 6. A typical Mach number distribution inside the test rhombus is shown in Figure 3. During the analysis of the results it was noted that for any nozzle build the data could be repeated to within the accuracy of instrumentation, i.e. to within about ±0.05 in. of mercury.

Figure 4 gives the percentage Mach number variation inside the entire test rhombus, while Figure 5 shows the improvement in uniformity when variations are considered in a restricted region more representative of the area required in the full-scale application. The restricted region has been taken to be 70 per cent of the linear dimensions of the nozzle outlet section and to have the shape shown in Figure 2.

For the initial build (0.250 in. shims) the variation in the restricted region, (see Figure 5), is ±2 per cent in the Mach number range 1.7 to 2.3, decreasing to $\pm1\frac{1}{2}$ per cent at a Mach number of 3.1. Figures 4 and 5 indicate that an improvement in the Mach number distribution can be achieved by displacing the pivots from the original build, but the displacement required varies with Mach number. In order to obtain the optimum performance from the full-scale nozzle it is suggested that the pivot position should be adjustable.

Figure 6 shows a comparison between the results obtained from the 2 x 2 in. nozzle in the Reynolds number range 0.4×10^6 to 0.72×10^6, as reported in Reference 1, and the 12 x 12 in. nozzle at Reynolds numbers between 10.0×10^6 and 12.25×10^6. The flow along the centre line within the test region is less uniform in the larger nozzle than in the smaller one, except for a small region around a Mach number of 2.35. The difference may be caused by unequal pressures behind the flexible plates as a result of the different sealing arrangements and ventilation pressures. Alternately it may be a true Reynolds number effect since the rate of growth of the boundary layer should be rather less for the larger nozzle, whereas the design allowance was the same (0.005 in/in.) for both. A further difference possibly accounting for the poorer performance of the larger nozzle is in conditions upstream, the smaller nozzle having a large settling chamber whereas the larger has a control valve and cascade corner in the 20 in. supply duct 21 diameters from the nozzle. The duct diameter increased to 30 in. 10 ft upstream of the nozzle.

Comparison with the results of some unpublished American work on a similar type of nozzle shows that the uniformity in the American design is intermediate between that of the 2 and 12 in. nozzles up to a Mach number 3.1.

5.0 Conclusions

From the experimental work the following conclusions have been reached.

(a) For Mach numbers between 2.4 and 3.1, the variation throughout the test region can be reduced to between ±1 and $\pm 1\frac{1}{2}$ per cent of the nominal Mach number.

(b) To obtain optimum performance over a wide Mach number range the position of the pivots for the nozzle blocks should be adjustable.

(c) The performance of the 12 in. nozzle was generally inferior to that of the 2 in. although the larger nozzle was better in the middle range, i.e. near Mach number 2.4.

(d) The modified silicon rubber seals proved satisfactory for the limited test running required but they had no hard wearing properties and it is clear that a different type would have to be used in any full-scale design.

ACKNOWLEDGEMENTS

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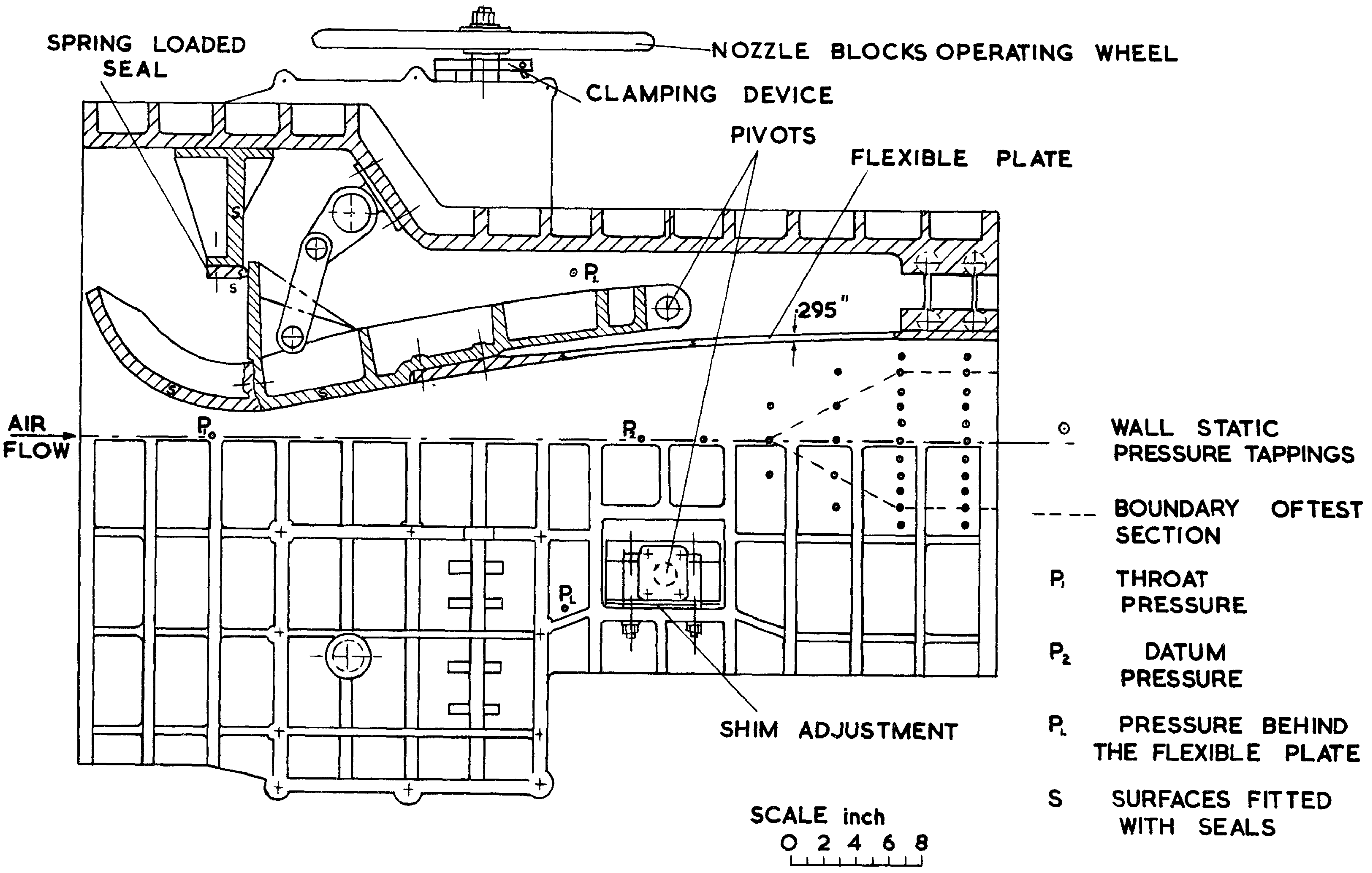
REFERENCES

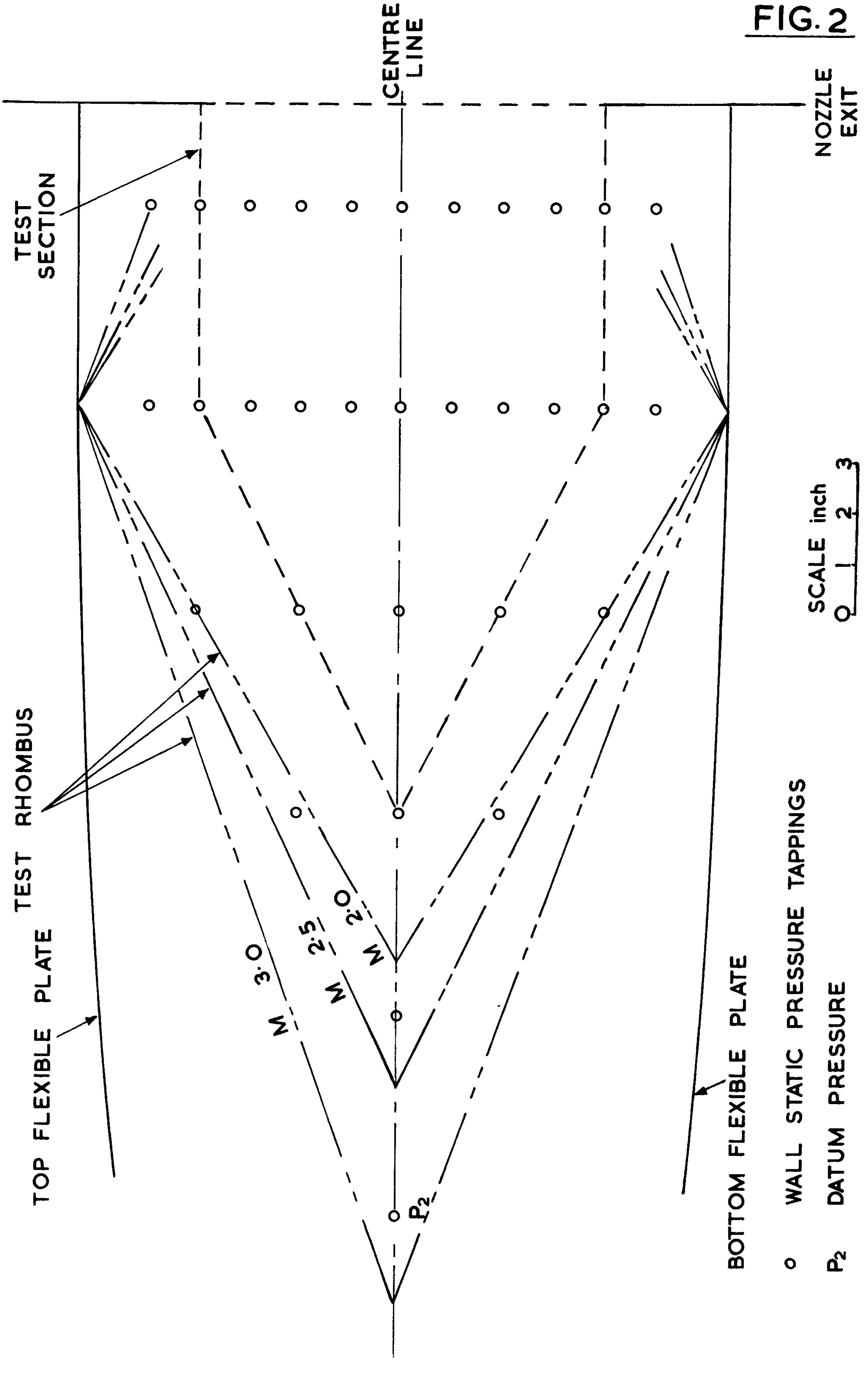
No.	Author(s)	Title, etc.
1	J. B. McGarry	The development of a variable Mach number effuser. A.R.C. R. & M.3097, August, 1957.
2	R. Staniforth	Unpublished work at N.G.T.E.
3	A. D. Carmichael	Unpublished work at N.G.T.E.

FIG. 1



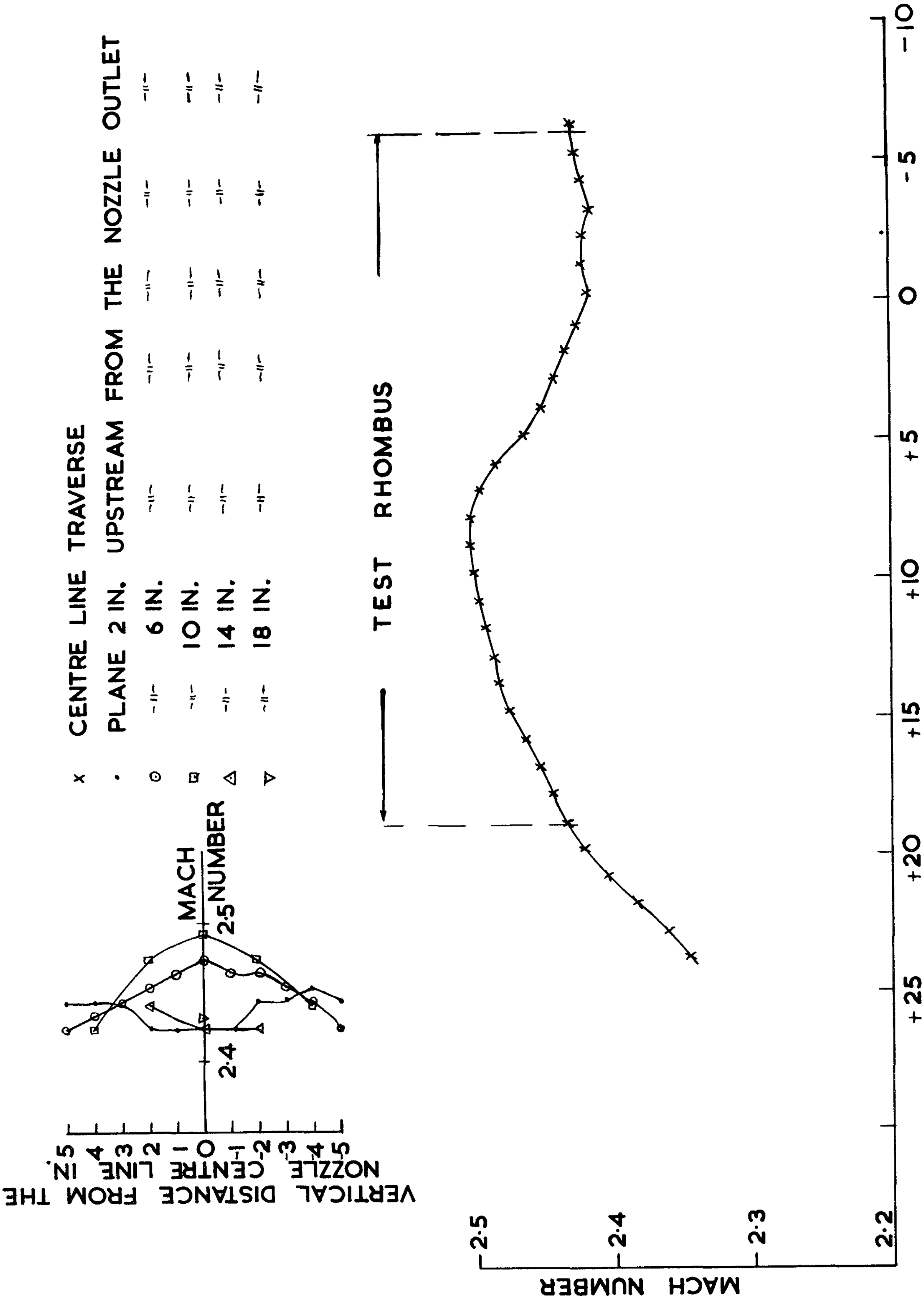
GENERAL ASSEMBLY OF THE 12×12 IN. VARIABLE MACH NUMBER NOZZLE

FIG. 2



SCHEMATIC DRAWING OF THE NOZZLE TEST REGION AND RHOMBUS

FIG. 3



TYPICAL MACH NUMBER DISTRIBUTION —

MEAN MACH NUMBER 2·46

INITIAL BUILD

TOTAL MACH NUMBER VARIATION WITHIN TEST RHOMBUS

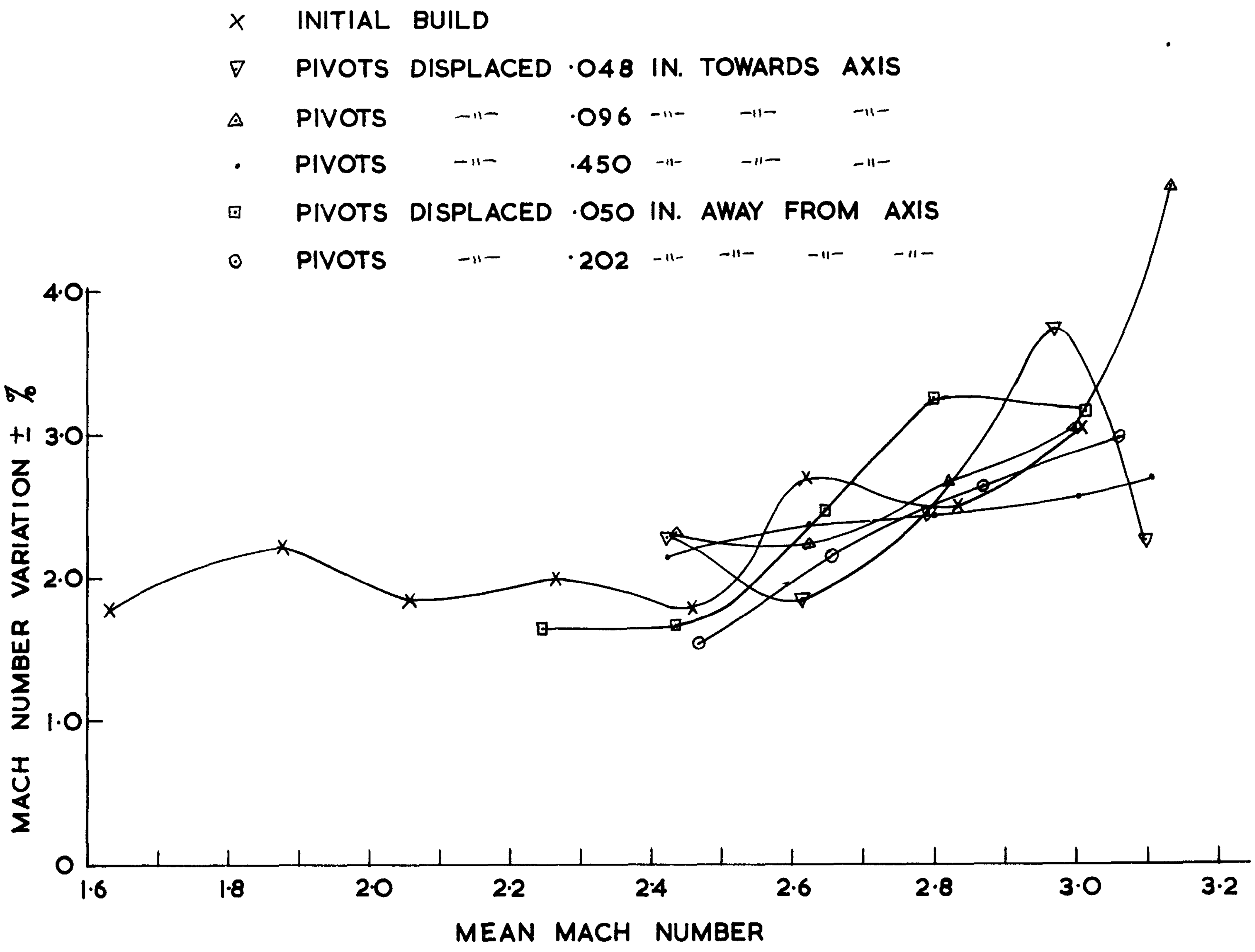
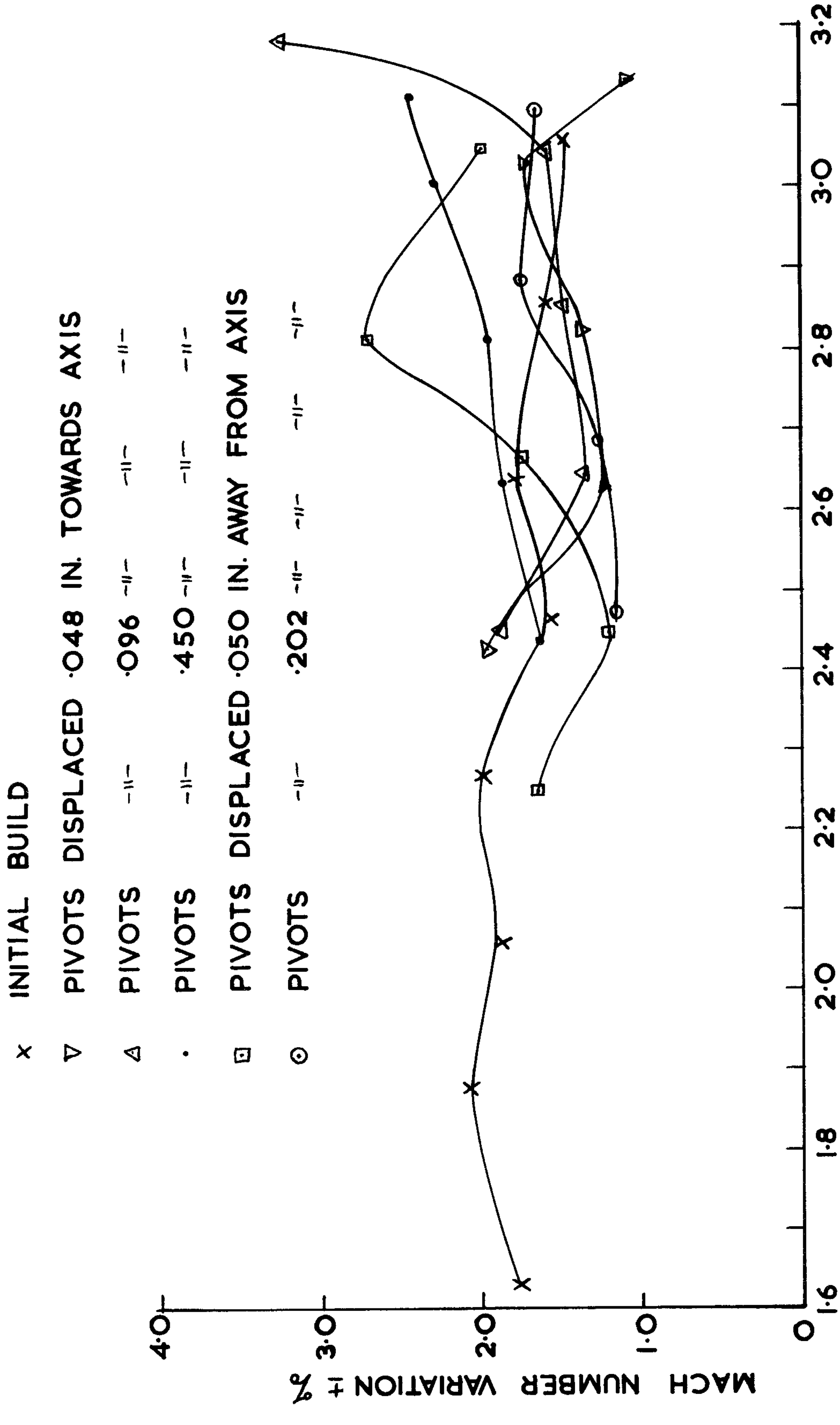


FIG. 4

FIG. 5



VARIATION OF MACH NUMBER WITHIN THE TEST REGION

DS 71553/1/Wt.58 K.4 1/63 CL & XL

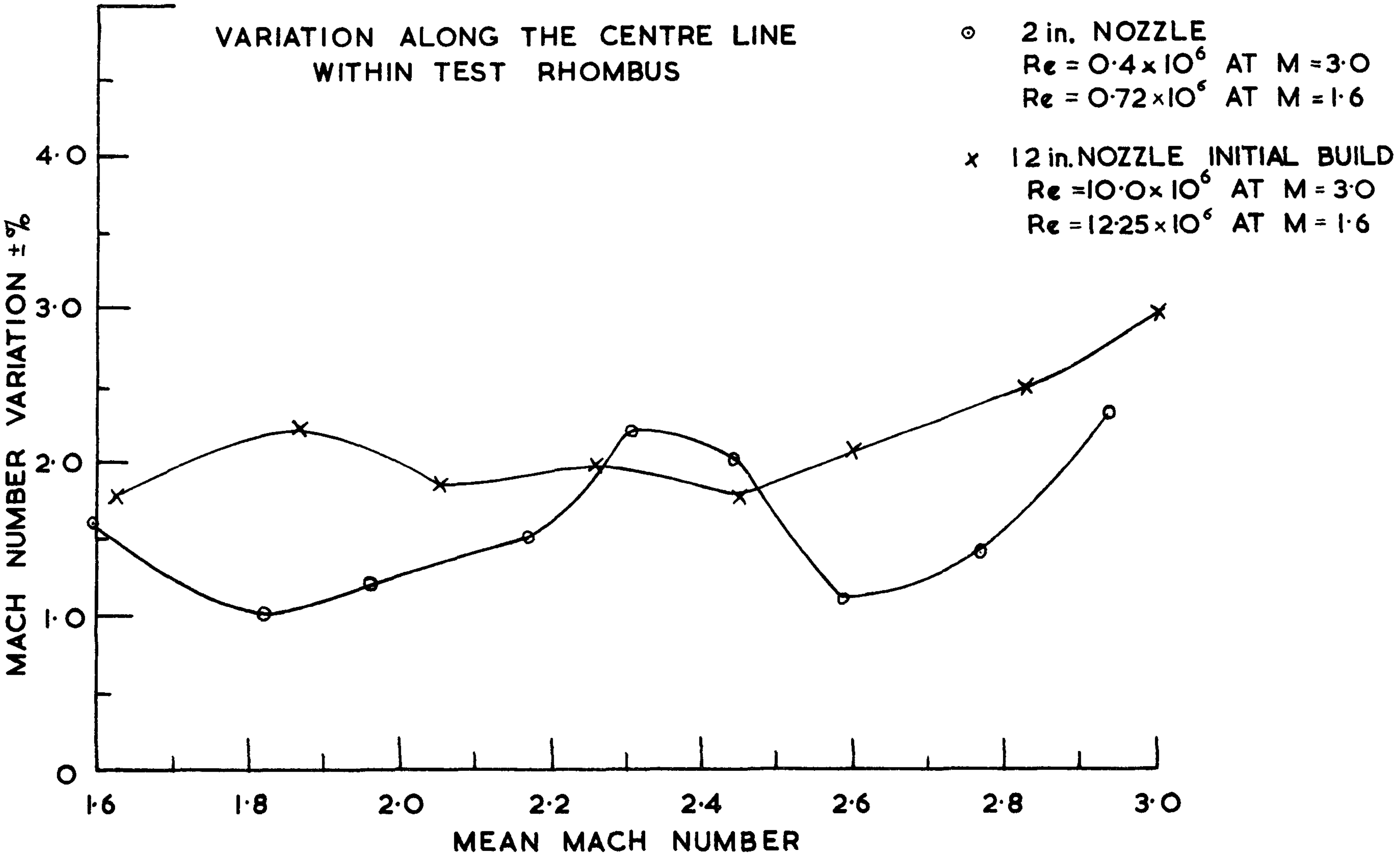


FIG. 6

COMPARISON OF THE PERFORMANCES OF THE 2 in. AND 12 in. NOZZLES

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