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The Performance of some Typical Turbo-jet Engine Exhaust Systems, with Particular Reference to the Effects of Swirl

By

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SUMMARY

A description is given of tests made to determine the effect of swirl on the performance of a quarter-scale model of a typical turbo-jet engine exhaust system and propelling nozzle. The losses in the system were derived from direct measurement of the thrust.

The non-dimensional thrust, expressed in terms of the nozzle area and the total pressure at inlet to the exhaust diffuser, was found to vary linearly with the ratio of ambient to inlet total pressures. At an expansion ratio of 2:1, the thrust with 40° of inlet swirl was only 4/7 of that with zero swirl, but since an increase of swirl angle had the effect of reducing the air mass flow, the thrust per unit of air flow was reduced to 5/7 of the zero swirl value.

Tests made at reduced pressure showed that to a sufficiently good approximation the pressure loss factor was a function of $(Re)^{-0.3}$ where Re is the Reynolds No. based on the nozzle diameter and nozzle exit conditions.

An exhaust arrangement suitable for use with reheat, in which the jet pipe diameter was equal to the turbine outside diameter, was found to have a lower overall loss factor than the standard system for inlet Mach Nos. less than 0.6, but at higher velocities it was necessary to use a longer bullet to maintain this superiority.

An annular nozzle was found to give slightly over 2% more thrust at the choking condition than the standard system for the same air mass flow.

The use of thin, cambered struts for supporting the diffuser bullet resulted in increased thrust at large swirl angles.

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1.0 Introduction

Measurements of the losses in exhaust systems for turbo-jet engines were made in 1941 by Reeman (Ref.1) with the object of obtaining information for design purposes. In these tests Reeman investigated the effect on the losses of the casing and bullet shapes and the amount of diffusion between the turbine exit annulus and jet pipe, covering a range of inlet Mach numbers from 0.3 to 1.0. He also briefly investigated the effects of swirl and the losses caused by the struts supporting the centre bullet. It was concluded that the losses in an exhaust cone without struts and with no swirl were mainly those due to skin friction and that the most satisfactory and practical design of diffuser was one using a straight-sided outer casing of 12° included angle in conjunction with a conical bullet, the area ratio (turbine exit annulus: jet pipe) being 0.8.

Virtually no systematic work on exhaust system performance was done after the publication of Reeman's paper and with the development of engines of higher performance it was thought desirable to re-open the investigation, paying particular attention to the effects of swirl. The present Report describes this work.

2.0 Description of Test Rig and Instrumentation

From the outset it was felt desirable to use a test rig on which thrust could be measured directly. In this way the performance of the various systems tested could be compared in terms of the most important parameter, thrust, and much tedious traversing avoided. It was also decided that the range of test conditions should include choking of the propelling nozzle and hence it was necessary to use metal rather than wood for the construction of the test model. It was partly owing to the necessity for the use of metal, but also because Reeman's tests had covered the subject fairly extensively, that it was decided not to investigate the effects of bullet and casing shape but to confine testing to a single model representing a "typical" exhaust system.

Fig. 1 shows a side elevation of the test rig. Air was introduced into the rig through a 90° cascaded bend thus ensuring that the entering air had no momentum component along the line of action of the thrust. The restraining force necessary to maintain the rig in its equilibrium position was, therefore, equal to the gross thrust.

Flexibility in the inlet duct was provided by two freely pivoted joints which were sealed by means of U-section asbestos rings held in place by the air pressure. The downstream end of the rig was supported by a cable suspended from the roof of the test cell and longitudinal guide rails running between ball bearings were provided to prevent lateral oscillation.

The thrust was measured by a spring balance, turnbuckles being used to compensate for the extension of the balance and restraining cable thus enabling the rig to be maintained in its zero position as the thrust increased.

The basic exhaust system design chosen for test consisted of a diffuser having a straight-sided outer casing of 12° included angle and a conical bullet of 32° apex angle, a jet pipe of length:diameter ratio 2.2 and a conical propelling nozzle having an included angle of 20°. The relative flow areas were chosen after making a survey of existing engine designs, the values being as follows:-

$$\frac{\text{Area of turbine exit annulus}}{\text{Jet pipe area}} = 0.760$$

$$\frac{\text{Nozzle area}}{\text{Jet pipe area}} = 0.754$$

Two geometrically similar models were manufactured, the sizes being in the ratio 4:3. The diameter of the propelling nozzle of the smaller model was chosen to enable choking conditions to be achieved, the maximum thrust being les than 500 lb. so that it could be recorded on an existing spring balance. The larger model was built with the intention of making detailed investigations of the losses by means of traverses and its propelling nozzle was too large to enable choking conditions to be reached. The models are illustrated in Fig.2.

The Reynolds No. range covered by the tests on the smaller model was similar to that of an engine four times the size. At choking conditions the model Reynolds No., based on the nozzle exit conditions and diameter was approximately 2×10^6.

Swirl was introduced into the incoming air by means of 36 untwisted sheet metal vanes of 29° camber having a pitch:chord ratio of 1.15 at mean diameter. A linkage enabled the incidence of all the vanes to be changed simultaneously whilst the rig was in operation. The inner and outer diameters of the vanes were identical with those of the inlet annulus of the large test model, the diameter ratio being 0.65. When the small test model was used, adaptors were fitted to the inner and outer walls as shown in Fig.2b.

Static tappings were provided on the outer casing in planes just upstream of the diffuser entry, at each end of the jet pipe and at the nozzle outlet, but as explained in para.5.1 these static pressure measurements were not used in the calculation of the performance. A cylindrical pitot tube spanned the jet pipe at its downstream end. Two bosses, spaced circumferentially at 90° and in the plane of the inlet static holes, were provided on the outer casing to accommodate a yawmeter and total head tube. The entire rig downstream of the swirl vanes could be rotated about its longitudinal axis to enable the circumferential variation of inlet total pressure and swirl angle to be determined.

3.0 Preliminary Tests

Preliminary tests were made to determine the distribution of total pressure and swirl angle around the inlet annulus. It was concluded that variations in these quantities could reasonably be neglected and so, to eliminate laborious traversing, the inlet conditions were determined from single point readings with the total head and yawmeter tubes placed at mid-annulus height.

Tests made to discover if any hysteresis could be detected in values of thrust determined with increasing and decreasing air flows gave a negative result and it was concluded that friction in the flexible joints was insufficient to affect the measured thrust. A similar conclusion was drawn from a test in which the rig was pressurized with the exhaust outlet blocked to determine the effect on the thrust balance of the force exerted by the sealing rings in the flexible joints.

4.0 Testing Technique

Tests were made at constant inlet swirl angle over a range of inlet Mach Nos. up to that corresponding to choking of the propelling nozzle. Values of air mass flow, thrust, inlet total and static pressures, inlet swirl angle and the static pressures at each end of the jet pipe and at the nozzle outlet were all determined for each Mach No. As the air mass flow was increased the setting of the inlet swirl vanes had to be changed slightly to maintain a constant air angle. At the conclusion of the tests the thrust balance was calibrated by applying known loads to the model, the yawmeter zero obtained from a test with the swirl vanes removed and the air meter calibrated by traversing the jet pipe with the diffuser bullet and swirl vanes removed.

5.0 Tests using Small Model

All tests discussed in this section were obtained with the model shown in Fig.2b.

5.1 Standard System without Bullet Support Struts

Figs. 3 and 4 show respectively the non-dimensional thrust, F/A_4P_{1t}, and the thrust per unit mass flow, $F/Q\sqrt{T_{1t}}$, plotted against P_a/P_{1t}, the inverse of the expansion ratio, for values of inlet swirl ranging from 0° to 40°. From Fig. 3 it is evident that, for constant swirl angle, a linear relationship exists between F/A_4P_{1t} and P_a/P_{1t}, a result which agrees with tests made on simple nozzles with non-swirling air. Also shown on Fig. 3 are values of F/A_4P_{1t} corresponding to isentropic flow in a nozzle having an area ratio appropriate to the expansion ratio considered. This curve does not therefore apply to a specific nozzle of fixed dimensions, but to one of infinitely variable area ratio.

It is convenient to define a "thrust coefficient" as the ratio of the actual thrust to that which could be obtained from an ideal nozzle without swirl operating at the same inlet conditions. Values of thrust coefficient for typical conditions are shown in Table I below:-

TABLE I

Variation of thrust coefficient with Swirl Angle

Swirl Angle		0°	10°	20°	30°	40°
Expansion Ratio P_{1t}/P_a	1.5	0.868	0.840	0.798	0.656	0.474
	2.0	0.909	0.880	0.845	0.700	0.516

Before the overall pressure loss factor, $(P_{1t} - P_{4t})/(P_{1t} - P_{1s})$, could be calculated, it was necessary to define the methods by which P_{4t} and P_{1s} were to be obtained. In view of the existence of radial variations of static pressure when swirl was present, it was decided to ignore the measured values of static pressure, which were obtained from wall tappings, and to calculate the mean inlet static, P_{1s}, from the measured mass flow and total pressure and to assume the mean nozzle outlet static, P_{4s}, to be equal to the ambient pressure. The nozzle exit total pressure, P_{4t}, was calculated from the measured thrust (see Appendix.).

Fig. 5 shows the overall loss factor, $(P_{1t} - P_{4t})/(P_{1t} - P_{1s})$, plotted against inlet Mach No., M_1, for lines of constant swirl angle. At low Mach Nos. the loss remains sensibly constant, but there is a tendency for it to increase sharply as M_1 exceeds 0.6. Since in deriving this loss factor it is assumed that there is effectively no swirl at the nozzle exit plane, a comparison with the losses obtained from traverses can only be made at the zero swirl condition.

It was found that individual values of loss factor calculated from the test measurements exhibited considerable scatter when plotted, and so the mean curves shown in Fig. 5 were obtained from smoothed values. The method of doing this and the reasons for the scatter are described in the Appendix.

The losses shown in Fig. 5 are overall values and include the losses in the propelling nozzle, so in order that the relative proportions of the losses in the diffuser and jet pipe and in the nozzle could be assessed for the zero swirl case, a test was made with the swirl vanes and bullet removed. The mean total pressure at the end of the jet pipe, P_{3t}, was then determined from traverses and the nozzle outlet total pressure, P_{4t}, obtained as previously from the measured thrust. The results are summarised in Table II below:-

TABLE II

Relative losses in nozzle and exhaust system

M_4	M_1	Loss $/(P_{4t}-P_{4s})$ Nozzle alone	Loss $/(P_{4t}-P_{4s})$ Complete system	% overall loss due to nozzle = $(P_{3t}-P_{4t})/(P_{1t}-P_{4t})$x 100%
0.6	0.518	0.056	0.204	27.5
0.7	0.584	0.056	0.204	27.5
0.8	0.638	0.055	0.204	27.0
0.9	0.675	0.051	0.197	25.9

Values of loss factor for the nozzle alone, expressed in terms of the entry dynamic pressure, are shown superimposed on Fig. 5.

The sharp rise in loss factor for the complete model noticeable in Fig.5 is attributed to increased losses in the diffuser since the nozzle loss factor increases only slightly as the exit Mach No. approaches unity.

The variation with pressure ratio of the isentropic expansion efficiency in the nozzle and the discharge coefficient are shown in Fig. 6.

5.2 Tests at Sub-Atmospheric Pressure

In order to investigate the effects of Reynolds No. on the performance, some tests were made at reduced pressure using an ejector rig. The tests were made at an inlet static pressure of 0.5 atm., this pressure being chosen as it enabled a wide range of entry Mach Nos. to be obtained with the ejector available. As in previous tests, losses were measured for swirl angles varying between 0° and 40°. Since a "connected" rig had to be used, thrust could not be measured and the losses were therefore determined directly as the pressure difference between a single fixed pitot tube at inlet, yawed in the direction of flow, and a second tube which was traversed across the downstream end of the jet pipe. This latter tube was set at the correct angle by rotating it until the minimum value of loss was recorded.

The results of these tests are given in Fig. 7 which shows that for swirl angles up to 20° the loss factor does not vary with inlet Mach No., M_1, but at greater swirl angles it decreases as M_1 increases. This result is in agreement with similar tests made with the rig exhausting to atmosphere. Fig. 8 shows the variation of the loss factor with swirl angle for the two cases. Also shown on this graph is a single point representing the loss factor calculated from thrust measurement for the case of zero swirl. Agreement between this and the value calculated from the traverses is seen to be good.

In Fig. 9 the loss factor is plotted against Reynolds No. for zero swirl conditions and from this it will be seen that the loss increases roughly 25% as Re changes from 2×10^6 to 0.75×10^6. A working formula for the range $0.8 \times 10^6 \leqslant Re < 2.0 \times 10^6$ is:-

$$\frac{P_{1_t} - P_{3t}}{P_{1_t} - P_{1_s}} = \frac{0.18}{\left(Re/10^6\right)^{0.3}}$$

5.3 Tests with Reheat-Type Jet Pipe

When an engine is fitted with reheat it is customary to retain the original exhaust diffuser and add an additional conical diffuser to lead in to the larger size of jet pipe required for the reheat installation. Superficially, this would seem to involve excessive length and tests were therefore made to determine the losses of a system utilizing a conical bullet in a jet pipe of constant diameter equal to that of the turbine outside diameter.

Four bullets of different lengths were tested, their relative dimensions being as shown in Fig. 10. The results of these tests, which were made without swirl, are given in Fig. 11 which shows the variation of overall loss factor with inlet Mach No., M_1. In general, the increase of loss factor with M_1 is greater than is the case for the standard bullet and jet pipe, the performance of which is represented by the dotted line. As would be expected, lengthening the bullet produces a progressive reduction of loss.

5.4 Annular Nozzle Tests

In some installations a jet pipe may not be required and in these cases some gain in performance should be made possible by the use of an annular nozzle. To verify this, a nozzle was constructed having an annulus area equal to that of the original circular nozzle and this was tested in conjunction with three of the conical bullets used for the tests described in para. 5.3. The relative dimensions of the rig are given in Fig. 12 and its performance in terms of non-dimensional thrust and thrust per unit air mass flow in Figs. 13 and 14 respectively.

Fig. 13 shows that the bullet length only influences the thrust at expansion ratios above the critical and even then the effect is small. In Fig. 14 the performance is expressed in terms of thrust per unit air mass flow and it is evident that here a slight advantage is to be gained by using a long bullet. However, these results refer to static tests and it is to be expected that in flight the bullet shape would exert an important influence on the overall drag. A comparison of the performance of the annular nozzle in conjunction with the long bullet with that of the standard rig is shown in Table III below:-

TABLE III

Annular Nozzle Performance at Zero Swirl Conditions

Expansion Ratio	F/AP		F/Q√T	
	Standard	Annular	Standard	Annular
1.25	0.304	0.338	1.07	1.12
1.5	0.471	0.510	1.43	1.47
2.0	0.683	0.693	1.84	1.88
2.5	-	0.788	-	2.12

6.0 Tests using Large Model

Although, as mentioned in para. 2.0, it was originally intended to use the large model for detailed investigations by means of traverses into the causes of loss, this objective was not achieved and testing was mainly confined to the small model. Those tests which were made using the large model are recorded below.

6.1 Jet Pipe Traverses

Total head traverses were made across the downstream end of the jet pipe in a plane immediately upstream from the commencement of the propelling nozzle. Typical results are given in Fig. 15 which shows the variation of loss factor $(P_{1t} - P_{3t})/(P_{1t} - P_{1s})$ across the pipe. It is obvious that two distinct regions exist, (a) one of low loss at approximately half way between the wall and the centre of the pipe and (b) a zone of high loss situated on the pipe axis.

As the swirl angle is increased from zero to about 10° (a) increases at the expense of (b) but thereafter losses in the central region increase rapidly. This effect could be observed visually, more particularly with the small model when operating at expansion ratios approaching the critical. The temperature drop in the high loss region was then sufficient to cause the water vapour present in the air to condense out as minute ice crystals which were visible against a dark background as a blue-grey haze. The haze had the appearance of a rod lying along the axis of the jet and as the swirl angle increased so also did the diameter of the haze core. The effect was recorded photographically when some shadowgraph pictures of the jet were taken, the high loss region appearing as a dark area on the photograph.

6.2 Effect of Support Struts on Thrust

Some brief tests were made with three sheet metal struts inserted between the bullet and the outer casing with the object of investigating their

their effect on thrust. The struts had a camber of 7°, a thickness:chord ratio of 2% and were set at an inlet angle of 7°. The leading edge was approximately 0.9 chord lengths downstream of the diffuser entry.

Tests were made at constant inlet swirl angle and varying inlet Mach No. for swirl angles between zero and 40°, typical results being shown in Fig. 16 in which non-dimensional thrust, $F/A_4P_{1_t}$, is plotted against swirl angle for values of P_a/P_{1_t} of 0.6 and 0.8. For swirl angles up to 10° the influence of the struts is seen to be small but at large swirl angles a greater thrust is obtained with the struts fitted. This effect is ascribed to the straightening effect of the struts which causes a reduction in the radial component of velocity in the jet and so increases the thrust.

7.0 Discussion of results and conclusions

The main objective of the work described in this report was to investigate the magnitude of the losses in a typical exhaust system resulting from residual swirl from the turbine. The results may be summarised as follows:-

(1) The non-dimensional thrust, expressed in terms of the nozzle area and total pressure at inlet to the diffuser, varies linearly with the ratio of ambient to inlet total pressure. At an overall expansion ratio of 2:1 the model without bullet support struts gives 7% less thrust with 20° of inlet swirl than it does with no swirl and this loss rises to 43% with 40° of swirl.

(2) At zero swirl and an inlet Mach No. of 0.6, the pressure loss for the diffuser and jet pipe is 18% of the inlet dynamic pressure, but this rises to 22% at conditions corresponding to choking in the propelling nozzle. The corresponding values for expansion efficiency in the nozzle are 97.0% and 97.3% respectively.

(3) At zero swirl the effect of Reynolds No. on the losses in the diffuser and jet pipe can be represented approximately by the formula:

$$\frac{P_{1_t} - P_{3_t}}{P_{1_t} - P_{1_s}} = \frac{0.18}{\left(Re/10^6\right)^{0.3}}$$

for $0.8 \times 10^6 < Re < 2.0 \times 10^6$

Where Re is the Reynolds No. based on the propelling nozzle diameter and nozzle exit conditions.

(4) Replacing the standard diffuser by a jet pipe having a diameter equal to the turbine outside diameter gives a possible reheat system for which the overall loss factor is lower than for the standard arrangement for inlet Mach Nos. less than 0.6, but in order to maintain this improvement when the propelling nozzle is choked it is necessary to lengthen the bullet by approximately 30%.

(5) At choking conditions an annular nozzle gives slightly over 2% more thrust than the standard exhaust system for the same air mass flow.

(6) The presence of thin, cambered bullet support struts does not affect the thrust when the swirl angle is less than 10°, but with greater swirl more thrust is obtained with the struts fitted.

REFERENCE

No.	Author	Title
1	J. Reeman	"Tests on exhaust ducts for jet propulsion units". R.A.E. Report No. E.3951 August, 1942.

APPENDIX

Definition of Loss Factor

The overall loss factor of the exhaust system is defined as the loss of total pressure between planes corresponding to the turbine outlet and the propelling nozzle exit divided by the inlet dynamic pressure measured in the direction of flow. Since, for most of the tests described in this Report, no direct determinations of pressure loss by traversing were made, the loss factor was calculated in the manner set out below:-

Method of calculating loss factor

Symbols

Air Mass Flow	Q
Swirl angle at inlet	θ
Inlet Total Pressure	P_{1_t}
Inlet Total Temperature	T_{1_t}
Inlet Static Pressure	P_{1_s}
Inlet Area	A_1
Gross Thrust	F_g
Nozzle outlet static pressure	P_{4_s} *
Nozzle outlet area	A_4
Ambient pressure	P_a

(1) Determine $\dfrac{Q\sqrt{T_{1_t}}}{A_1 \cos\theta P_{1_t}}$ and hence find inlet Mach No. M_1 and static pressure P_{1_s}

(2) Momentum thrust $F_m = F_g - (P_{4_s} - P_a)A_4$

(3) Jet Mach No. $M_4 = \sqrt{\dfrac{F_m}{\gamma A_4 P_{4_s}}}$ Hence P_{4_t}/P_{4_s}

(4) Nozzle outlet total pressure $P_{4_t} = P_{4_s} \times P_{4_t}/P_{4_s}$

(5) Overall loss factor $= \dfrac{P_{1_t} - P_{4_t}}{P_{1_t} - P_{1_s}}$

In the method of calculation given above the overall pressure loss is obtained as the difference between two separately obtained quantities, P_{1_t} and P_{4_t}. In the tests described this difference varied between 4% and 9% of P_{1_t} and hence small errors in either P_{1_t} or P_{4_t} were reflected in large

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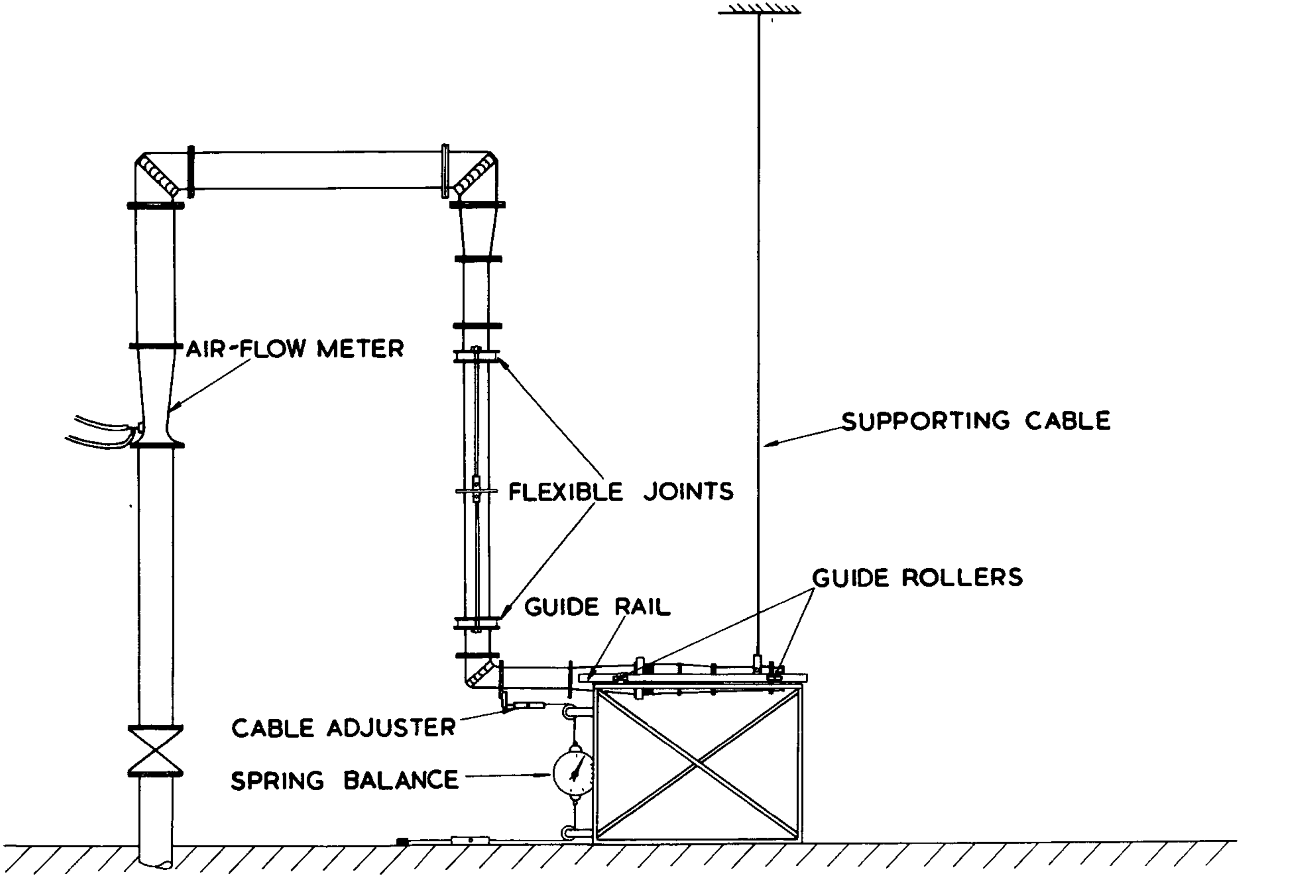
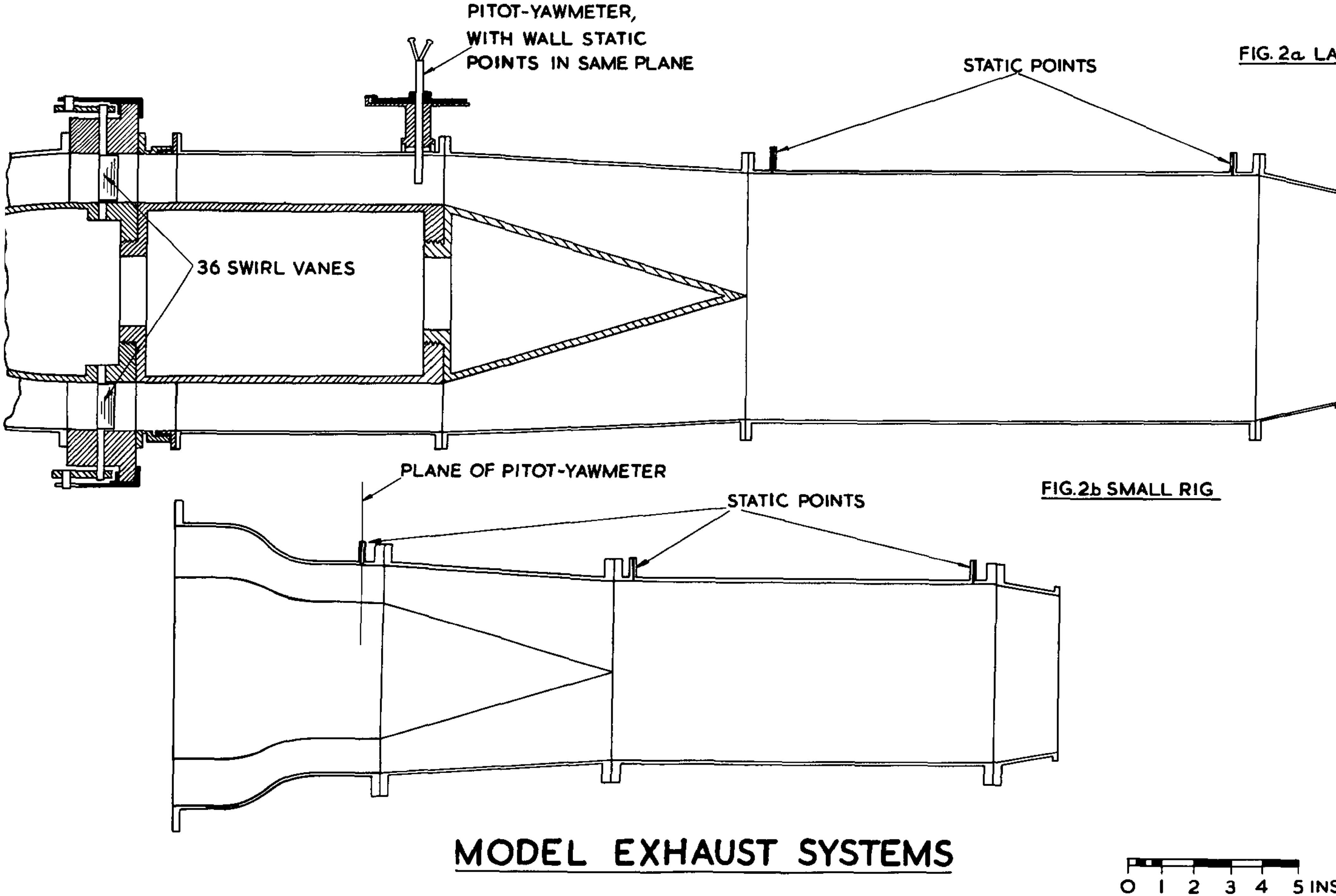
* Although the static pressure in the plane of the nozzle exit, P_{4_s}, was measured by means of wall tappings, the values so obtained were not used in calculation as they were not representative of the mean pressure, particularly at large swirl angles. All the results given in this Report have been calculated assuming $P_{4_s} = P_a$.

variations of loss factor. As a result, the values of loss factor calculated directly from the test measurements exhibited considerable scatter when plotted against inlet Mach No. and to overcome this difficulty "smoothed" values of P_{1_t}, P_{4_t}, $(P_{1_t} - P_{1_s})$ and M_1 were obtained by plotting each against a reference pressure, such as upstream total pressure. Mean values of the loss factor found in this way are shown by the curves of Fig. 5.



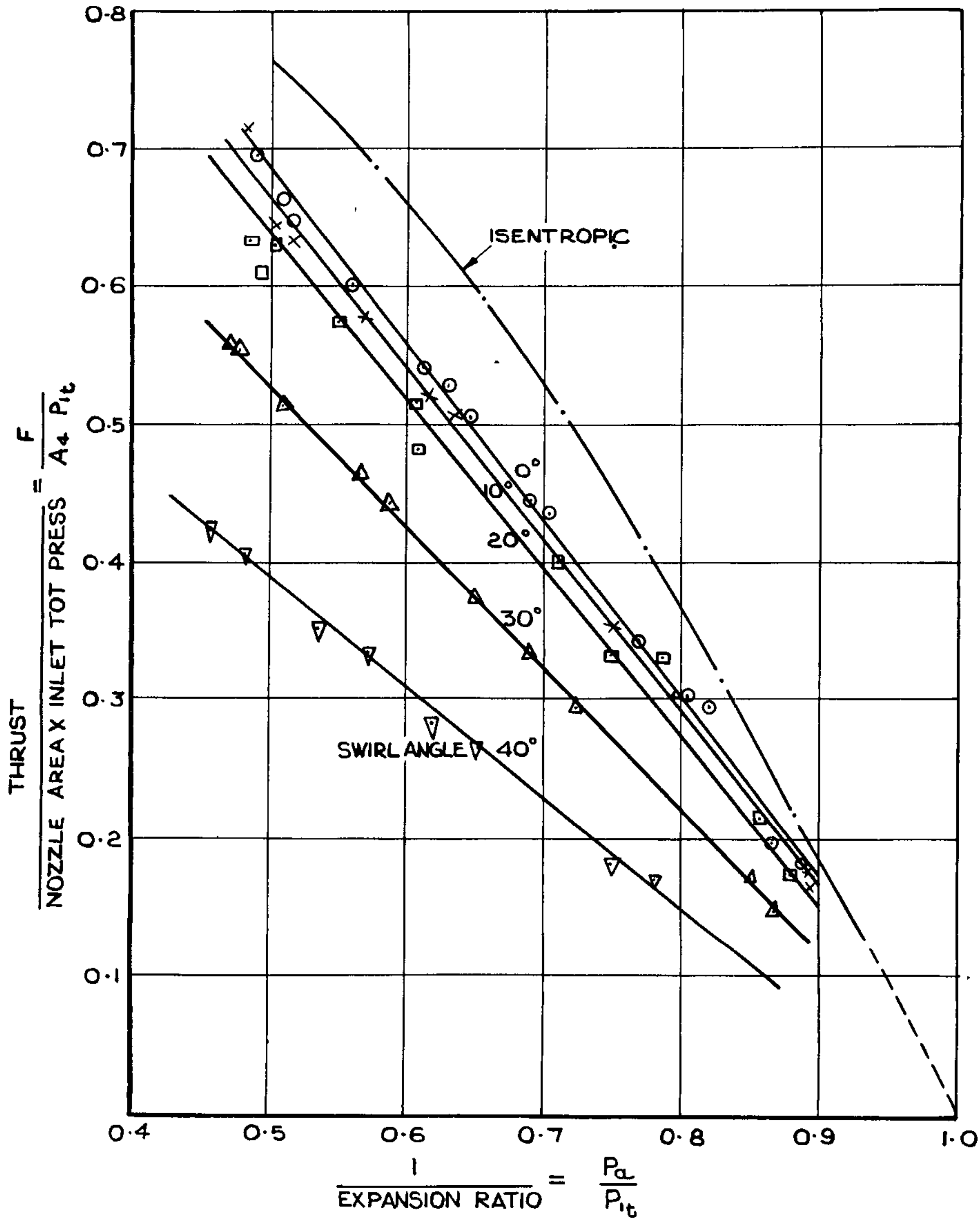
EXHAUST SYSTEM TEST RIG

FIG. 1.



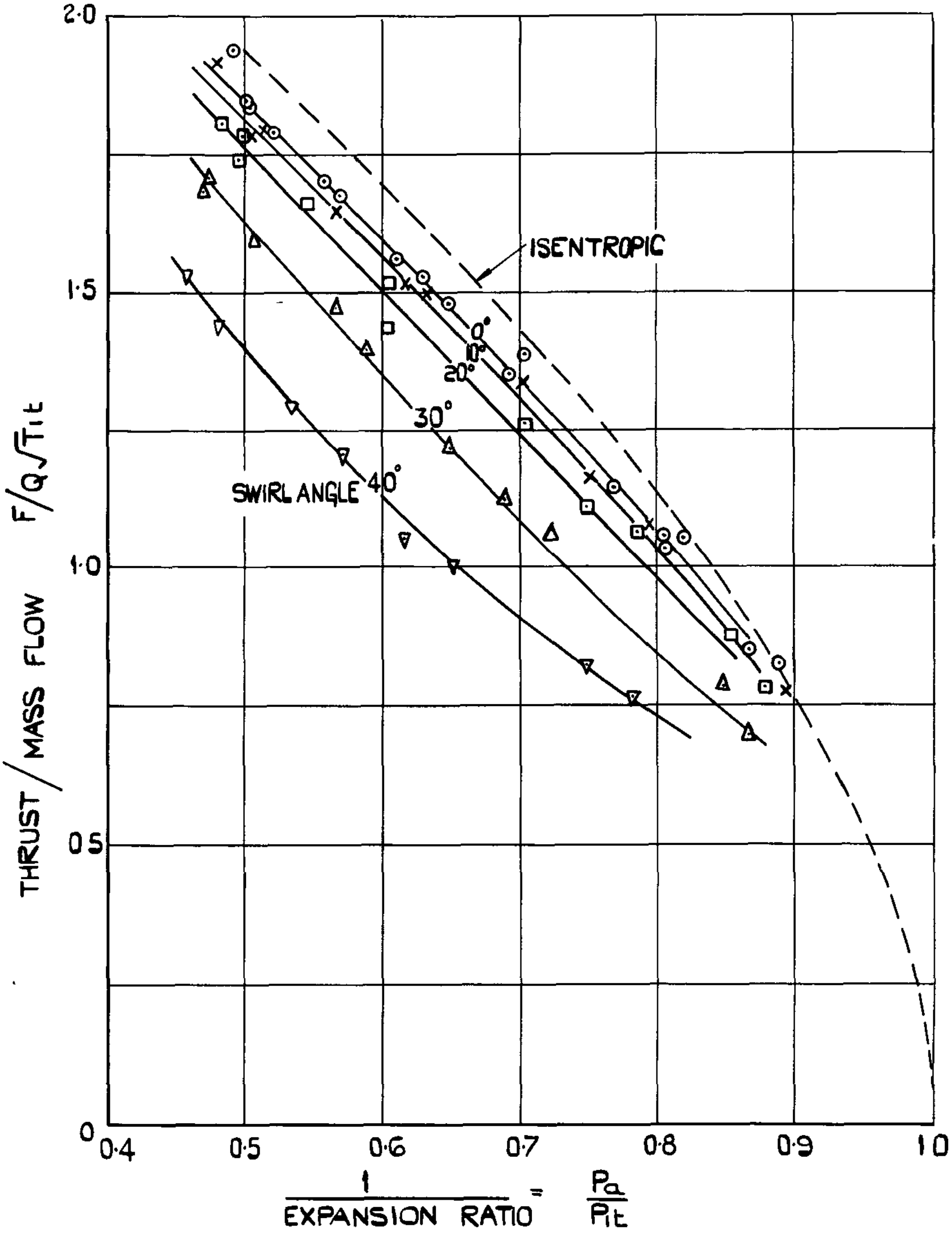
MODEL EXHAUST SYSTEMS

FIG. 2.



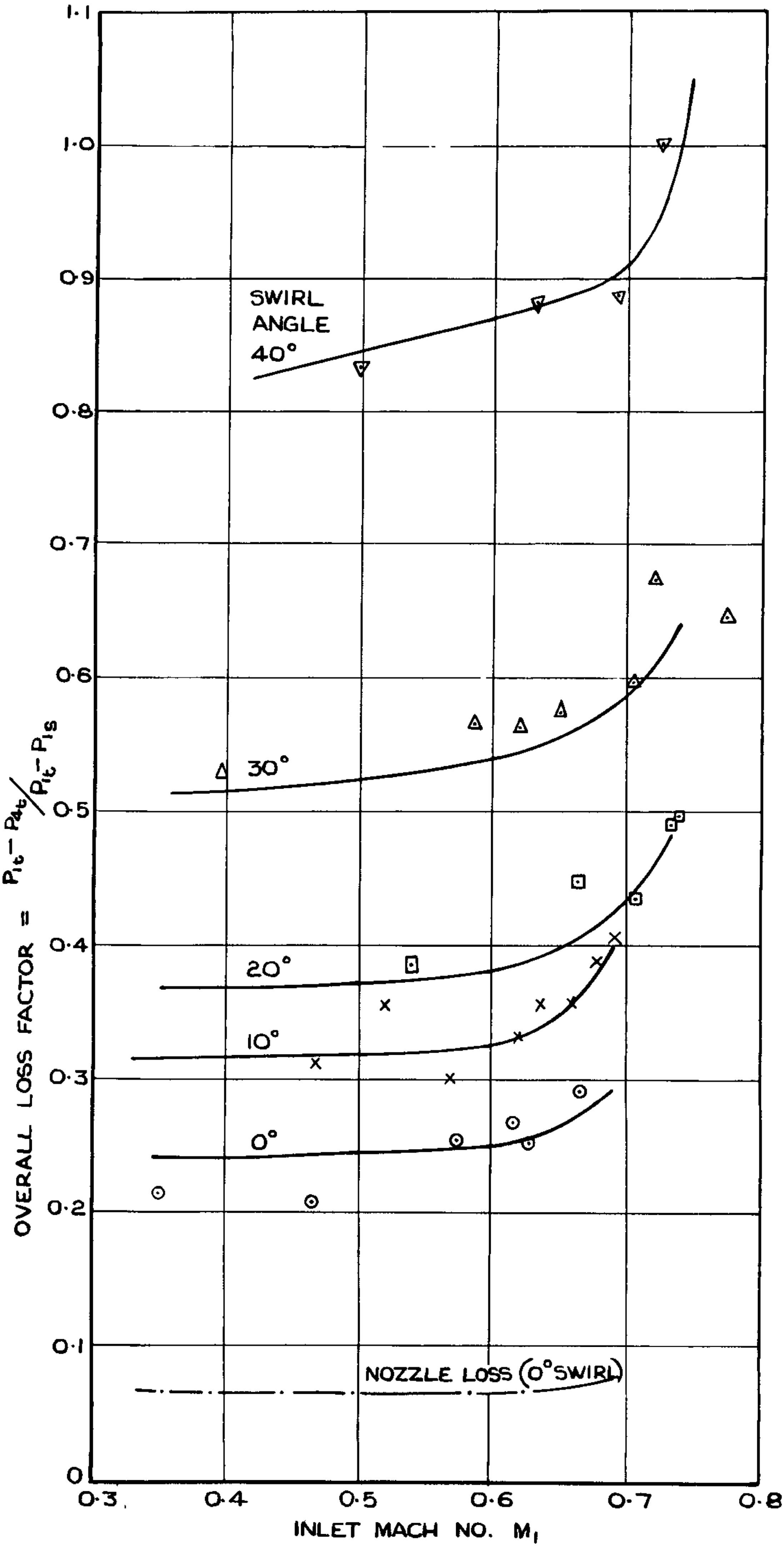
PERFORMANCE OF STANDARD SYSTEM.

FIG 4.



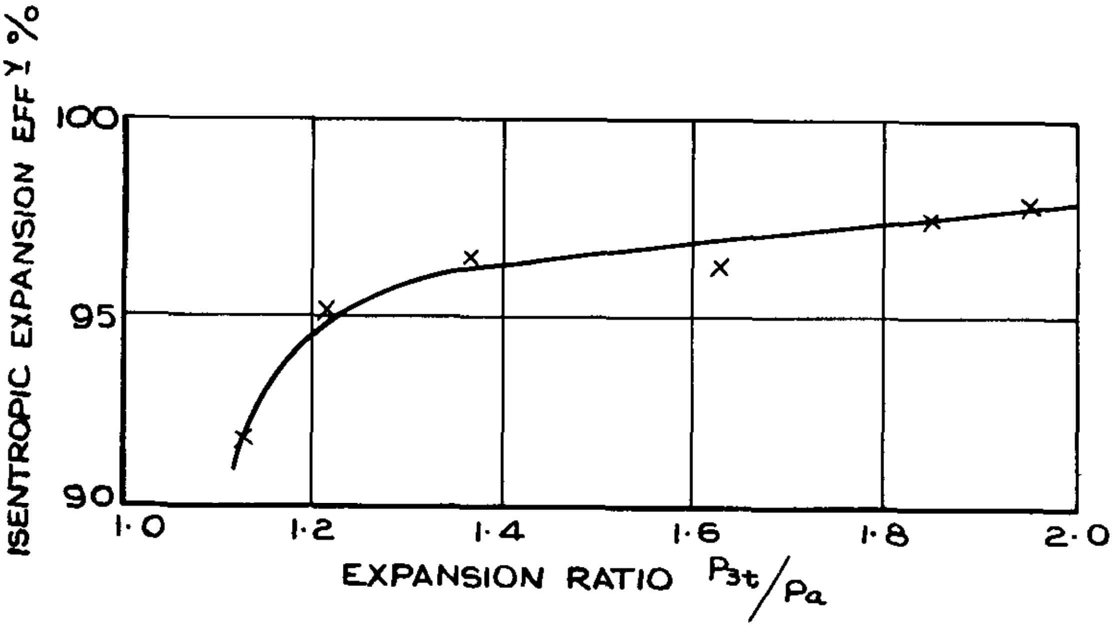
PERFORMANCE OF STANDARD SYSTEM.

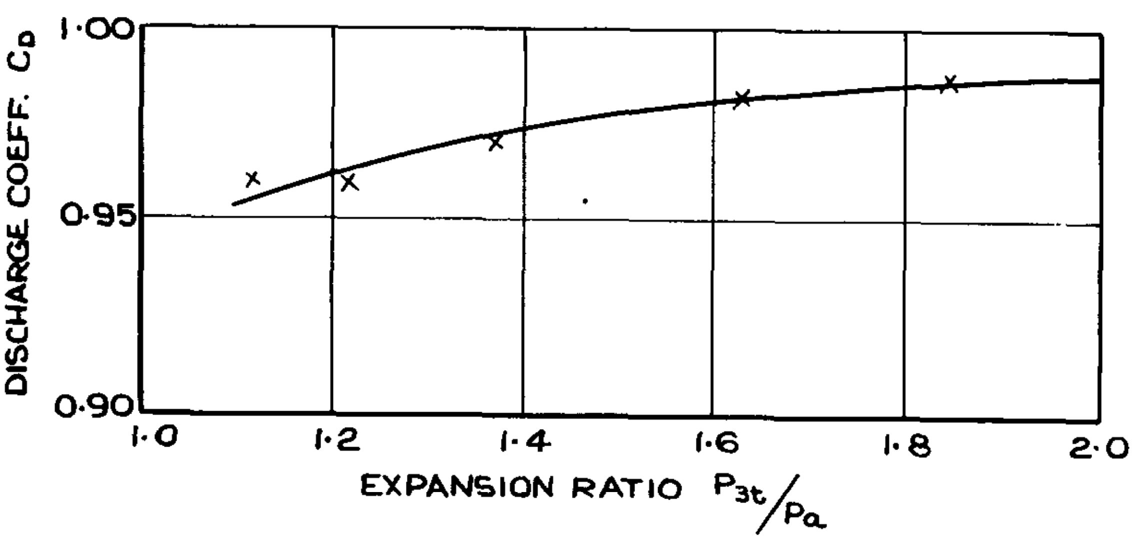
FIG. 5



PERFORMANCE OF STANDARD SYSTEM.

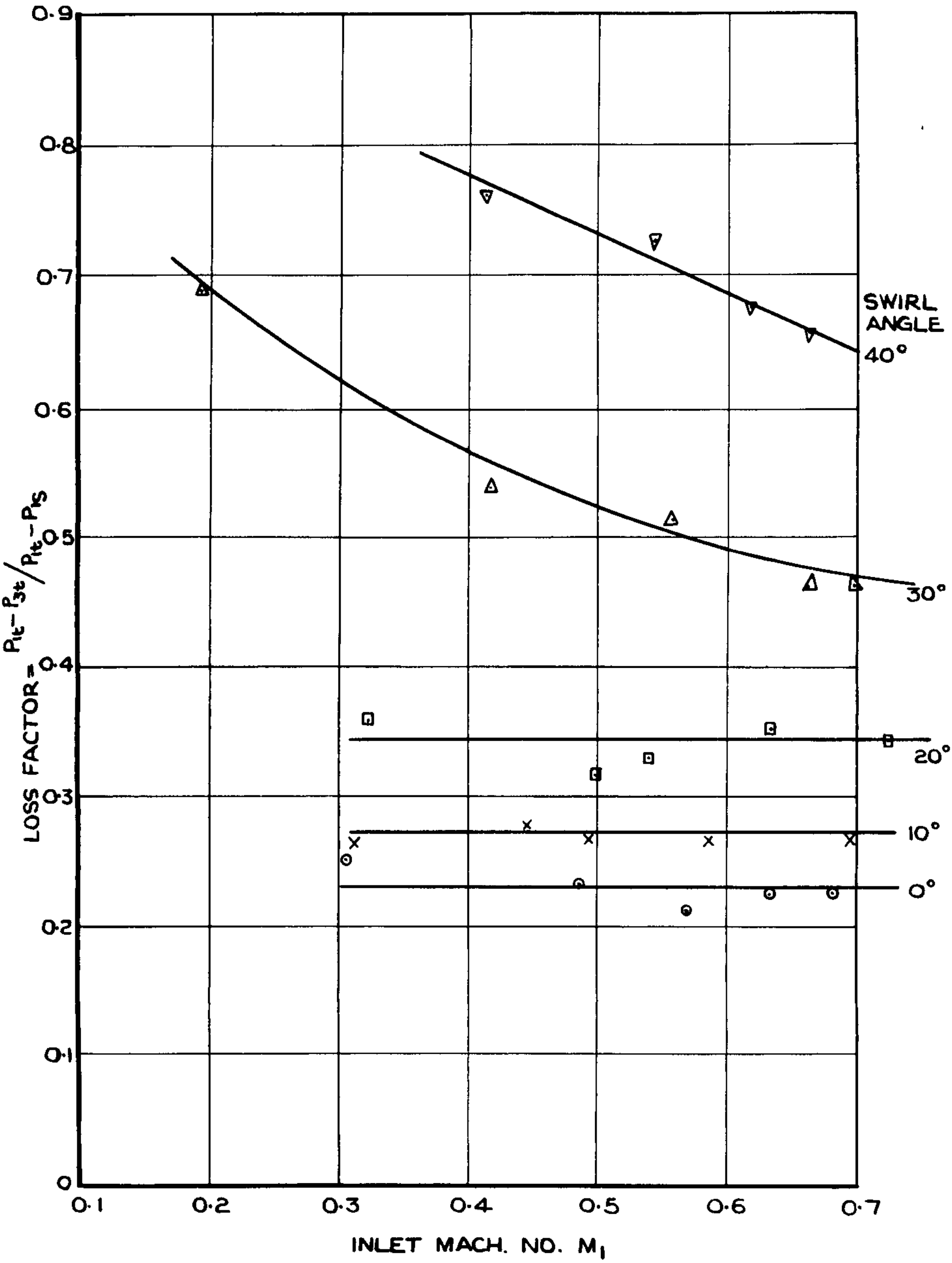
FIG. 6





PROPELLING NOZZLE PERFORMANCE.

FIG.7



TESTS AT REDUCED PRESSURE.

FIG. 8

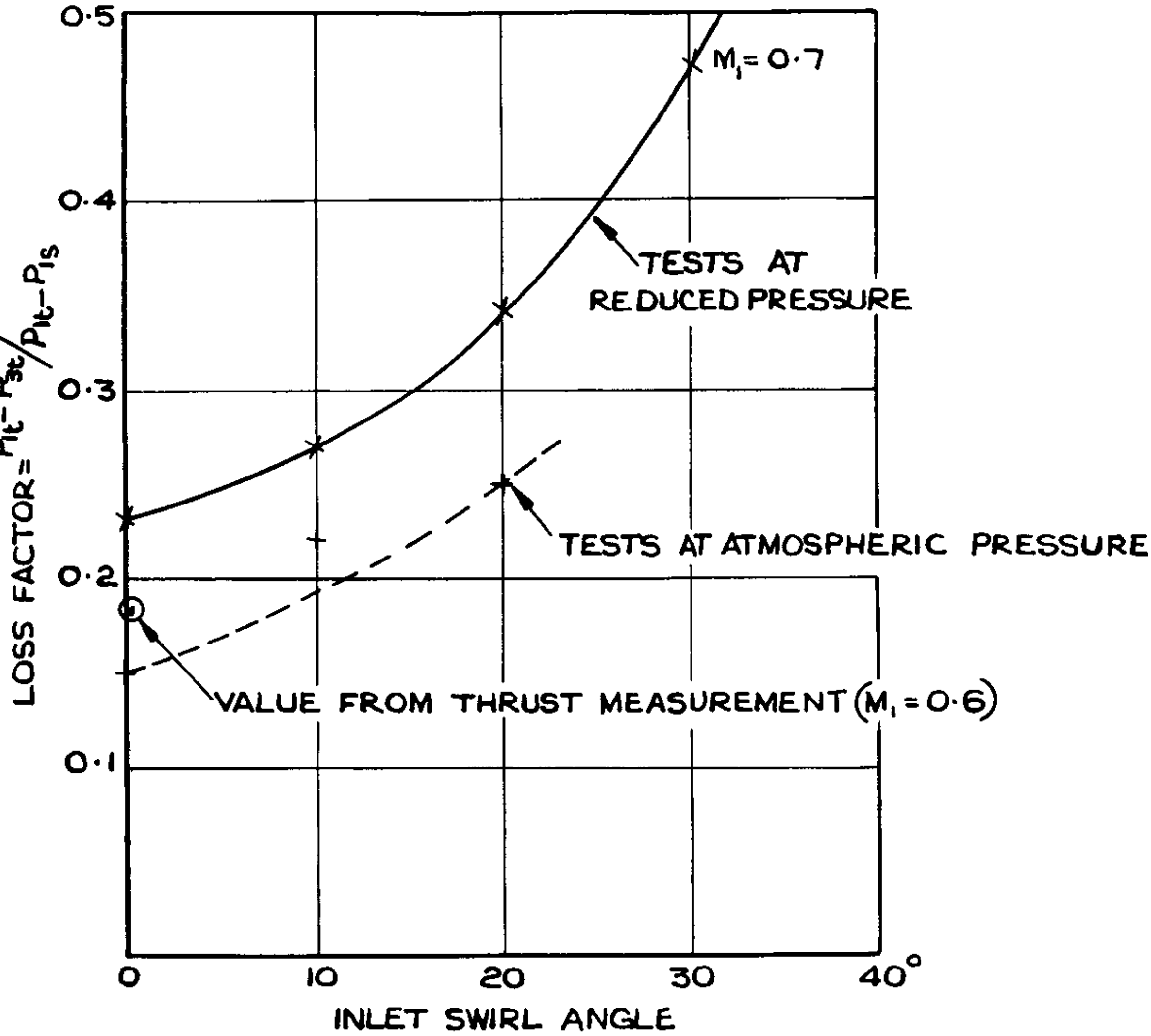
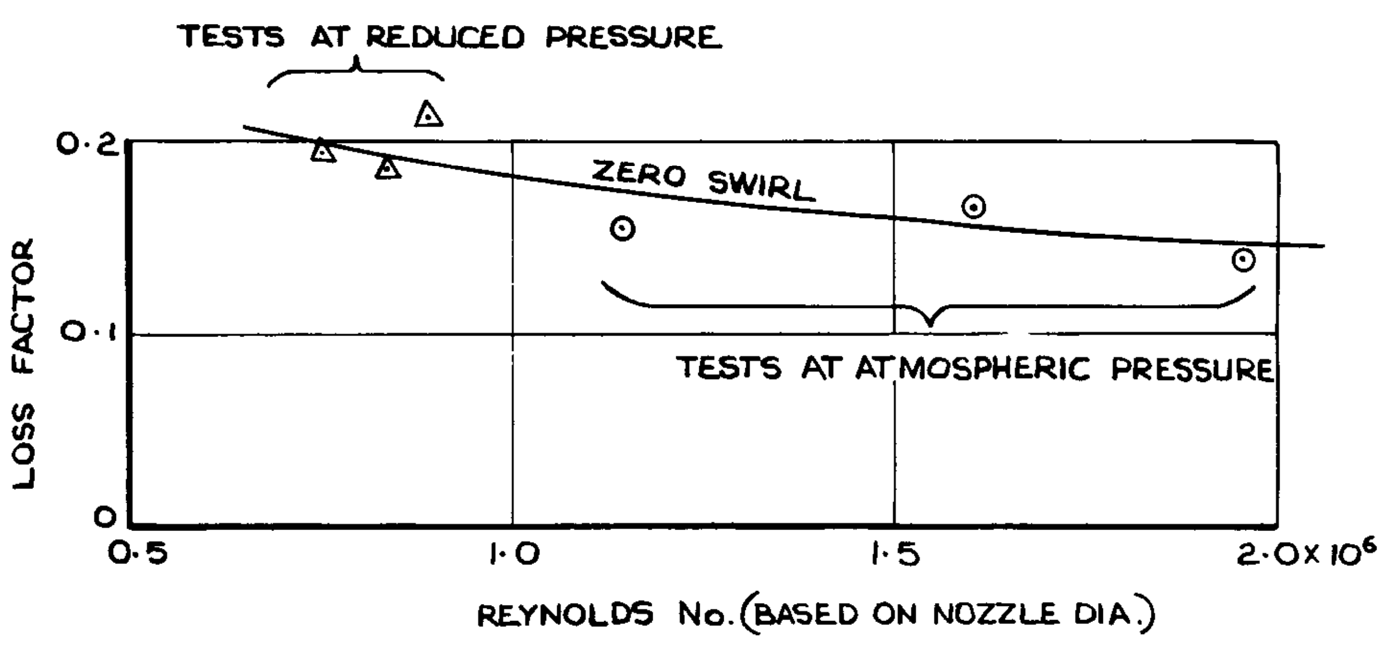
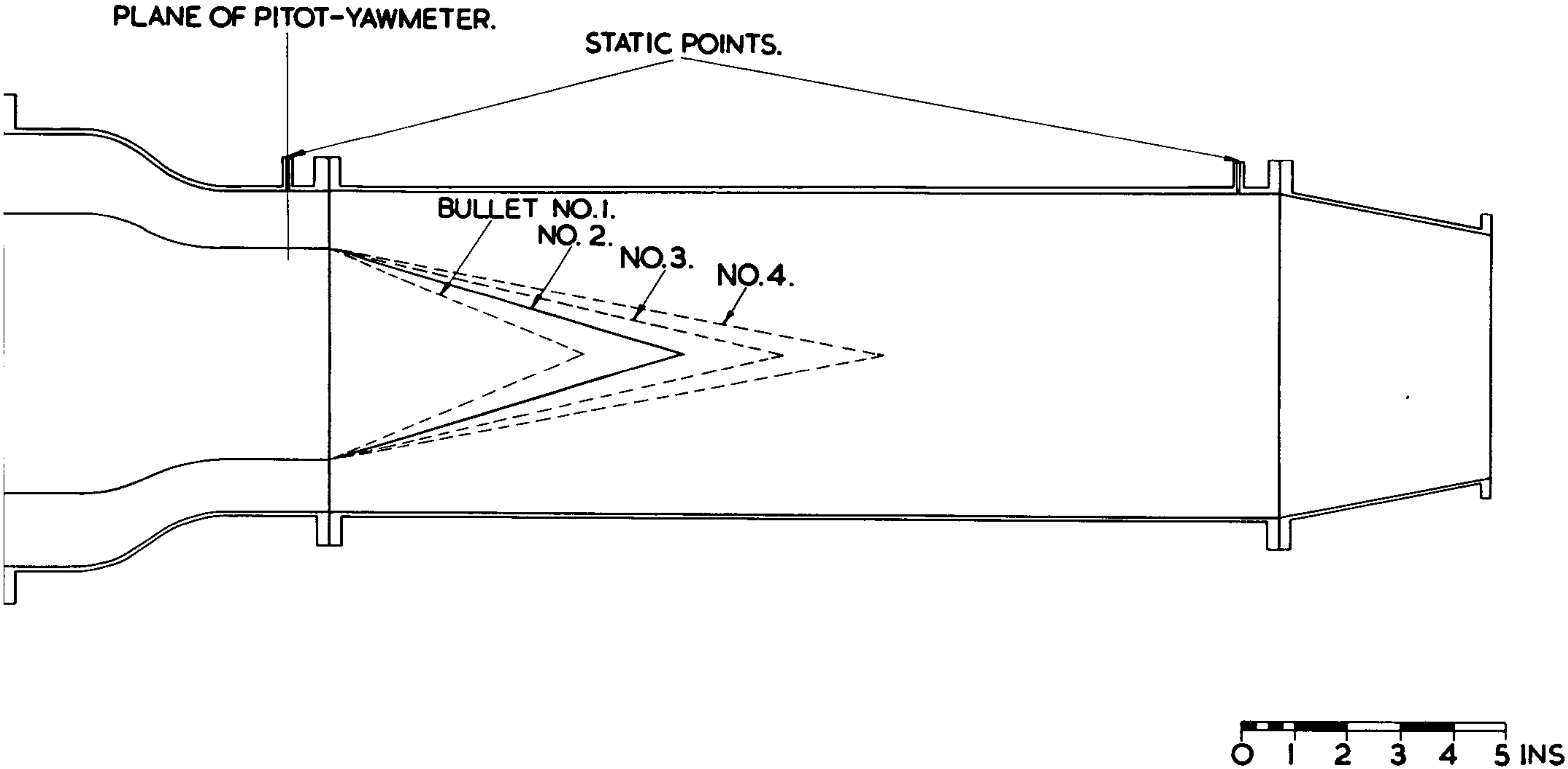


FIG. 9

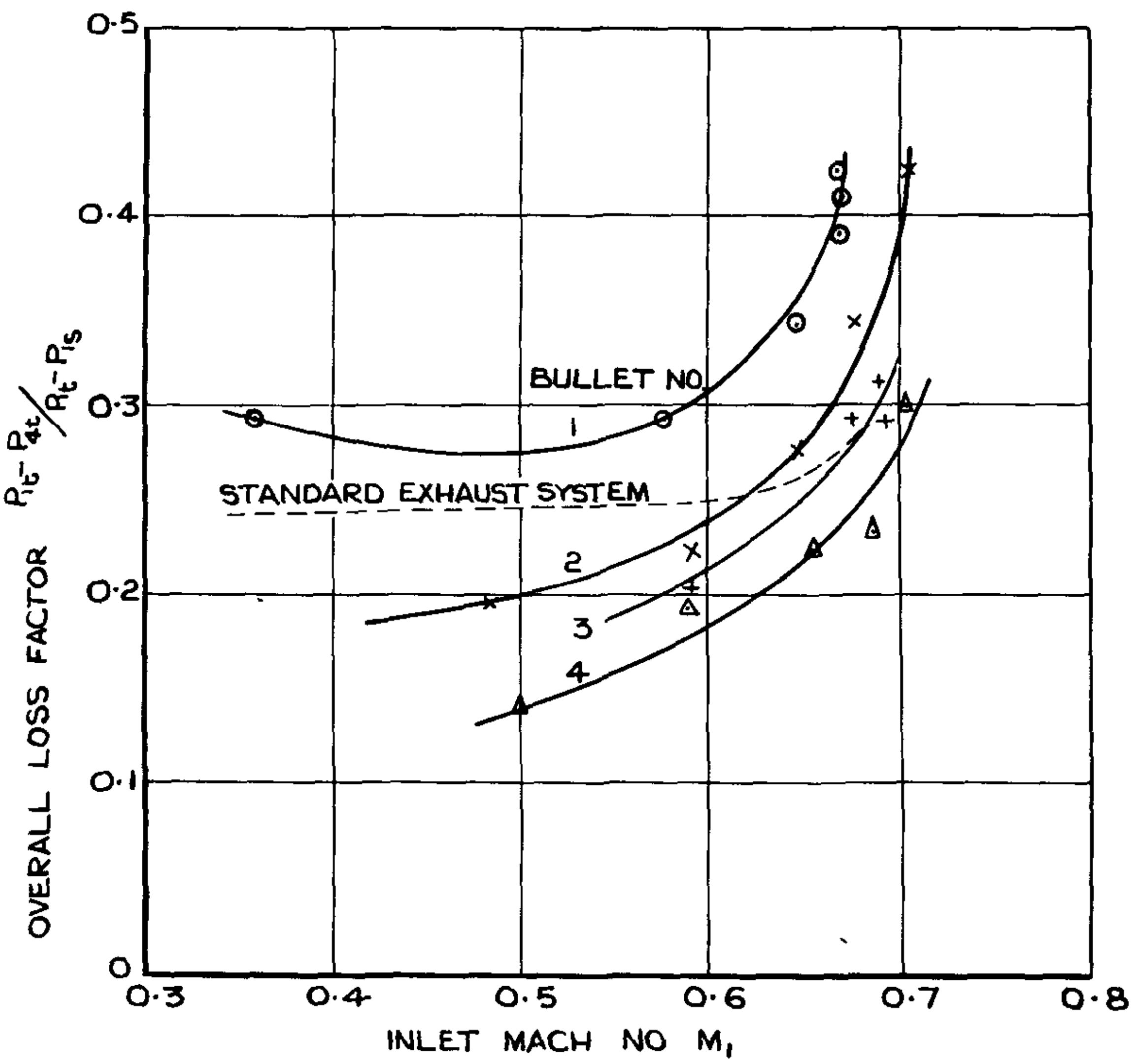


EFFECT OF REYNOLDS No. ON PERFORMANCE.

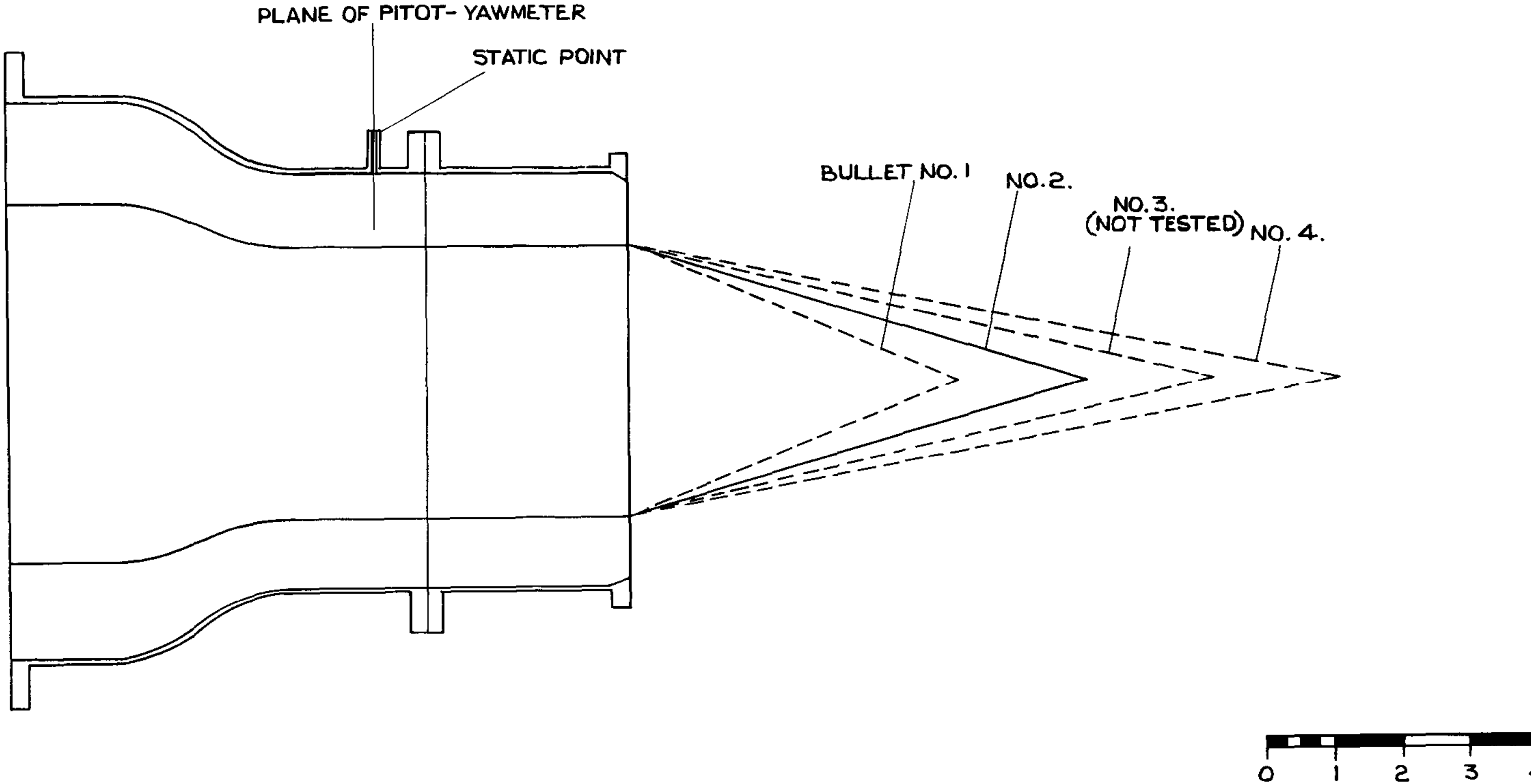


REHEAT EXHAUST SYSTEM.

FIG.10



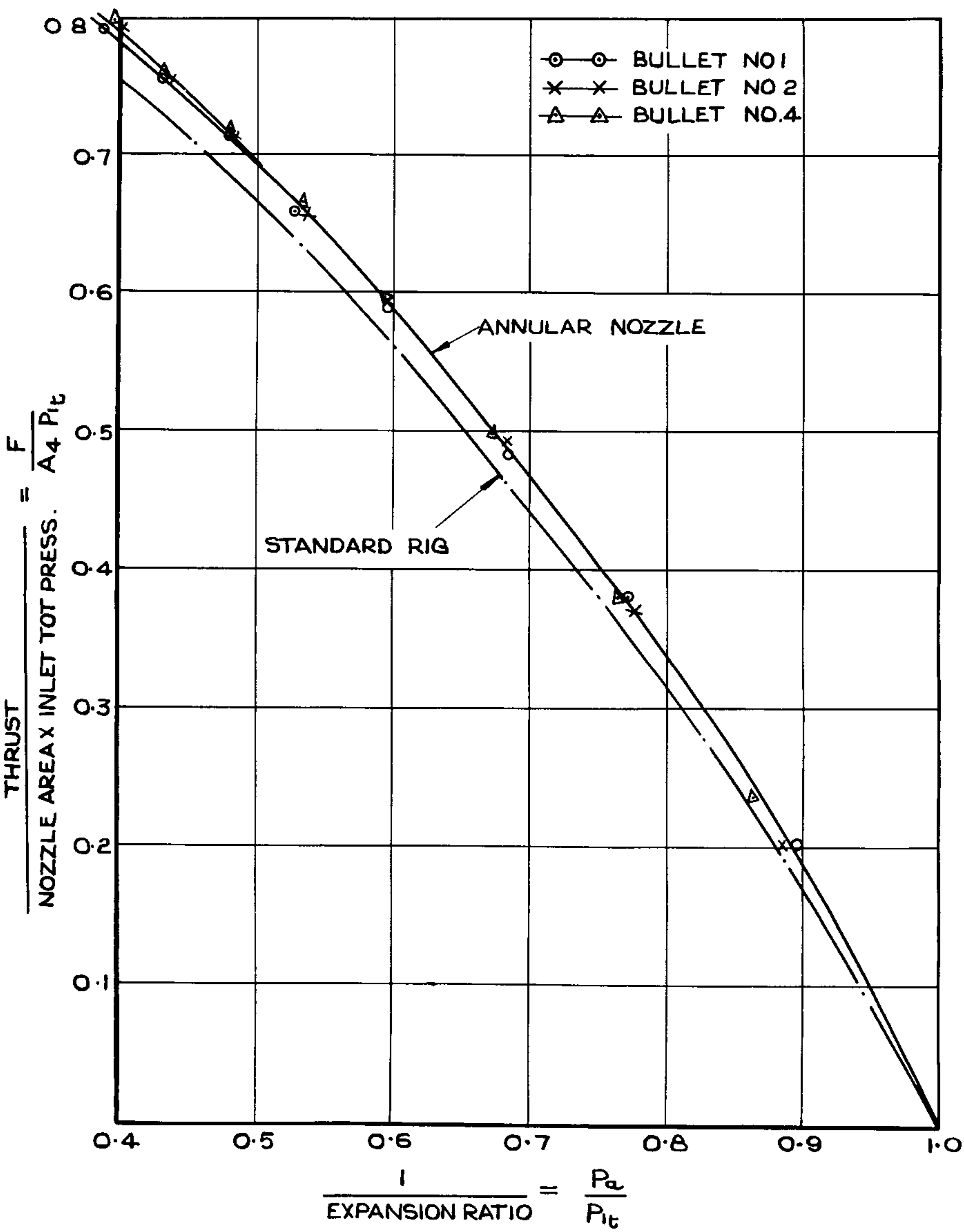
PERFORMANCE OF REHEAT SYSTEM.



ANNULAR PROPELLING NOZZLE.

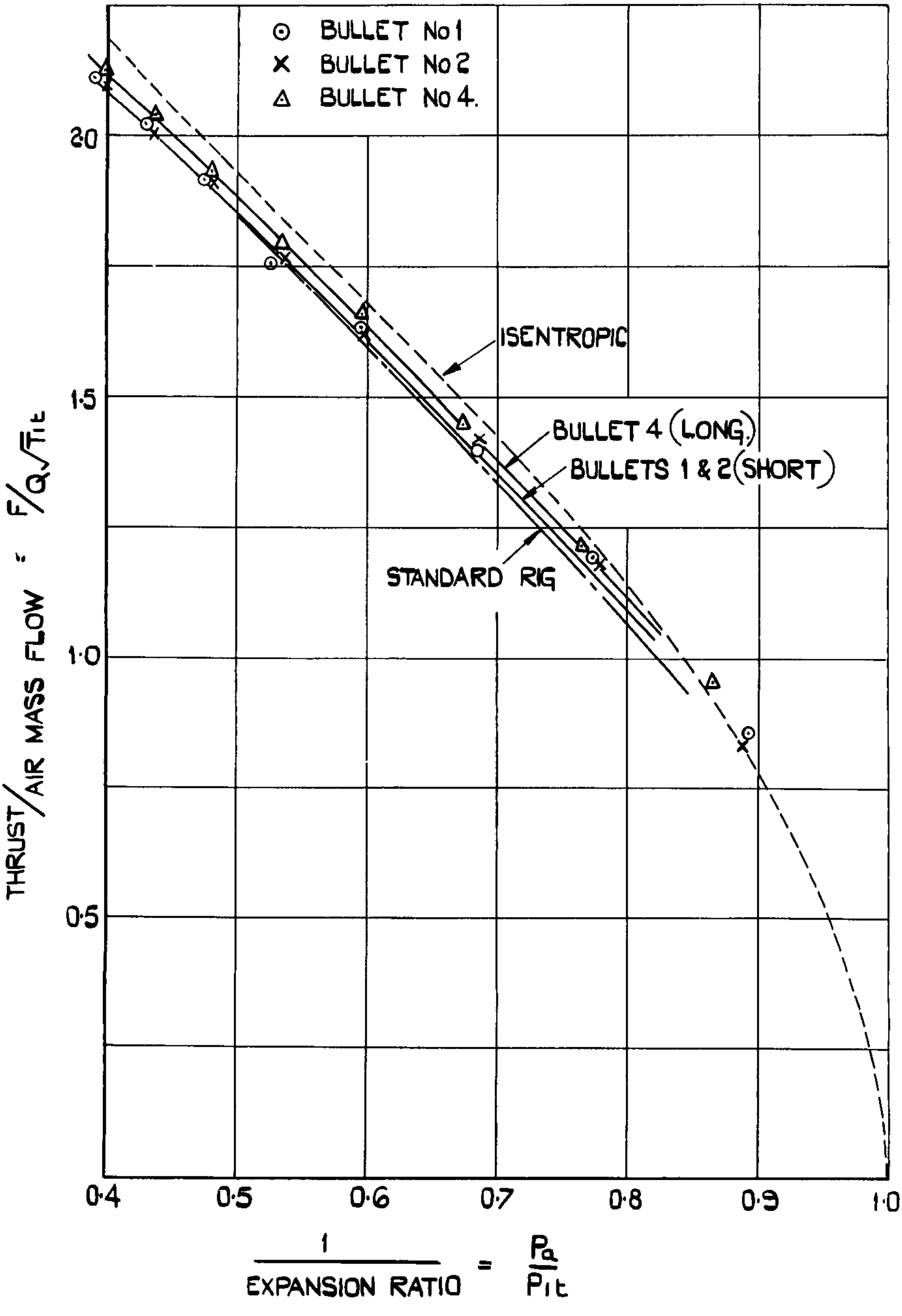
FIG. 12

FIG. 13

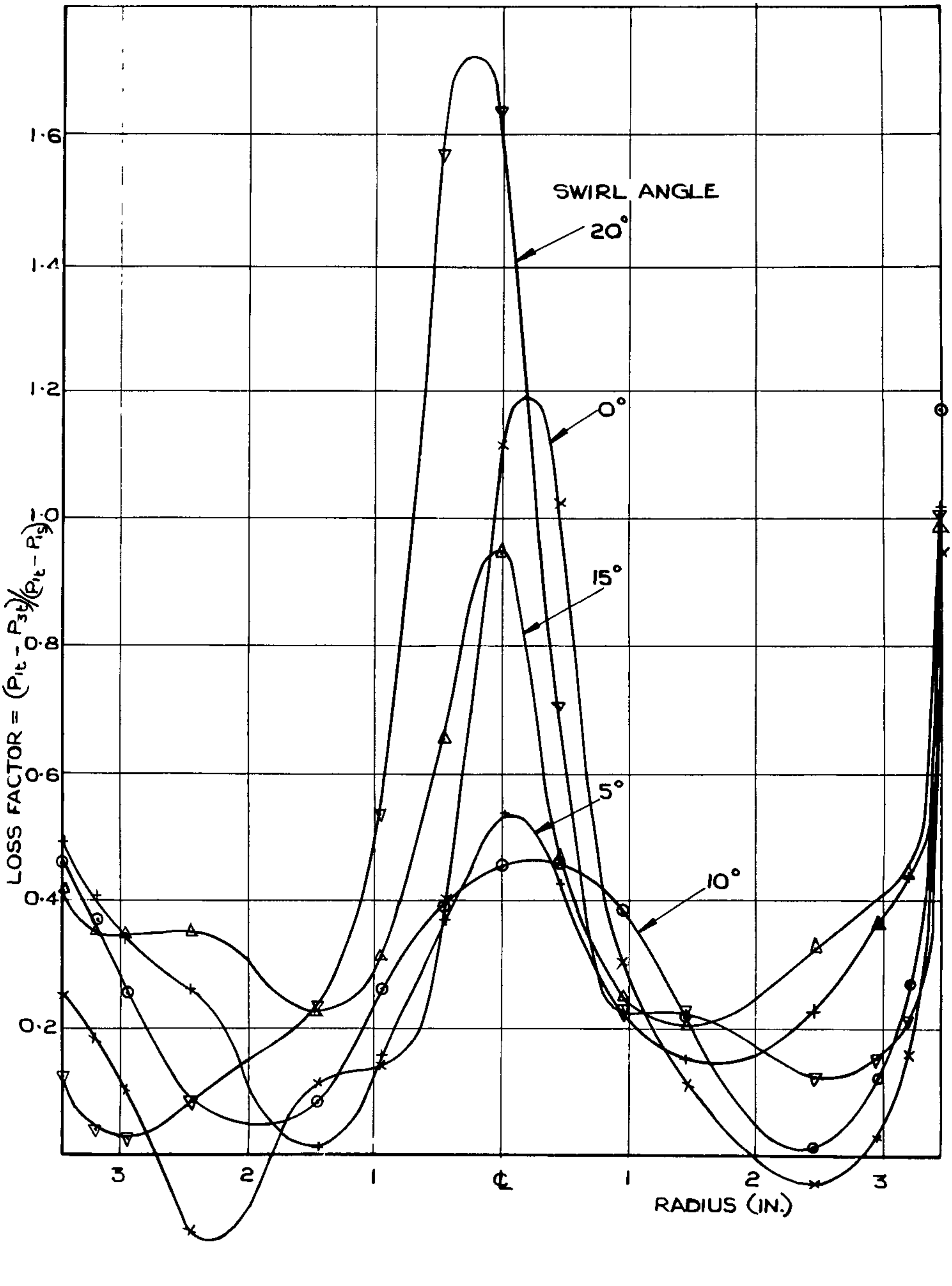


PERFORMANCE OF ANNULAR NOZZLE SYSTEM.

FIG 14.

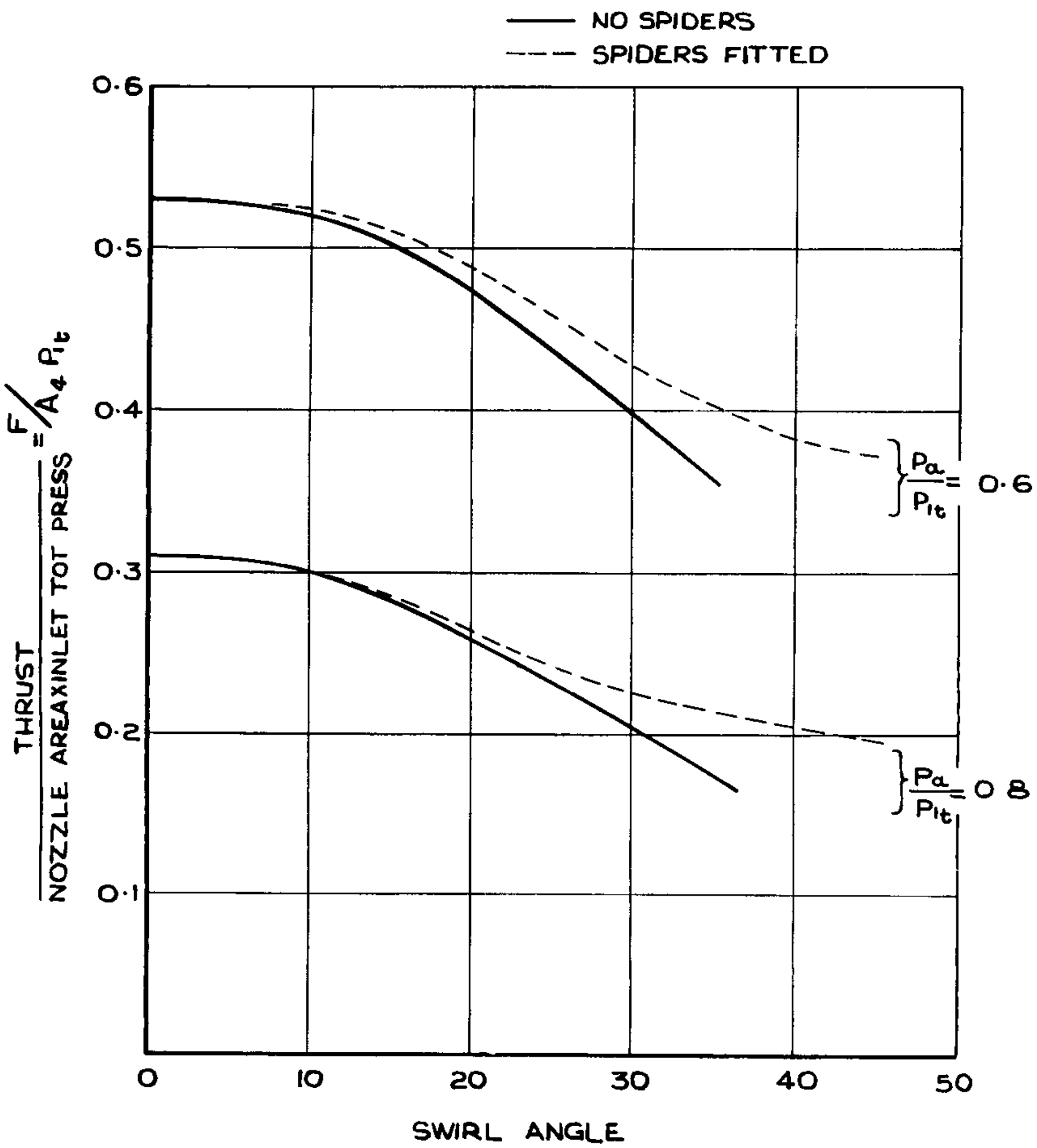


PERFORMANCE OF ANNULAR NOZZLE SYSTEM.



JET PIPE TRAVERSES (LARGE RIG)

FIG.16



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