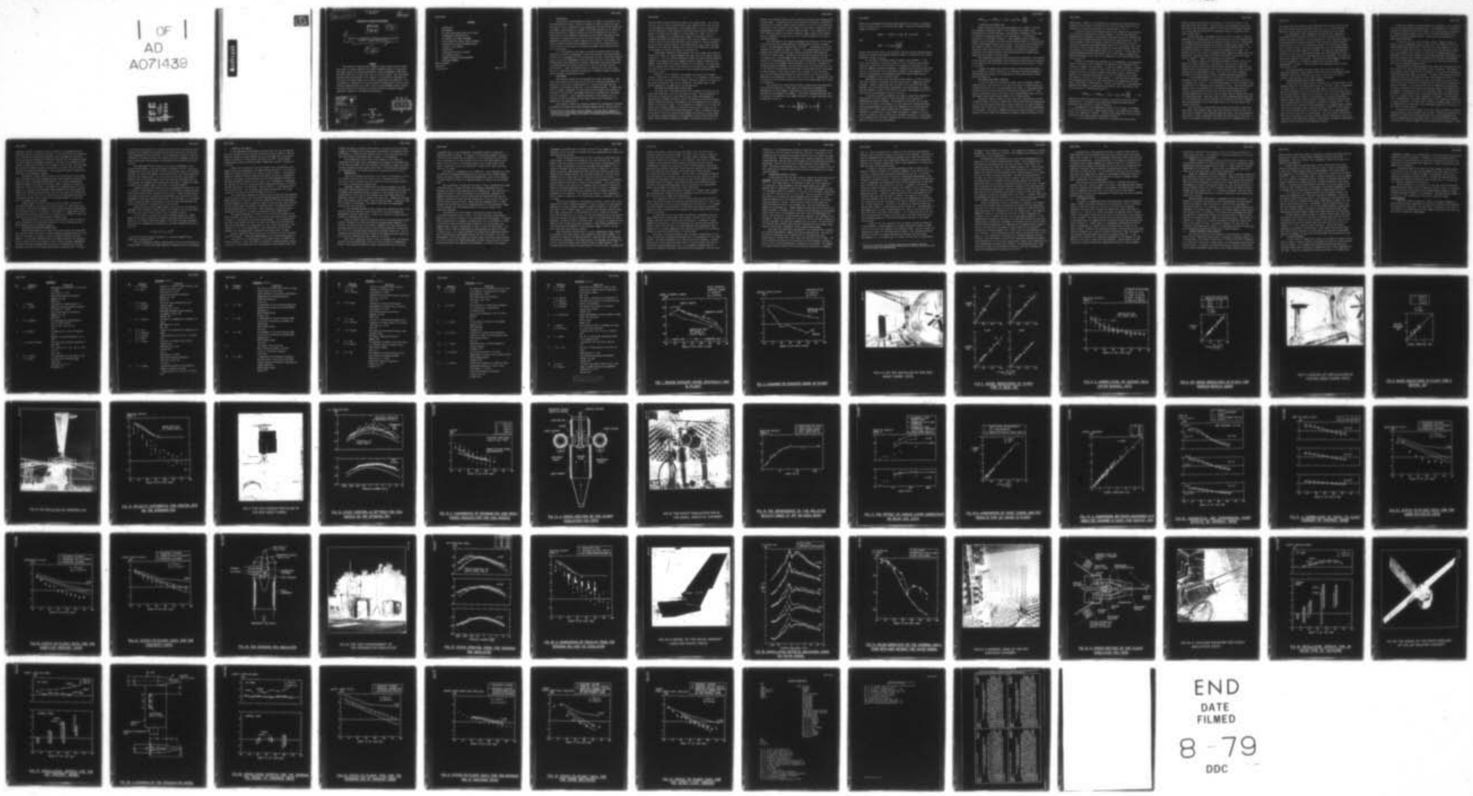
AD-A071 439 NATIONAL GAS TURBINE ESTABLISHMENT FARNBOROUGH (ENGLAND) F/G 20/1
A REVIEW OF THE RESEARCH AT NGTE CONCERNING THE EFFECTS OF FLIG--ETC(U)
SEP 78 W D BRYCE

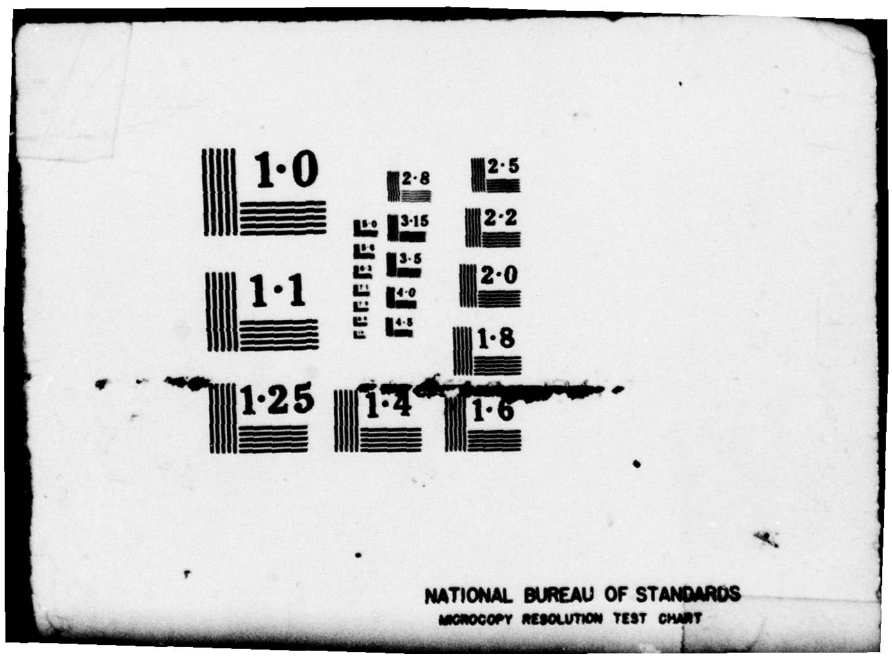
UNCLASSIFIED NGTE-R78007 DRIC-BR-65126 NL

| OF |

AD
A071439



END
DATE
FILMED
8-79
DDC


1·0
2·8
2·5
3·15
2·2
3·5
2·0
1·1
4·0
4·5
1·8
1·25
1·4
1·6
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

(18) DRIC

UDC 621.45.035.5
534.836.2

(19) BR-65126

(14) NGTE-R78007

NATIONAL GAS TURBINE ESTABLISHMENT

REPORT R78007

(11) SEPT 1978

(12) 78p.

(6)

# A review of the research at NGTE concerning the effects of flight on engine exhaust noise


by

(10) W. D. Bryce



SUMMARY

The problem of explaining the changes of engine exhaust noise in going from static to flight conditions has puzzled research workers for some years. This paper reviews the various experimental research programmes at NGTE which have been carried out on this topic over the last five years. The step-by-step progress which has been made in the analysis of the problem is described and the results from some recent tests, hitherto unpublished, are presented. It is concluded that, together with the characteristics established for jet noise and internally-generated noise in flight, acoustic and aerodynamic effects arising from the installation of engines in aircraft constitute necessary, perhaps sufficient, features of the required explanation.



Accession For
NTIS GRA&I
DDC TAB
Unannounced
Justification

By

Distribution/

Availability Codes

Dist | Avail and/or special
A

DDC
RECEIVED
JUL 13 1979
D



Copyright
©
Controller HMSO London
1978


242 000


79 07 06 067

CONTENTS

## 1. INTRODUCTION

The problem of understanding the effect of flight on the exhaust noise from aero-engines has been a topic for research at NGTE for some five years. That there is such a problem was first demonstrated by Bushell[1], who showed that the exhaust noise produced by a number of different engines did not reduce in going from static to flight conditions as would be expected for jet noise. The solution of this problem is important not only because there may be some reduction in aircraft noise to be won, but also because the uncertainty undermines our ability to predict engine noise in flight. This ability is needed to enable aircraft noise guarantees to be met and to enable the best use to be made of the results from engine development tests conducted statically on the ground.

It is the purpose of this paper to review the research which has been carried out at NGTE in attempting to resolve the problem. The review extends from the first experiments in 1973 and describes, in more or less chronological order, the various developments which have taken place up to the present time. Although some recent discoveries, hitherto unpublished, have greatly improved our understanding, the problem cannot yet be said to have been resolved satisfactorily. Hence the research work is continuing and the lines along which it is expected to develop are indicated. We begin, however, by describing the problem in quantitative terms.

## 2. THE PROBLEM

The essential features of the problem are evident from Figure 1. The noise levels shown here are from one of the first controlled experiments[2] to measure the noise from an engine mounted on a static test stand and also installed in an aircraft flying over a noise recording station. In going from static to flight conditions, it can be seen that the engine noise reduces in the rear arc but at 90° to the engine axis and in the forward arc the engine noise is increased*. At the operating condition of this engine, the jet velocity is high but subsonic and the engine noise would be expected to be dominated by jet mixing noise.

Now Lighthill's theory of convected quadrupoles[3], subsequently developed and modified by Ribner[4] and Ffowcs Williams[5] amongst others, was and still is

---

*The noise levels and angles referred to here, and elsewhere in this paper, relate to emission time co-ordinates, that is, to the angle and distance between the aircraft and the noise measuring point at the time the noise is emitted, rather than to reception time co-ordinates which refer to the conditions when the noise is received.

the most widely accepted theoretical model of jet mixing noise. For a static cold air jet, the overall sound pressure level (OASPL) at 90° to the jet axis is calculated to be proportional to the eighth power of the jet velocity, $V_j^8$, and to be modified at other angles by convective effects which increase the noise in the rear arc and reduce it in the forward arc. When a jet is in flight, its mixing rate is reduced, the length of its potential core is increased and Ffowcs Williams concluded in 1963 that the change in the acoustic volume of the jet would cause the noise source strength to reduce according to the relative jet velocity raised to the seventh power, $V_{rel}^7$, rather than $V_{rel}^8$. Changes in the convective effects would cause the noise reductions in flight to be greater in the rear arc than in the forward arc.

Using these theoretical relationships, the static engine noise would be predicted to reduce in flight throughout the noise field by the amount depicted in Figure 1. It is the obvious differences between the actual and the expected changes in the engine noise, the comparison shown in Figure 1 being but one example, which formed the original definition of the problem. The observation that the engine noise levels in the forward arc in flight could be higher than the static noise levels often gave rise to the problem being described as "forward arc lift".

Because it is the changes in the engine noise which are of primary concern, rather than the absolute noise levels, it is convenient to plot results of the type shown in Figure 1 in the manner depicted in Figure 2, in which the base line is the noise under static conditions. The larger scale of this diagram emphasises the magnitude of the discrepancies.

## 3. THE FIRST WIND-TUNNEL TESTS ON JET NOISE

The first step in the NGTE research was to examine the validity of the reductions predicted to occur for jet noise in flight. The determination of the effect of flight on jet noise from aircraft flyover measurements is complicated by a number of factors, such as the impurity of the noise source, engine installation effects, the properties of the atmosphere and the transient nature of the acoustic signal. It was possible to eliminate, or at least alleviate, most of these problems by carrying out tests with a "clean" jet rig installed in an acoustically-treated wind-tunnel. The 24 ft diameter free-jet wind-tunnel at the Royal Aircraft Establishment was selected for this purpose. By choosing a large wind-tunnel, the microphones could be located within the tunnel airflow thereby minimising the number of corrections that had to be applied to the measured data in order to derive the noise levels representative of true flight. In actual practice, the microphone was moved in a downstream direction as the flight (tunnel) speed increased, to allow for the downstream convection of the jet noise by the external flow and hence to enable the noise measurements to be made at a constant emission angle. As a consequence, the only correction needed to the data to simulate flight correctly was a Doppler shift in frequency to correct for the lack of motion between the jet nozzle and the microphone.

The first phase of the research programme was carried out in 1973, most of the data being for single-stream jets issuing from a circular convergent nozzle of 102 mm diameter supplied with cold air[6,7]. A photograph of the rig installed in the tunnel is shown in Figure 3. The upstream end of the nozzle assembly was suitably contoured and a wooden fairing was fixed around the vertical air supply pipes. Cylindrical silencers can be seen at the base of each supply pipe. The photograph shows the microphone mounted at the jet height on a traversing pylon and also the tunnel driving fan which recirculates the air to the 24 ft diameter nozzle upstream of the jet rig. Although the extensive acoustic treatment in the working section can be seen, much of it is in the form of flat foam slabs and the acoustic environment was far from ideal. In fact, because of this and the lack of any treatment in the flow return duct, the jet spectra were distorted to such an extent that all of the data measured in the forward arc of the jet had to be discarded. Nevertheless, rear arc data for jet velocities from 230 to 340 m/s with flight speeds up to 30 m/s were obtained.

The correlation of these data was greatly simplified by the observation that the noise reductions at each angle were essentially independent of frequency so that the changes in the spectral levels could be adequately described by the changes in the OASPLs. Theoretical considerations were used to show that the reduction in the OASPL from static to flight conditions could be expected to vary as

$$\Delta OASPL = 10 \log_{10} \left[ \left( \frac{V_j}{V_{rel}} \right)^m \left( 1 + M_a \cos\theta \right) \right] \quad \ldots.(1)$$

where m is an experimentally-derived index depending on the angle, θ, measured to the jet axis, and $M_a$ is the flight Mach number. Hence, if a modified OASPL change is defined as

$$\Delta OASPL' = \Delta OASPL - 10 \log_{10} \left(1 + M_a \cos \theta\right) \quad \ldots.(2)$$

then

$$OASPL' = 10 \log_{10} \left(\frac{V_j}{V_{rel}}\right)^m \quad \ldots.(3)$$

and the data should be able to be correlated, and the relative velocity index m obtained, by plotting the modified change in OASPL as a function of the velocity parameter, $10 \log_{10} (V_j/V_{rel})$.

On this basis, the results shown in Figure 4 were obtained. At the static test conditions, the ejector effect of the jet induces a small tunnel velocity, $V_{TO}$, which has been included by an appropriate correction to the velocity parameter forming the abscissae. Considering that the noise reductions are only a few decibels, the correlations in Figure 4 show remarkably little scatter and proportional relationships between the modified OASPL and the velocity parameter could be defined readily.

The measured value of the relative velocity index, m, at $90^{\circ}$ to the jet axis was 5.1 which is noticeably less than the value of 7 suggested by Ffowcs Williams[5]. However, some recent work by Larson et al[8] has shown that good agreement can be obtained between experimental noise measurements on unheated jets and Lighthill's model of jet noise if turbulence measurements are used to characterise the aerodynamic structure of the jet.

A tentative prediction method for jet noise in flight was produced by modifying the jet noise theory of Ffowcs Williams by the inclusion of experimentally-derived constants. An allowance for the effect of jet temperature was included in this method[7], not from theoretical considerations but from earlier experiments on the effect of temperature on jet noise measured statically[9,10]. These studies showed that jet temperature effects can be adequately correlated with $(\rho_j/\rho_o)^{\omega}$ where the exponent ω depends on the jet velocity and where $\rho_j$ and $\rho_o$ are the jet and ambient densities. On this basis, it was suggested that the noise reduction for a hot jet could be "corrected" to that for a cold jet using the relation

$$\Delta OASPL_{cold} = \Delta OASPL_{hot} - 10\left(\omega_j - \omega_{rel}\right)\log_{10}\left(\frac{\rho_j}{\rho_o}\right) \quad \ldots.(4)$$

## 4. A COMPARISON WITH ENGINE DATA

Bushell analysed flyover noise measurements for a number of aircraft and presented an important paper[1] in 1975 comparing the exhaust noise characteristics with the wind-tunnel results given in Reference 6 (which does not include the predicted effects of jet temperature). His principal conclusion is illustrated in Figure 5. This diagram contains information similar to that of Figure 2 but the relative velocity index, m, is used instead of the actual change in noise level in order to account for the differing jet and flight velocities of the various engines. Even though the wind-tunnel results for pure jet noise show less reduction in flight than originally predicted on theoretical grounds, large discrepancies still remain except perhaps at small angles to the jet axis.

This comparison stimulated some international controversy. The validity of the aircraft noise measurements was questioned and there are still those who do not agree that the wind-tunnel results represent truly the effect of flight on jet noise.

Although the engine data quoted by Bushell covered mixed and unmixed by-pass engines as well as turbo-jets, the subsequent research programmes at NGTE concentrated initially on the problem with turbo-jets because of their relative simplicity.

## 5. THE SECOND WIND-TUNNEL PROGRAMME

In the first phase of wind-tunnel testing, jets of nominally ambient temperature were used and most of the tests were done with single-stream jets although some coaxial jet noise measurements were taken. In the second phase, carried out early in 1975, the work was extended to heated jets[11,12]. Both types of nozzle were tested, and various jet silencing nozzles also, but only the single-stream conical nozzle results will be discussed here.

Initially, however, further cold jet tests were conducted with nozzles of smaller diameter in order to answer the criticism that the noise measurements in the first test series, made along a linear traverse at 21 nozzle diameters distance, were carried out too close to the jet for true far-field measurements to be obtained. The results, examples of which are shown in Figure 6, did not indicate that this effect was significant, bearing in mind the accuracy of the measurements. However, as a consequence of the additional data obtained, the relative velocity index of jet noise at $90^{\circ}$ to the jet axis, which is a key parameter in the prediction method, was revised from 5.1 to 5.4.

The hot jet tests were conducted with a 65 mm diameter nozzle installed in the RAE 24 ft wind-tunnel as shown in Figure 7. The air was heated by a hydrogen burner installed in the primary flow supply pipe and to attenuate any burner noise the downstream section of the pipe was lined internally. The jet flow was heated to 880 K and because subsonic jet velocities up to 450 m/s could now be obtained, the maximum tunnel speed of 50 m/s could be used. From the point of view of safety, this installation posed some problems - ensuring the integrity of the wooden-bladed tunnel fan, for example. In the event, the hydrogen purging and monitoring systems and the other safety instrumentation worked effectively and the rise in the temperature of the recirculating tunnel flow was only $2^{\circ}$C.

Ideally, to establish the importance of jet temperature, the experiments should be carried out over a range of jet temperatures and wind-tunnel velocities for a range of jet velocities. It was not, however, possible to explore such a wide range of variables in these tests, and the limited amount of data obtained could only be used to establish first-order effects. According to Equation (4), the noise reductions for a hot jet in flight should be rather less than for a cold jet at the same velocity. It was found that qualitatively this expectation was true, but that quantitatively the differences were only about three-tenths of those expected. Clearly, discrepancies of this magnitude emphasise the simplicity underlying the jet density term. Nevertheless, the use of Equation (4) modified arbitrarily to

$$\Delta OASPL_{cold} = \Delta OASPL_{hot} - 3\left(\omega_j - \omega_{rel}\right)\log_{10}\left(\frac{\rho_j}{\rho_o}\right) \quad \ldots(5)$$

enabled the prediction method for cold jets to correlate the hot jet results satisfactorily. An example of the comparisons between the predicted and measured noise reductions is shown in Figure 8.

The magnitude of the temperature correction is not large. For example, at $90^{\circ}$ the relative velocity index changes from 5.4 for unheated jets to about 4.6 at a jet temperature of 880 K. Obviously this change does not have a major influence on the flight problem illustrated in Figure 5.

It is worth digressing at this point to introduce the results from another research exercise which was carried out in the wind-tunnel at the same time as the hot jet work. The objective of the programme was to relate the results from wind-tunnel research to those from the Rolls-Royce spinning rig at Aston Down which provided an alternative means for conducting flight tests at model scale.

The spinning rig, a photograph of which is shown in Figure 9, consists essentially of a rotating arm of 10 m radius driven by a tip jet supplied with air passing from the hub through the aerofoil section of the arm. Measurements of the noise from the moving tip jet are made by sampling the signals from microphones placed in the plane of the rotor but some distance from it. The wing can be tethered to allow static noise measurements to be taken. The standard tip jet unit contains a kerosene-burning combustion chamber and, using heated jets, the results from this facility are similar to those for engine noise in flight[13]. Figure 10 illustrates this conclusion[14].

In trying to resolve the discrepancy between the results from the two methods of flight simulation, it was decided to begin with cold jet tests using the so-called "HSA" nozzle which does not incorporate a combustion can. Instead, the air supply pipes in the wing feed directly into a short tailpipe leading to the 76 mm diameter nozzle. This tip jet unit was originally designed for shielding tests for which a Hartmann generator was attached.

It was thought advisable for the tests in the wind-tunnel[15] to reproduce, as far as possible, the installation of the nozzle on the wing of the spinning rig. Hence, as can be seen from Figure 11, the first metre of the wing section of the spinning rig was reproduced in wood. The bluff obstruction inboard of the tip represents one of the adjustable drag plates which are fitted to the spinning rig wing in order to allow some variation in the relation between the jet thrust and the tip speed, that is, between the jet and the flight velocities. These were fixed to give the maximum drag because only in this configuration could the spinning rig be slowed to velocities comparable with those obtainable in the wind-tunnel when the jet was operating at high subsonic velocities.

The noise levels from the HSA nozzle measured statically in the wind-tunnel were a few decibels higher than those expected for pure jet noise but there was no evidence of any internally-generated noise. The noise reductions from static to flight conditions were rather less than those for pure jets; at $90^{\circ}$, for example, the relative velocity index was 3.8 compared with 5.4. It was thought that the relatively high turbulence levels in the jet flow at the nozzle exit plane (spatial variations from 4 per cent to 12 per cent were measured) could be affecting the jet noise both statically and in flight.

The complementary test programme on the spinning rig, conducted in collaboration with Rolls-Royce (1971) Ltd, initially produced results far removed from those obtained in the wind-tunnel but it was found that these cold jet measurements were being distorted by noise from the air supply system[16]. Pressurised air for the rig is supplied by a bleed flow from an Avon engine and, as Figure 12 shows, only when the engine was run at the minimum possible rev/min could consistent spectra be obtained. The spectral levels measured statically on the rig, though markedly higher than those predicted for pure jets[17], were then similar to those measured in the wind-tunnel. In flight too, much better agreement was obtained. The static-to-flight changes in noise can be seen from Figure 13 to compare reasonably well with the tunnel measurements[18]. However, this conclusion of the experiment was not finally reached until 1977.

The broad agreement obtained between the results from these two, completely different, flight simulation facilities was an encouraging outcome although why the results differed from those of pure jets could only be surmised. We will return to this topic later in the paper.

## 6. FLIGHT SIMULATION USING A SMALL AIRSTREAM

Even prior to the second series of tests in the 24 ft wind-tunnel, it was becoming clear that the flight problem would not be easily solved. Furthermore, the tunnel facility, being limited in flight speed, in the quality of its acoustic environment and in its availability, was not exactly an ideal vehicle for pursuing intensive research on the problem. Now, in the USA, flight simulation research had been carried out successfully at the United Technologies Research Center using a small secondary airstream to simulate flight and with the microphones placed in the ambient air outside the secondary jet[19]. Such data require to be corrected for the propagation of the sound through the shear layer of the secondary stream. Using the theory of Amiet[20] for this purpose, the results from UTRC tests on jet noise were shown to be in good agreement with the results from the 24 ft wind-tunnel. Since the acoustic facilities at NGTE could be modified to use this technique, and the limitations of the 24 ft wind-tunnel could thereby be overcome, it was decided to change our experimental approach and to develop the new technology required.

Before the technique could be applied with confidence, it was considered that two questions should be answered; what is the minimum size of airstream necessary to simulate the effect of flight on jet noise (because the provision of a large but quiet secondary flow is one of the main experimental difficulties of flight-simulation studies), and what are the limitations of the shear layer corrections?

To this end, the jet rig in the small anechoic chamber at NGTE was modified to the configuration shown in Figure 14 by the addition of the secondary flight-simulating stream. In this facility, which measures 5.2 m by 5.2 m by 4.6 m high, the jet axis is vertical and the jet exhausts through a hole in the chamber roof. Figure 15 illustrates the somewhat elephantine appearance of the rig and displays the traversing microphone boom prominently. From tests conducted over a range of subsonic jet velocities using unheated air, and at flight speeds up to 75 m/s, it was found that the two questions posed could be answered satisfactorily[21].

By testing with different primary nozzle sizes, and including data from other sources, the result shown in Figure 16 was constructed. This depicts the relative velocity index at $90^{\circ}$ as a function of the area ratio between the flight-simulating and primary airstreams. The angle of $90^{\circ}$ has special significance here since near this angle the shear layer refraction effects are negligible and uncorrected data can be used. From Figure 16, it can be seen that an area ratio of about 30 is required before the full noise reductions in flight are reached. It is believed that this is essentially an aerodynamic criterion, determined by the need for an adequate length of the primary jet to be immersed in the potential core of the secondary stream. Not surprisingly, therefore, a more detailed study of the spectra shows that the required area ratio is a function of the lowest frequency to be studied. A low frequency limit corresponding to a Strouhal number ($fD/V_j$) of 0.1 requires an area ratio of about 50 whereas if the limit can be raised to a Strouhal number of 0.3, as for example when jet noise data at only the higher angles are of interest, an area ratio of 20 will suffice.

An indication of the validity of the shear layer corrections is given by examining Figure 17 which presents rear arc data. Without any corrections, no asymptote is reached by the uncorrected data and the raw measurements are clearly inadequate at the lower area ratios. Corrections have been applied according to the theory of Amiet[20], who developed equations applying to a plane interface, and also according to that of Jacques[22], who examined the more realistic case of a cylindrical interface. It can be seen that the corrections for a cylindrical interface give generally better agreement with the wind-tunnel data and are adequate for correction provided that the secondary stream is large enough for aerodynamic simulation. But there is a tendency for the theory to over-correct the data at a low angle to the jet axis. In this region the corrections become large and vary rapidly with angle; such data should therefore be treated with suspicion. The corrections derived by Jacques have been used in all subsequent studies.

By mid-1975, shortly after the end of the second series of wind-tunnel tests, the main conclusions regarding the new flight-simulation technique were known and a short programme was undertaken[23] in the recently-commissioned anechoic chamber of the Noise Test Facility (NTF) at Pyestock to extend the flight data on jet noise using a rig similar in its general layout to that of Figure 14. The primary and secondary nozzle diameters were 86 mm and 483 mm respectively, giving an effective area ratio (in the plane of the primary jet exit) of 25. As is usual for this type of test, the microphones were placed a considerable distance away to ensure far-field measurements, in this case, about 130 primary nozzle diameters.

Flight speeds up to 105 m/s were used and the extent to which this increased the range of the data can be seen in Figure 18. These results are for unheated jets and the agreement with the prediction method, developed from the wind-tunnel results, is excellent. Jets heated to a temperature of 880 K were tested at velocities from 290 m/s to 530 m/s and, as Figure 19 shows, the agreement with the predictions was again remarkably good.

The work described in this section, a more detailed survey of which is given in Reference 24, established confidence in the new technique and laid the foundation stone for further research.

## 7. THE EFFECT OF FLIGHT ON INTERNAL NOISE

Having established that jet noise alone cannot explain the flight problem, the next logical step was to consider internally-generated noise, the only other source known to contribute to the low-frequency exhaust noise from engines. In the higher frequency parts of an engine spectrum, the compressor, fan or turbine noise from the engine can have a major influence, depending on the engine type and operating condition, and it is therefore only the low-frequency noise that is attributed unequivocally to exhaust noise. To study the internal noise radiation in a general sense would need considerable effort because of the complexities arising from the modal structure of the internal noise propagating down the jet-pipe. At low frequencies, however, around the frequency of the peak jet noise, the internal noise will propagate in the jet-pipe in plane waves and the amount of experimental data required can be much reduced.

The experiments[25] were carried out by siting a loudspeaker in the primary plenum chamber of the jet rig shown in Figures 14 and 15. The noise was measured over an arc from 30° to 130° to the jet axis, and, by narrow-band analysis, the polar field shapes of the internal noise tone could be separated from the total exhaust noise. It can be seen from the static data shown in Figure 20 that as the Mach number of the flow from the cold primary jet ($M_j$) is increased, the internal noise becomes more directional. Indeed, the shapes of these curves resemble those of jet noise at the same frequency.

Forward speed was then simulated using a secondary-to-primary area ratio of 170 which, being adequate for jet noise at this frequency, should more than suffice for internal noise radiating from the nozzle. Figure 20 shows some of the flight results after correcting the measurements for the effects of sound propagation through the secondary shear layer. The directivity of the internal noise is reduced slightly; the radiation in the rear arc being decreased and that in the forward arc increased with no effect at 90°.

Both the static and the flight results can be seen to be in excellent agreement with the theory of Munt[26] except at low angles to the jet axis where the shear layer corrections are known to be of doubtful accuracy.

In an attempt to correlate the static-to-flight changes in a simple manner for prediction purposes, the available data have been plotted, as in Figure 21, at constant flight Mach numbers. The results collapse reasonably well and can be represented (in decibels) by an aircraft Doppler-type term of the form

$$10 \log_{10} \left(1 + M_a \cos\theta\right)^{-6}$$

A term of this type but with an exponent of -4 has been suggested from theoretical considerations[27].

With this admittedly somewhat limited amount of data on the radiation of internal noise in flight, the flight problem for engines can now be re-assessed.

## 8. A REVIEW OF THE PROBLEM

If the experimentally-determined characteristics for jet and internal noise are introduced into an analysis of the sort shown in Figure 2, then the observed tendency for engine exhaust noise in the forward arc to increase in flight can be partly reconciled with the model results[28]. The discussion presented here centres around the example comparisons detailed in Figures 22, 23 and 24.

Because the proportions of jet and internal noise contributing to the exhaust noise from an engine are not known with any precision, it is useful to present the flight predictions for a range of relative levels. The predicted changes in exhaust noise have therefore been made a function of a parameter Z defined as the amount (in dB) by which the total OASPL measured statically at any angle exceeds the OASPL of the jet noise. As a consequence, Z represents the reduction in the total noise that would be measured statically if a perfect jet-pipe liner were to be installed. Clearly, where $Z = 0$, the prediction is for jet noise alone. For the engine data being discussed here, the actual values of Z are likely to lie in the region of 0.5 to 1.

In all the cases presented, the engine noise in flight has been measured from an aircraft flyover, while the static measurements have been made with the engine mounted on a test bed. It has been pointed out[29] that the measurement distances generally differ in these two types of tests and that, apart from the obvious inverse square law effects, corrections need to be applied because of the distributed nature of jet noise. Such corrections, calculated using an approximate procedure[30], can modify the measured results significantly.

The engine measurements in Figure 22, for the Viper 601 engine in the HS125 aircraft[2], are from tests at a jet velocity lower than that for the data in Figure 2. Both results are from an unlined engine. It is interesting to note that tests carried out with a jet pipe liner showed that the liner was distinctly more effective in flight than in static tests, particularly in the forward arc. One of the implications of this observation is that neither compressor nor airframe noise is dominating the engine noise in flight.

Figure 23 presents data from tests on a Jet Provost aircraft overflying the Severn Bridge[31]. These noise measurements are of unusually good quality.

Some results for a mixed engine of low by-pass ratio, the JT8D[29], are shown in Figure 24. While the results corrected for traverse distance effects are similar to the predictions with the inclusion of some internal noise, the greater the amount of internal noise present, the more the static-to-flight changes of the engine noise become better represented by the measured values. Nevertheless, it does seem that engines differ in their characteristics and that the collapse of the engine data in Figure 5 is coincidental.

From comparisons such as these, there appears to be a basis for explaining the aircraft flight measurements at low angles to the engine axis in the rear and forward arcs, but substantial discrepancies remain, and these are more pronounced on some engines than others. This conclusion represents the understanding of the flight problem as it existed at the end of 1975.

## 9. WHITHER NOW?

From the information available at this point in the narrative, it was by no means clear what the most fruitful line of research would be. The "obvious" areas for research had been covered but the gap between prediction and practice remained tantalisingly large.

Although a number of possibilities were being considered, and some exploratory testing conducted also, only one approach seemed at all attractive; to simplify the problem by trying to explain not the aircraft data but the characteristics of hot jets on the spinning rig at Rolls-Royce which are apparently similar to those of engines (see Figure 10). Perhaps hot turbulent jets, with internal noise present, could provide the answer. Certainly, there were a number of indications, from various theoretical and experimental sources, that this could be so.

It was therefore decided to test a copy of the standard tip unit of the spinning rig under simulated flight conditions[32]; once the spinning rig measurements could be reproduced in a static test facility it should then be possible to determine their cause.

Figure 25 shows a section through the rig that was constructed for this purpose. Because of the fire risk from the kerosene-burning combustor, it could not be tested in one of the anechoic chambers but it was found that an existing outdoor test site could be relatively easily modified to enable the rig to be run in an acoustically-acceptable environment (Figure 26). The jet operating conditions were related to those of the spinning rig and covered jet velocities up to 500 m/s and flight speeds up to 75 m/s.

Under static conditions, that is, with no secondary flow, the measured spectral levels exceeded those of pure jet noise as Figure 27 demonstrates. However, the spinning rig exhibits similar characteristics and it has been concluded[14] that, at low frequencies, a substantial amount of combustion-associated noise is present. An analysis of the spectral changes occurring in simulated flight showed that the behaviour at low frequencies was consistent with a combination of jet and internal noise, while the high-frequency noise behaved like jet noise. The resultant effect on the overall noise levels, shown in Figure 28, was for the reductions in flight to be rather less than those for jet noise.

This result is remarkable for its simplicity. A hot turbulent jet, with the addition of combustion-associated noise, may constitute a highly complex source, involving a number of different mechanisms but, even so, its behaviour in flight seems to be able to be described simply in terms of jet and internal noise.

But the important outcome from the point of view of explaining the flight problem was that, as Figure 28 shows, the simulation experiments did not reproduce the flight effects measured on the spinning rig. Since there was no sustainable reason to doubt the validity of the simulation technique, the simplest conclusion which could be drawn from this observation was that the spinning rig behaviour arose from the installation of the tip unit on the rig and not from the tip unit itself. Recall that the agreement which had been obtained with the HSA nozzle on the spinning rig and in the wind-tunnel (Figure 13) was obtained with the outboard section of the wing included in the simulation experiment.

Concurrently with this research, installation effects were being considered from another point of view. It is well known that installing an engine in an aircraft can result in the radiated noise being changed. In under-wing configurations, for example, the engine noise can be increased as a result of reflections from the wing and small allowances, of a few decibels, are commonly made in project calculations in order to allow for such effects. In research studies aimed at quantifying and understanding the effect of flight on engine noise, it is clearly desirable that engine noise measurements should not be complicated by installation effects and, for this reason, the noise measurements on the static engine are usually made with the bare engine mounted on a test bed while the flight measurements are made using an aircraft in which installation effects are expected to be negligible. In the UK, the research programmes on the HS125 and Jet Provost aircraft[2,31] are examples of this approach. But is it correct to assume that such configurations are indeed free from installation effects?

It was therefore decided early in 1976 to conduct an exploratory test using a model of the HS125 in conjunction with a hot subsonic jet. A simple model of the rear portion of the HS125 was constructed, at approximately 1/9 scale, using a half-section of the rear fuselage with the addition of flat plates to represent the fin and tailplane as shown in Figure 29. In order to obtain an accurate comparison between the noise levels with and without the model aircraft assembly present, the fuselage was mounted so that the entire assembly could be swung clear of the nozzle while the jet was running. To provide the jet for this experiment, a supply of air was heated in a hydrogen-burning combustor upstream of a nozzle of 38 mm diameter. It was known from previous tests on this particular arrangement that it radiates a substantial amount of internally-generated noise (in the form of a tone at a frequency of about 1.6 kHz) when used without the silencer which is normally installed downstream of the combustor. The silencer was omitted in this experiment in order to give an indication of the installation effects on internal as well as jet noise.

With the jet operated at a high subsonic velocity, 525 m/s, and a total temperature of 860 K (conditions similar to those for Figure 1), noise spectra measured in the small anechoic chamber are shown in Figure 30. The results were taken in the "flyover" plane at a constant polar distance from the nozzle. The largest changes occur in the forward arc of the jet where the internal noise tone increases by up to 12 dB. In the high-frequency part of the spectra above the internal tone and its harmonic, where it is believed that jet noise dominates, increases of about 2 dB can be seen. Ironically, the spectra at low angles to the jet axis do not show increases in noise clearly attributable to reflections from the underside of the tailplane, indeed, at 30° to the jet axis, some noise reductions are evident.

Such installation effects were, of course, unexpectedly large; indeed, the changes in the noise levels in the forward arc were clearly audible. To indicate the reason for the measured effects, follow-up tests were conducted using various components of the complete model, the fuselage, the fuselage and the fin, and the tailplane alone (supported from its upper surface). The fuselage alone had an effect peaking around 90° to the jet axis, increasing the internal noise about 3 dB and the jet noise about 1 dB. The fin was the principal cause of the effects evident up to $60^{\circ}$ to the jet axis in Figure 30 including the noise reductions at $30^{\circ}$. At higher angles, the major changes could be attributed to the presence of the tailplane. This point is illustrated in Figure 31 which shows the field shape of the internal tone in various circumstances. Because the tailplane is some 6 nozzle diameters from the jet axis and no jet/surface interaction effects would be expected at this distance, it is concluded that the principal installation effect arises from the scattering of noise by the tailplane. On this basis, the distortion evident in the field shape of the internal tone at $90^{\circ}$ to the jet axis (Figure 31) can be explained by interference effects between the direct noise signal and that scattered from the tailplane. And, bearing in mind the distributed nature of jet noise, this scattering hypothesis can also explain why the installation effects are stronger on internal noise than on jet noise.

Similar tests, using the same jet operated at a slightly lower velocity, were conducted with a model of the rear fuselage of the Jet Provost aircraft and with the jet in an under-wing configuration.

The installation effects on the Jet Provost model were much less than those from the HS125 model; the internal tone showed increases up to about 4 dB in the forward arc but the jet noise changes were less than 1 dB. It is thought that these effects can be attributed to scattering, and possibly jet/surface interaction noise, arising from the fuselage cowl which extends beyond the exit plane of the nozzle.

In tests with the jet in an under-wing position, representing the core engine exhaust from a high by-pass ratio engine, increases up to 7 dB in the internal tone and 2 dB in the jet noise were measured. In addition, a hump appeared in the spectra at very low frequencies and, because the wing was relatively close to the jet axis (3.3 nozzle diameters) and extended well downstream of it (7.7 nozzle diameters), this has been attributed to an interaction between the jet and the wing surface or trailing edge.

As a result of these preliminary tests on various installations, it was clear that here was an approach which might lead to an explanation of the flight problem. But some shortcomings in the results so far were apparent. Firstly, because parts of the models were more than 0.5 m from the nozzle exit and the microphone traverse distance was only 2 m, the measured changes would not necessarily represent accurately those which would be measured in the far field.

Secondly, it is the installation effects in flight which are relevant to the problem and so far only static data had been obtained. Furthermore, it was recognised that scattering from adjacent surfaces could not explain the spinning rig results. Low-frequency internal noise radiates strongly in the downstream direction, like jet noise, and consequently scattering bodies positioned downstream of the jet exit can produce large increases in the forward arc noise. The wing of the spinning rig is, however, entirely upstream of the jet exit plane and the scattered signal would therefore be expected to be of negligible strength.

## 10. INSTALLATION EFFECTS IN FLIGHT

In the autumn of 1976 the small anechoic chamber was closed down and all subsequent research has been carried out in the anechoic chamber of the NTF[33,34]. This large facility, illustrated in Figure 32 is 26 m square and 14 m high and is lined throughout with fibre-glass wedges that render it anechoic down to frequencies of about 90 Hz. The noise measurements are made in a horizontal plane at a distance, in the tests to be described, varying from 3.6 m at $30^{\circ}$ to the jet axis to 7.2 m at $135^{\circ}$. The jet rig used for installation tests in the facility is shown diagrammatically in Figure 33. This consists essentially of a two-stream silencer and the diameter of the flight-simulating nozzle is 530 mm. Given the need to keep the test model well within the potential core of the secondary flow, this size determines the diameter of the primary jet. Flight simulation tests were first carried out on models relating to the HS125, the Jet Provost and the spinning rig, and primary nozzles from 12 mm to 32 mm diameter were used. The noise measurement distances, varying from 100 to 600 primary nozzle diameters, were considered to be acceptable. Because the capability to heat the flow for such small nozzles was not then available, the tests were conducted with cold jets. But this limitation did mean that internal noise could be introduced into the primary system simply by installing a loudspeaker in the primary plenum chamber.

Once again, the developing requirements of the research were stretching the available experimental capabilities and new problems arose. The need for such small nozzles gave rise to difficulties in reproducing the noise characteristics obtained with larger jets, both statically and in flight. The static problems were resolved by controlling the jet-pipe/nozzle contraction ratio but the full noise reductions in flight were not attained. For example, the relative velocity index at $90^{\circ}$ for the smallest nozzle was 4.0 compared with 5.4. This is believed to be a result of the relatively large external boundary layer and further studies of the effect are in progress. Difficulties were also experienced with obtaining an adequate noise output from the loud-speaker; only with tones could sufficiently high noise levels be obtained and then only in a frequency range from 1 kHz to 4 kHz compared with a frequency as high as 15 kHz for the peak jet noise.

In order to study the scattering mechanism further, an aerofoil was mounted, as shown in Figure 34, five nozzle diameters to the side of the jet at a series of positions both upstream and downstream of the jet. In the most downstream of these positions, the aerofoil corresponded approximately to the tailplane of the HS125 aircraft. Only this configuration will be discussed here since, as expected, the installation effects reduced progressively as the aerofoil was moved into the forward arc of the jet. A summary of the results obtained is shown in Figure 35 in terms of the changes in the jet and internal noise which occur, statically and in flight, as a result of the presence of the downstream aerofoil. Because of phase cancellation and reinforcement of the internal noise tone when the model is present, the changes in the internal noise vary markedly with the tone frequency but the magnitudes of the effects are indicated by plotting the spread of the results obtained from tests carried out at seven frequencies. Statically, the observed installation effects are qualitatively similar to those measured earlier (Figure 30). The magnitudes of the changes are, of course, reduced because the lower jet velocity of 300 m/s used here reduces the source directionality. At a flight speed of 60 m/s, the fully-corrected data* of Figure 35 indicate that only slight reductions occur. The scattering mechanism is therefore undoubtedly important in such engine installations.

A model of the rear fuselage of the Jet Provost aircraft was tested in a similar manner. The photograph of the model reproduced as Figure 36 shows that the fin is the only component not accurately scaled. The test results are presented in Figure 37 in the same style as before. The installation effects measured statically are again qualitatively consistent with the earlier measurements but it is notable that, in flight, the jet noise is significantly

---

*In these, and all subsequent tests, the measured spectra have been corrected for shear-layer propagation effects, the noise produced by the secondary jet and the self-noise of the test model before calculating the OASPLs under flight conditions.

increased by the presence of the model. This suggests the presence of another phenomenon. Tests conducted on models of the spinning rig installation shed further light on this observation.

The spinning rig was modelled in the form shown diagrammatically in Figure 38, the so-called "extended nozzle" version. This configuration had been tested on the spinning rig, with the assistance of Rolls-Royce, and exhibited forward arc lifts even with unheated subsonic jets. With the addition of the wing alone, that is, without the drag plates, no installation effects were seen in the NTF simulation tests, either statically or in flight. This is, of course, as would be expected. But when the drag plates were attached, the results in Figure 39 were obtained. The lack of any effect on the internal noise is consistent with the expected absence of scattering effects but there is a distinct installation effect on the jet noise. Further tests conducted with flat plates positioned upstream of the nozzle indicated that the phenomenon arose from an interaction between the wake from the bluff plate and the jet; the distance of the plate from the jet axis was found to have a strong influence on the magnitude of the effect. It appears likely that the mechanism involves the excitation of the jet by turbulence in the external flow in a manner analogous to jet excitation by internal noise[35,36].

Since no installation effects, aerodynamic or otherwise, were measured with the zero-incidence wing, the spinning rig results with the drag plates retracted (the minimum drag configuration) are compared in Figure 40 with the usual predictions for a combination of jet and internal noise. The measured changes are similar to the predicted line for Z=1 which corresponds to a plausible level of internal noise for this rig operating condition. In the maximum drag configuration, NTF data of the type shown in Figure 39 have been interpolated to estimate the aerodynamic installation effect on the jet noise and the resulting predictions are compared with the measured data in Figure 41. The Z=1 line would still be expected to apply (since the jet operating condition has remained constant) and it can be seen that discrepancies of only 1 or 2 dB exist. A full discussion of this result is beyond the scope of this paper; it will suffice here to conclude that a passable agreement has been obtained. Note from Figures 40 and 41 that although the minimum and maximum drag configurations of the rig give qualitatively similar noise characteristics, their explanations are essentially different, the minimum drag result being influenced strongly by the presence of internal noise and the maximum drag result being dominated by the installed jet noise.

Returning now to the engine-related data, it appears likely that the explanation for the installation effect on the jet noise from the Jet Provost model, seen in Figure 37, is the aerodynamic installation effect found from the spinning rig simulations. The exhaust nozzle of the engine is recessed inside a fuselage cowl of larger diameter (see Figure 36) and it is not difficult to imagine that the turbulent flow between the jet and the cowl, perhaps with the additional turbulence from the external fuselage boundary layer, could be sufficient to excite the jet. It can therefore be said that acoustic scattering effects are exemplified in Figure 35, aerodynamic installation effects in Figure 39, and that the Jet Provost behaviour in Figure 37 probably results from a combination of the two mechanisms.

The data acquired on installation effects in the above work are for unheated jets only. Recently, some hot jet tests, using improved model designs, have been completed and the analysis is proceeding. The indications so far are that jet temperature does not have a first order effect on the results presented here and hence some comparisons with engine data can now be attempted, albeit somewhat cautiously.

## 11. THE CURRENT POSITION

In Figure 22 a comparison between the measured and predicted changes in flight, without installation effects, has been presented. The jet and flight speeds for this HS125 data ($V_j$ = 375 m/s, $V_a$ = 82 m/s) are not grossly dissimilar from those used to obtain the installation effects data shown in Figure 35 ($V_j$ = 300 m/s, $V_a$ = 60 m/s) and hence the measured values, the mean values of the spread of the data in the case of internal noise, can be taken as a first estimate. With these increases in the jet and internal noise included in the predictions, the comparison with the measured engine result becomes that shown in Figure 42. Clearly there is a considerable improvement and the Z=1 line, corresponding to a likely level of internal noise, is a good fit at shallow angles. Moreover, the installation effects included here are only those from the tailplane, and it will be recalled from Section 9 that the presence of the fuselage introduced additional effects at angles around 90°. It can therefore be concluded that a tentative explanation for the behaviour of the HS125 aircraft data in flight has been formulated. Further support for this conclusion is gained from the fact, mentioned in Section 8, that an exhaust system liner installed in the engine was found to be much more effective in flight than statically. The mechanism of tailplane scattering can now be seen as an explanation of this phenomenon.

Taking a similar approach for the Jet Provost data in Figure 23, using the installation effects in flight from Figure 37, gives the comparison between measured and predicted changes shown in Figure 43. Again, there is a marked improvement in the prediction. In this case, the aerodynamic installation effect on the jet noise makes a significant contribution.

These two comparisons reveal a remarkable level of agreement between the NTF simulation tests and the full-scale aircraft. However, it must be borne in mind that certain doubts remain over the accuracy of the model data presented. Thus it would not be prudent to conclude at this stage that the inclusion of aerodynamic and acoustic installation effects into the current predictions for jet and internal noise is all that is needed to predict the static-to-flight changes of engine exhaust noise. It is, however, certainly clear that there is little hope of obtaining generally successful predictions unless installation effects are included.

Having obtained some measure of agreement for turbo-jet engines, it is important to consider the relevance of these developments to by-pass engines. Because such engines originally appeared to behave in the same manner as turbo-jets (Figure 5), it is tempting to conclude that the same mechanisms are responsible to a similar degree. However, for unmixed engines of high by-pass ratio in particular, the presence of the by-pass flow surrounding the primary jet might have a significant influence on the directivity of internal noise from the core engine and hence change any scattering effects. And clearly the response of a coaxial jet to external turbulence in flight will differ from that on the primary jet alone. On present evidence it is clear that the collapse of the engine data in Figure 5 is coincidental and that the resolution of by-pass engine characteristics must await further research.

## 12. COMMENTS REGARDING FUTURE RESEARCH

The technique which has been employed for the simulation of internal noise has been considered further and as a consequence a different approach is now developing. The original technique was to inject tones from a loudspeaker at a sufficiently high level to enable them to be distinguished from the broad-band jet noise. In research on installation effects, the use of tones gives rise to phase interference effects but it can be shown theoretically that such effects could be quantified simply by installing a reference microphone near the nozzle exit in order to extract phase information from the normal noise measurements. There are, however, more fundamental reasons which render this approach unsatisfactory.

Firstly, from the practical point of view, difficulties can be experienced in obtaining a sufficiently high noise level and also the acquisition of data over a wide frequency range is time-consuming. The second reason is the inability of the technique to simulate correctly jet excitation by internal noise[35,36]. Only if the internal noise is similar spectrally to that in engines will data relevant to engine be obtained. Finally, it has been found that the correct internal noise intensities should be simulated because of non-linear effects. The particularly high harmonic distortion of the tone evident at 30° to the jet axis in Figure 30 is a consequence of non-linear propagation and it is believed that the same effects are evident in high-velocity jet noise.

It is clear that to progress usefully from the present position, the simulation techniques used to date must increase in complexity. Not only do the internal noise simulations require to be improved as just described, but the need to carry out unmixed by-pass engine simulations in flight at the same time has been mentioned earlier. Furthermore, the test models require to be more accurate and complete, not only for the purposes described in this paper, but also to enable studies to be made of jet/flap interaction noise[37] which constitutes yet another engine installation effect which has been identified.

Finally, mention should be made of cross-flow effects which arise from the external flow relative to the nozzle not being aligned with the jet axis. Preliminary tests, carried out with an angle of 10° between the axis of a hot single-stream jet and the flight stream, have shown that the jet noise can change by 1 or 2 dB at typical flight conditions. Usually the noise is increased but instances of reduced noise in the forward arc have been found. Such effects may be important in certain engine installations, delta-winged aircraft for example, in which the cross-flow angles can be particularly high.

## 13. CONCLUDING REMARKS

In this review of research work carried out at NGTE, an attempt has been made to present a coherent picture of the manner in which the current position has been reached. As it happens, the progress which has been made can be described without major diversions to present the work of other researchers in the field. There is no intention to belittle such work, it is rather that a comprehensive summary of all contributions to the problem under study would be beyond the scope of this paper. Furthermore, the false starts and blind alleys which occurred along the way have been omitted from the account, and these must be balanced against any appearance of unusual perspicacity in the manner of the narrative.

The problem posed by the static-to-flight changes in engine exhaust noise has been such that many new developments have taken place over a relatively short period of time and a range of experimental facilities and analytical procedures have been involved. Now that the essential features explaining the engine characteristics are becoming clear, it is likely that less transient programmes can be defined.

In the situation as it existed a few years ago, when the mechanisms dominating engine exhaust noise in flight were totally unknown, it could have been said that this constituted the last-remaining major mystery in understanding the general behaviour of aero-engines. Although much work remains to be done, it is now considered that the mystery remains no longer.

Acknowledgements

The author wishes to express his thanks to the many colleagues at Pyestock who have been responsible for carrying out the bulk of the research work described in this paper. And the helpful co-operation of the staff of Rolls-Royce and the Royal Aircraft Establishment during the use of their test facilities is gratefully acknowledged.

## REFERENCES


| No. | Author(s) | Title, etc |
|---|---|---|
| 1 | K. W. Bushell | Measurement and prediction of jet noise in flight<br>AIAA Paper No. 75-461<br>Second Aero-Acoustics Conference<br>Hampton, Va, USA<br>March 1975 |
| 2 | J. R. Brooks<br>R. J. Woodrow | The effects of forward speed on a number of turbo-jet exhaust silencers<br>AIAA Paper No. 75-506<br>Second Aero-Acoustics Conference<br>Hampton, Va, USA<br>March 1975 |
| 3 | M. J. Lighthill | On sound generated aerodynamically<br>Part 1: General theory<br>Proc Roy Soc, A211, 564-587<br>1952 |
| 4 | H. S. Ribner | The generation of sound by turbulent jets<br>Advances in Applied Mechanics, Vol. 8<br>1964 |
| 5 | J. E. Ffowcs Williams | The noise from turbulence convected at high speed<br>Phil Trans Roy Soc, Vol. 255, No. 1061, 469-503<br>April 1963 |
| 6 | B. J. Cocking<br>W. D. Bryce | An investigation of the noise of cold air jets under simulated flight conditions<br>NGTE Report No. R.334<br>September 1974 |

REFERENCES (cont'd)

| No. | Author(s) | Title, etc |
|---|---|---|
| 7 | B. J. Cocking<br>W. D. Bryce | Subsonic jet noise in flight based on some recent wind-tunnel tests<br>AIAA Paper No. 75-462<br>Second Aero-Acoustics Conference<br>Hampton, Va, USA<br>March 1975 |
| 8 | R. S. Larson<br>C. J. McColgan<br>A. B. Packman | Jet noise source modification due to forward flight<br>AIAA Paper No. 77-58<br>Fifteenth Aerospace Sciences Meeting<br>Los Angeles, Calif, USA<br>January 1977 |
| 9 | B. J. Cocking | The effect of temperature on subsonic jet noise<br>NGTE Report No. R.331<br>May 1974 |
| 10 | R. G. Hoch<br>J. P. Duponchel<br>B. J. Cocking<br>W. D. Bryce | Studies of the influence of density on jet noise<br>J Sound and Vib, Vol. 28, No. 4, 649-668<br>1973 |
| 11 | B. J. Cocking | The effect of flight on the noise of subsonic jets<br>NGTE Report No. R.343<br>October 1976<br>Also:<br>AIAA Paper No. 76-555<br>Third Aero-Acoustics Conference<br>Palo Alto, Calif, USA<br>July 1976 |
| 12 | B. J. Cocking | A prediction method for the effects of flight on subsonic jet noise<br>J Sound and Vib, Vol. 53, No. 3, 435-453<br>1977 |

## REFERENCES (cont'd)

| No. | Author(s) | Title, etc |
|---|---|---|
| 13 | W. Smith | The use of a rotating arm facility to study flight effects on jet noise<br>Paper presented at the Second International Symposium on Air Breathing Engines<br>Sheffield University<br>March 1974 |
| 14 | D. J. Way | An assessment of the noise from heated and unheated jets measured on the Rolls-Royce spinning rig<br>NGTE Internal Report<br>October 1976 |
| 15 | D. J. Way | An assessment of the noise from the 'HSA' tip jet unit installed in the RAE 24 ft wind-tunnel<br>NGTE Internal Report<br>June 1976 |
| 16 | D. J. Way | An assessment of the noise from the 'HSA' tip jet unit installed on the Rolls-Royce spinning rig<br>NGTE Internal Report<br>June 1976 |
| 17 | - | Jet exhaust noise prediction<br>Draft revision proposed to AIR 876<br>Society of Automotive Engineers<br>April 1976 |
| 18 | D. J. Way | A comparison of the effects of flight on the noise from a cold air jet (the 'HSA' nozzle) using two alternative techniques for flight simulation<br>NGTE Internal Report<br>August 1977 |

## REFERENCES (cont'd)


| No. | Author(s) | Title, etc |
|---|---|---|
| 19 | A. B. Packman<br>K. W. Ng<br>R. W. Paterson | Effect of simulated forward flight on subsonic jet exhaust noise<br>AIAA Paper No. 75-869<br>Eighth Fluid and Plasma Dynamics Conference<br>Hartford, Conn, USA<br>June 1975 |
| 20 | R. K. Amiet | Correction of open-jet wind-tunnel measurements for shear layer refraction<br>AIAA Paper No. 75-532<br>Second Aero-Acoustics Conference<br>Hampton, Va, USA<br>March 1975 |
| 21 | D. J. Way<br>B. J. Cocking | The use of co-flowing airstreams for the simulation of flight effects on jet noise<br>NGTE Report No. R.345<br>June 1977 |
| 22 | J. R. Jacques | The noise from the moving aircraft; some relevant models<br>PhD Thesis, Cambridge University<br>August 1975 |
| 23 | D. J. Way<br>E. M. Francis | An assessment of subsonic jet noise using a co-flowing stream to simulate flight<br>NGTE Internal Report<br>April 1977 |
| 24 | D. J. Way | The simulation of flight effects on jet noise using co-flowing airstreams<br>AIAA Paper No. 77-1305<br>Fourth Aero-Acoustics Conference<br>Atlanta, Ga, USA<br>October 1977 |

REFERENCES (cont'd)

| No. | Author(s) | Title, etc |
|---|---|---|
| 25 | R. A. Pinker<br>W. D. Bryce | The radiation of plane-wave duct noise from a jet exhaust, statically and in flight<br>AIAA Paper No. 76-581<br>Third Aero-Acoustics Conference<br>Palo Alto, Calif, USA<br>July 1976 |
| 26 | R. M. Munt | The interaction of sound with a subsonic jet issuing from a semi-infinite cylindrical pipe<br>Jour of Fluid Mechanics, Vol. 83, Part 4, 609-640<br>1977 |
| 27 | J. R. Stone | On the effects of flight on jet engine exhaust noise<br>NASA TMX-71819<br>November 1975 |
| 28 | W. D. Bryce | Comparisons of measured and predicted effects of flight on engine exhaust noise<br>NGTE Internal Report<br>May 1976 |
| 29 | S. J. Cowan | Unpublished work at Boeing Commercial Airplane Company<br>December 1975 |
| 30 | E. M. Francis | Corrections required to jet noise measurements to obtain true far-field levels<br>NGTE Internal Report<br>December 1976 |
| 31 | J. R. Brooks | Flight noise studies on a turbo-jet using microphones mounted on a 450 ft tower<br>AIAA Paper No. 77-1325<br>Fourth Aero-Acoustics Conference<br>Atlanta, Ga, USA<br>October 1977 |

REFERENCES (cont'd)


| No. | Author(s) | Title, etc |
|---|---|---|
| 32 | R. A. Pinker<br>I. M. Casey | Concerning the effects of flight on the noise from a combustor/nozzle combination<br>NGTE Internal Report<br>May 1978 |
| 33 | D. L. Martlew<br>J. M. Hawkins<br>R. L. Brooking<br>A. S. Kennedy | The design, construction and operation of the noise test facility at the National Gas Turbine Establishment<br>The Aeronautical Journal of the Royal Aeronautical Society<br>January 1976 |
| 34 | F. W. Armstrong | Recent developments in noise research at NGTE<br>Ninth ICAS Conference<br>Haifa, Israel<br>August 1974 |
| 35 | D. Bechert<br>E. Pfizenmaier | On the amplification of broadband jet noise by a pure tone excitation<br>J Sound and Vib, Vol. 43, No. 3, 581-587<br>1975 |
| 36 | C. J. Moore | The role of shear-layer instability waves in jet exhaust noise<br>J Fluid Mech, Vol. 80, Part 2, 321-367<br>1977 |
| 37 | J. K. C. Low | Effects of forward motion on jet and core noise<br>AIAA Paper No. 77-1330<br>Fourth AIAA Aero-Acoustics Conference<br>Atlanta, Ga, USA<br>October 1977 |
| 38 | W. Olsen<br>R. Friedman | Jet noise from coaxial nozzles over a wide range of geometries and flow parameters<br>AIAA Paper No. 74-93<br>January 1974 |


REPORTS QUOTED ARE NOT NECESSARILY
AVAILABLE TO MEMBERS OF THE PUBLIC
OR TO COMMERCIAL ORGANISATIONS

124081

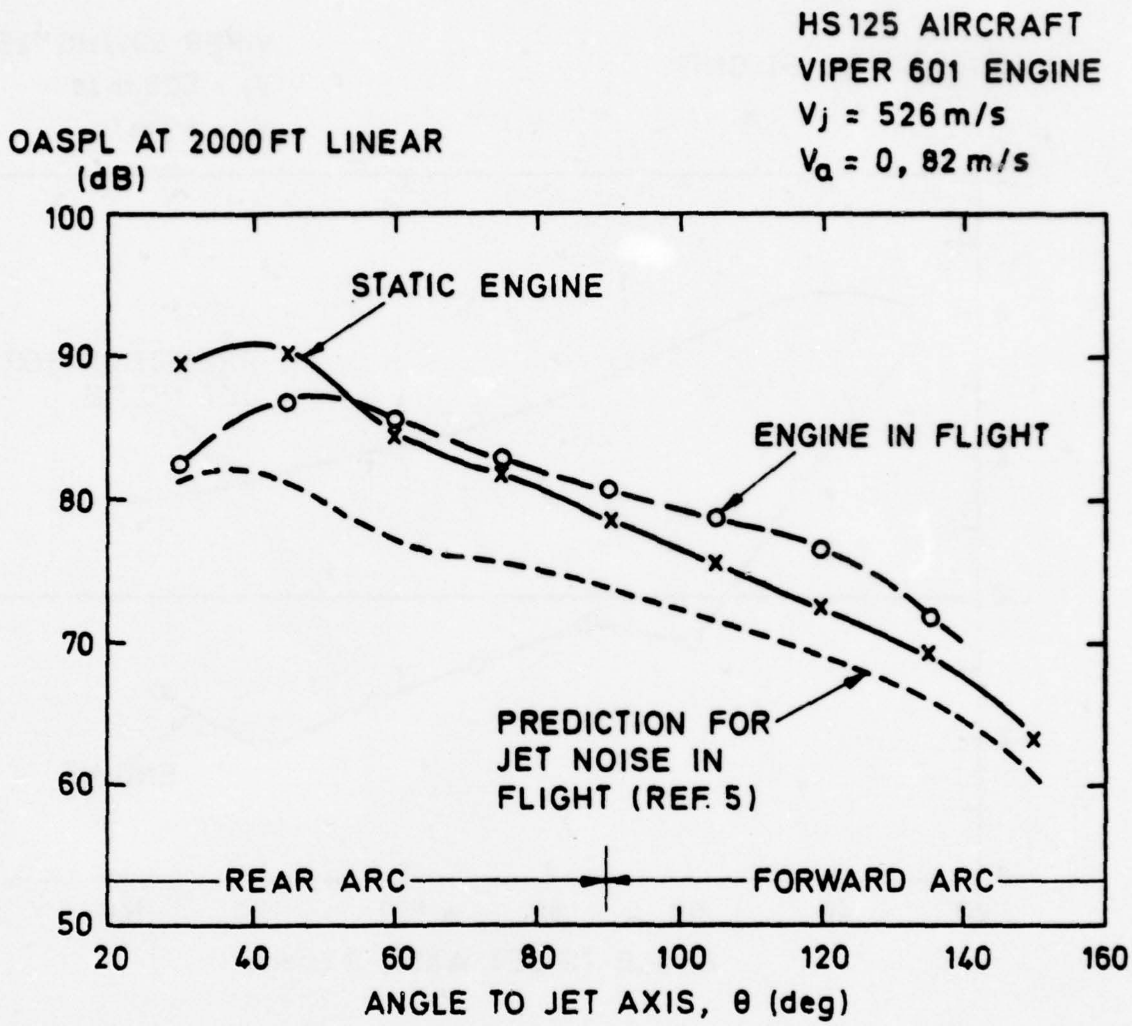



FIG. 1 ENGINE EXHAUST NOISE, STATICALLY AND IN FLIGHT

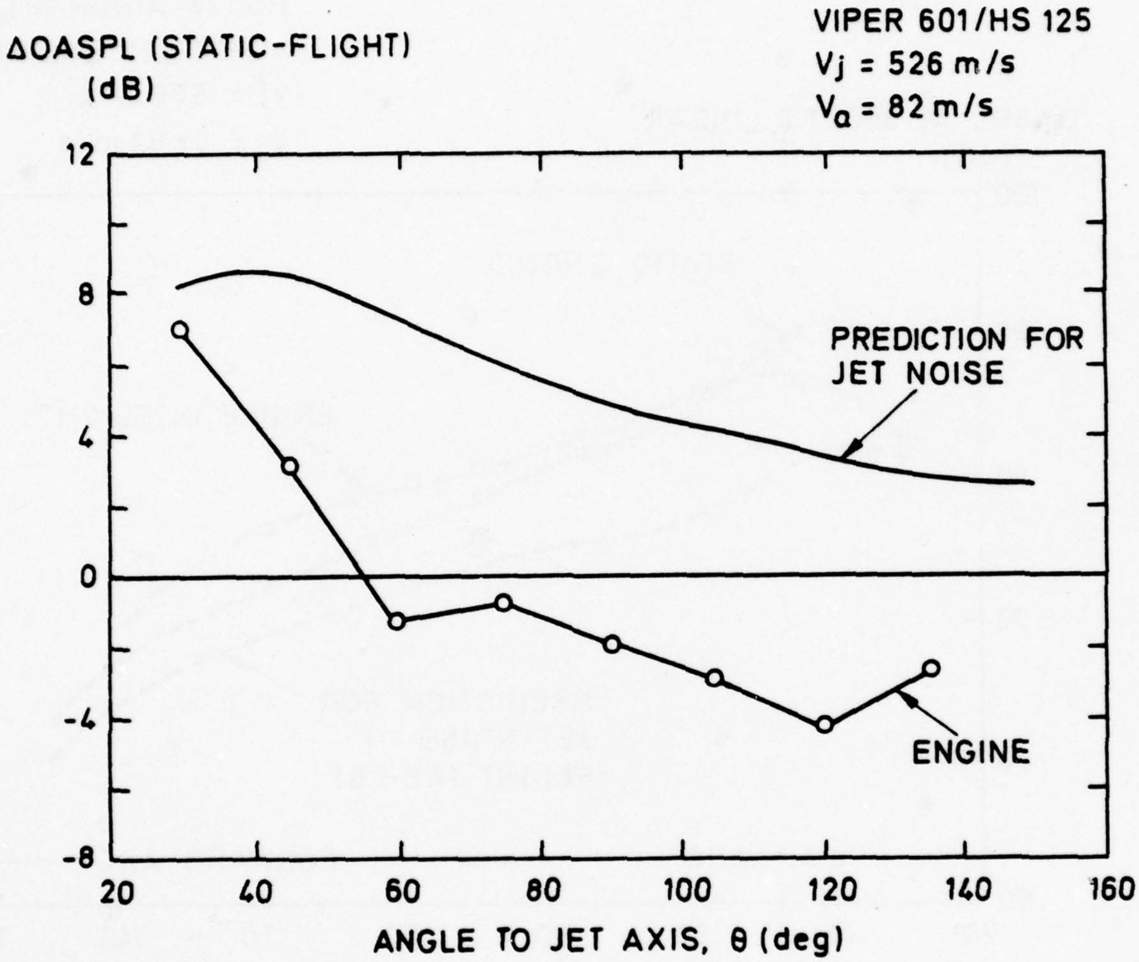



FIG. 2 CHANGES OF EXHAUST NOISE IN FLIGHT

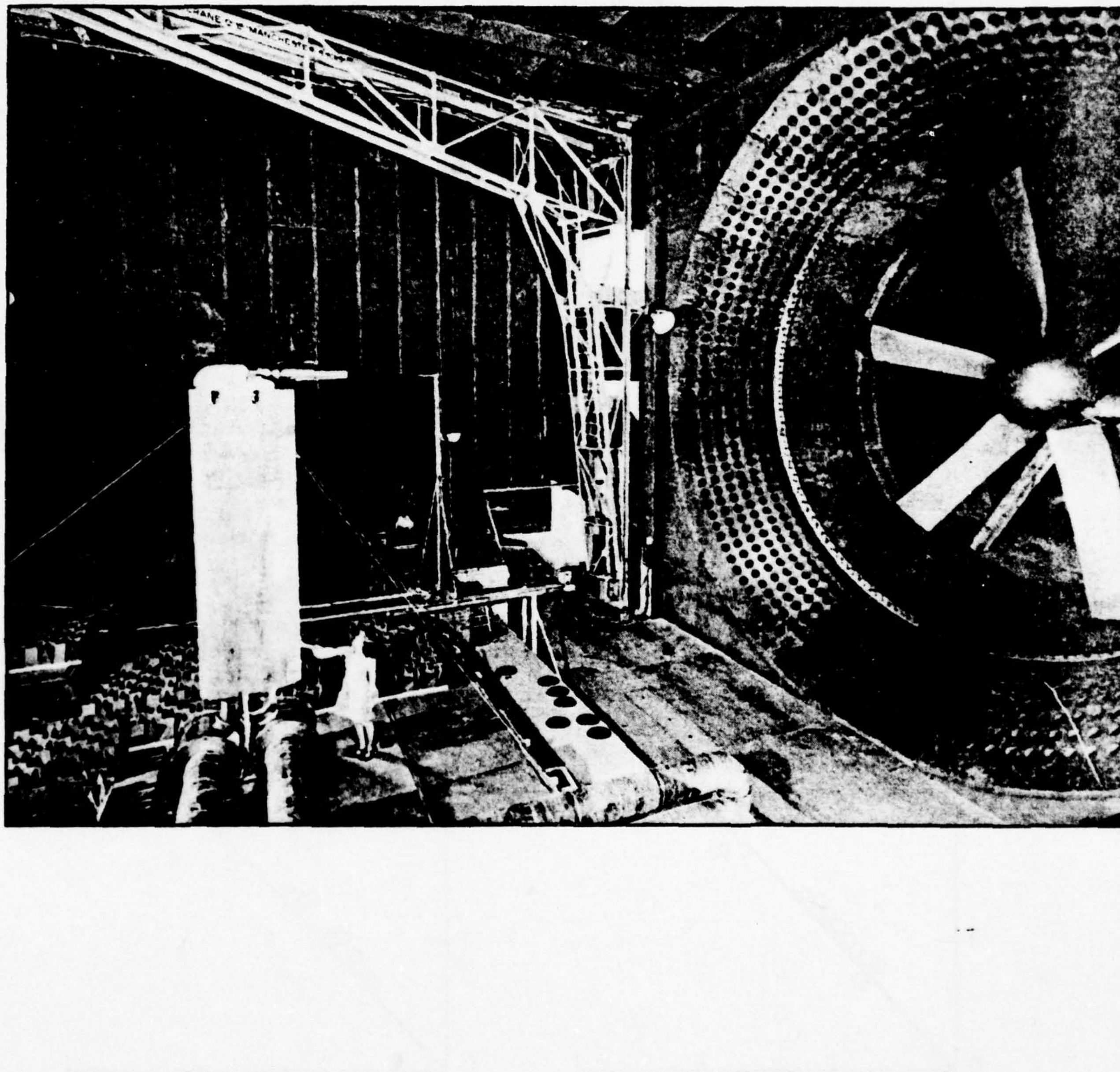


FIG.3 A JET RIG INSTALLED IN THE RAE WIND-TUNNEL (1973)

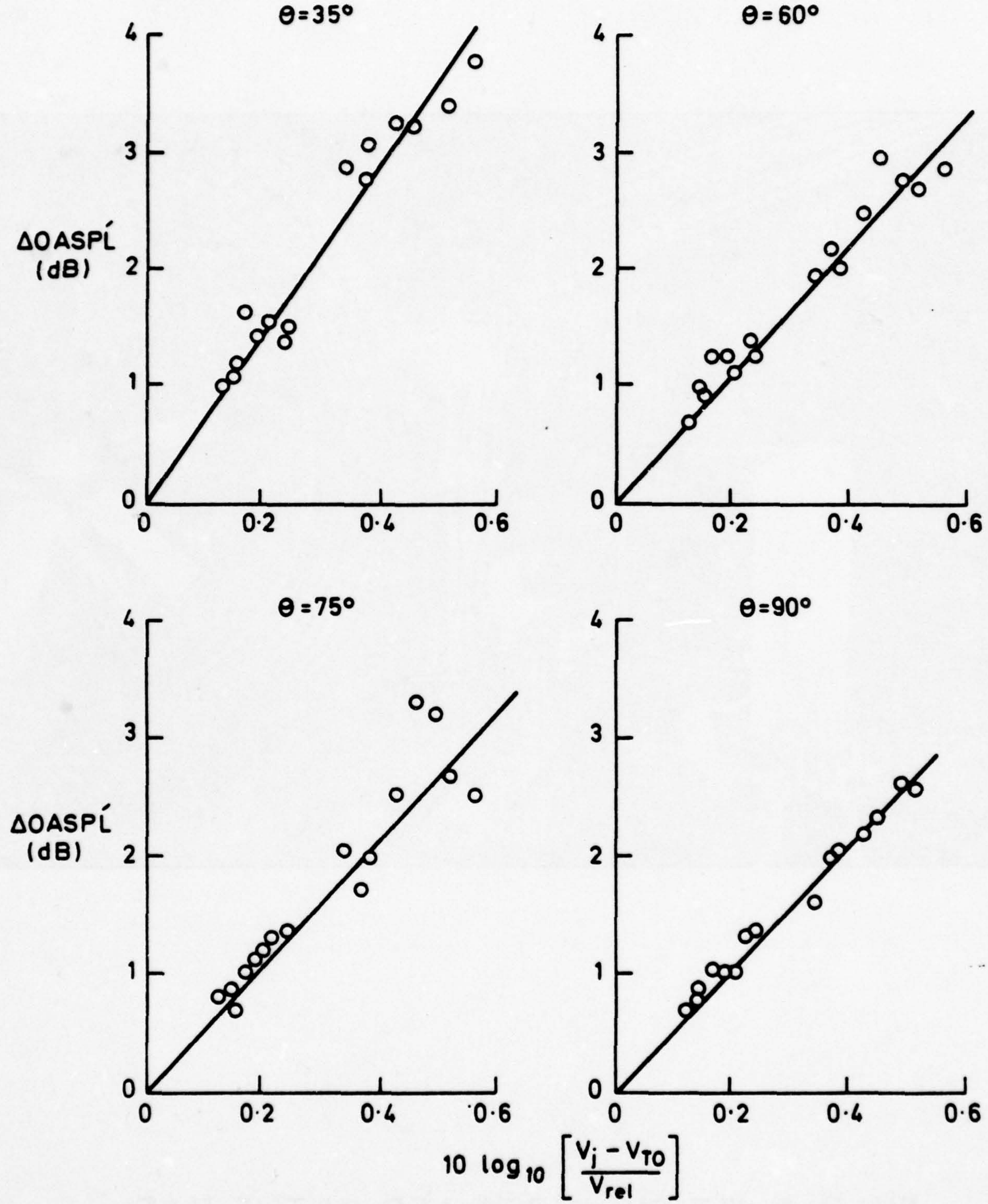



FIG. 4 NOISE REDUCTIONS IN FLIGHT FOR A COLD JET

124084

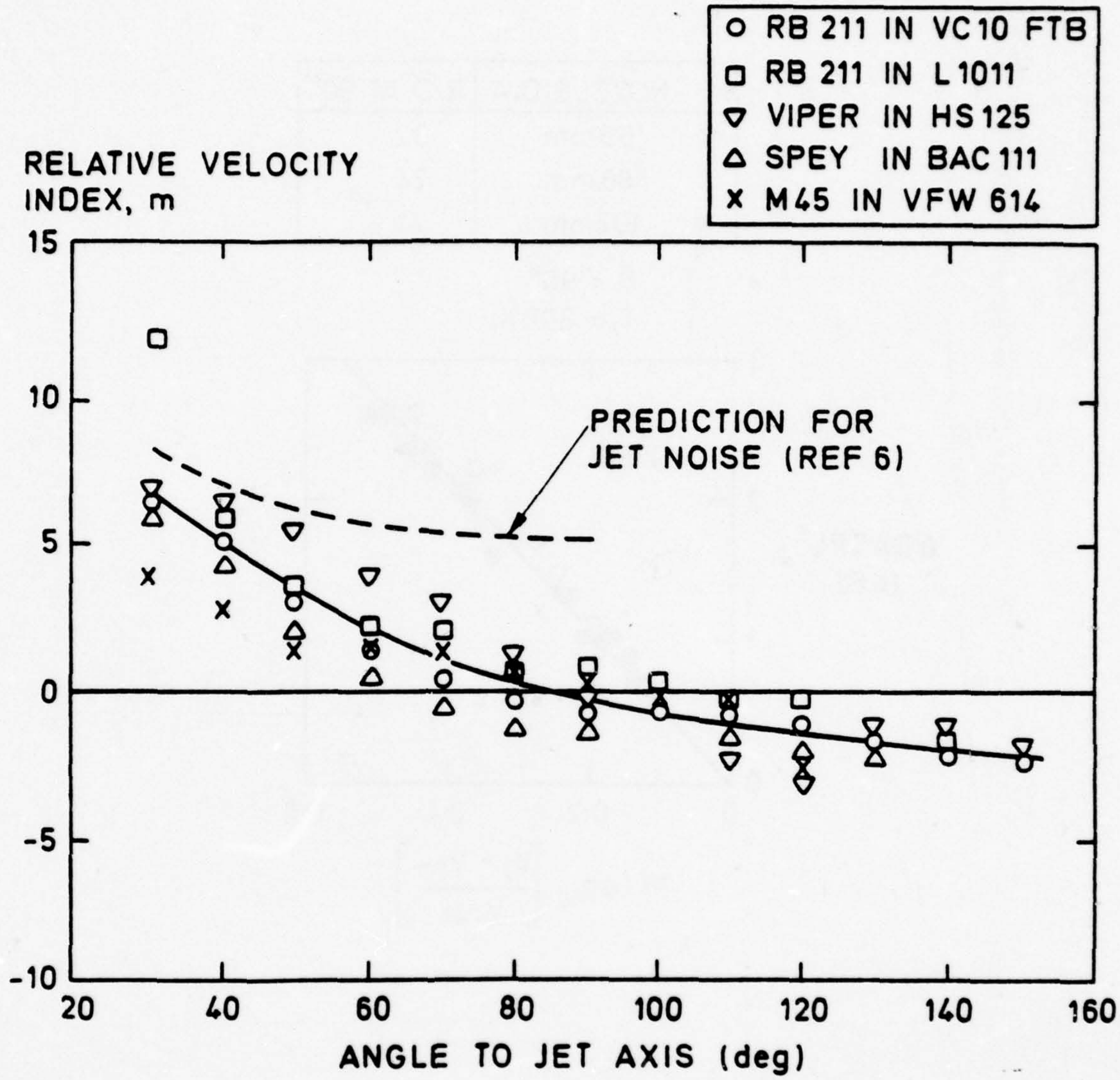



FIG. 5 A CORRELATION OF ENGINE DATA (AFTER BUSHELL, 1975)

| | NOZZLE DIA | R/D AT 90° |
|---|---|---|
| o | 65mm | 32 |
| x | 88mm | 24 |
| ● | 102mm | 21 |

$\theta = 90°$
$T_j = 300K$

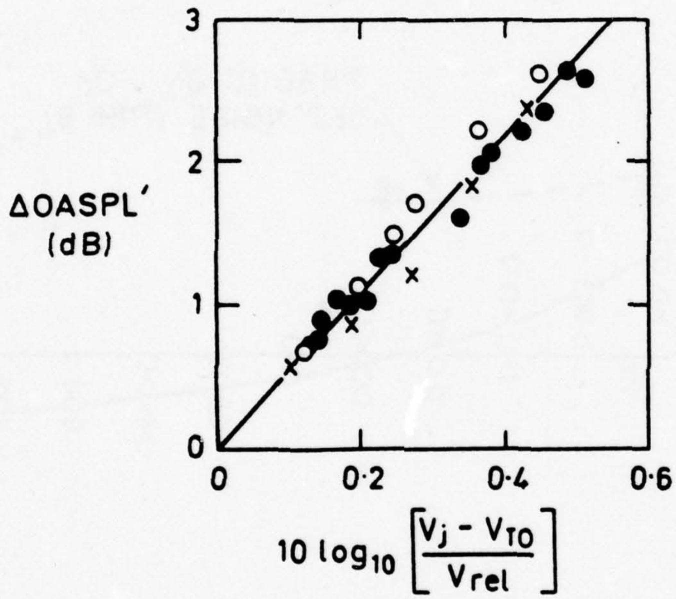



FIG. 6 JET NOISE REDUCTIONS IN FLIGHT FOR VARIOUS NOZZLE SIZES

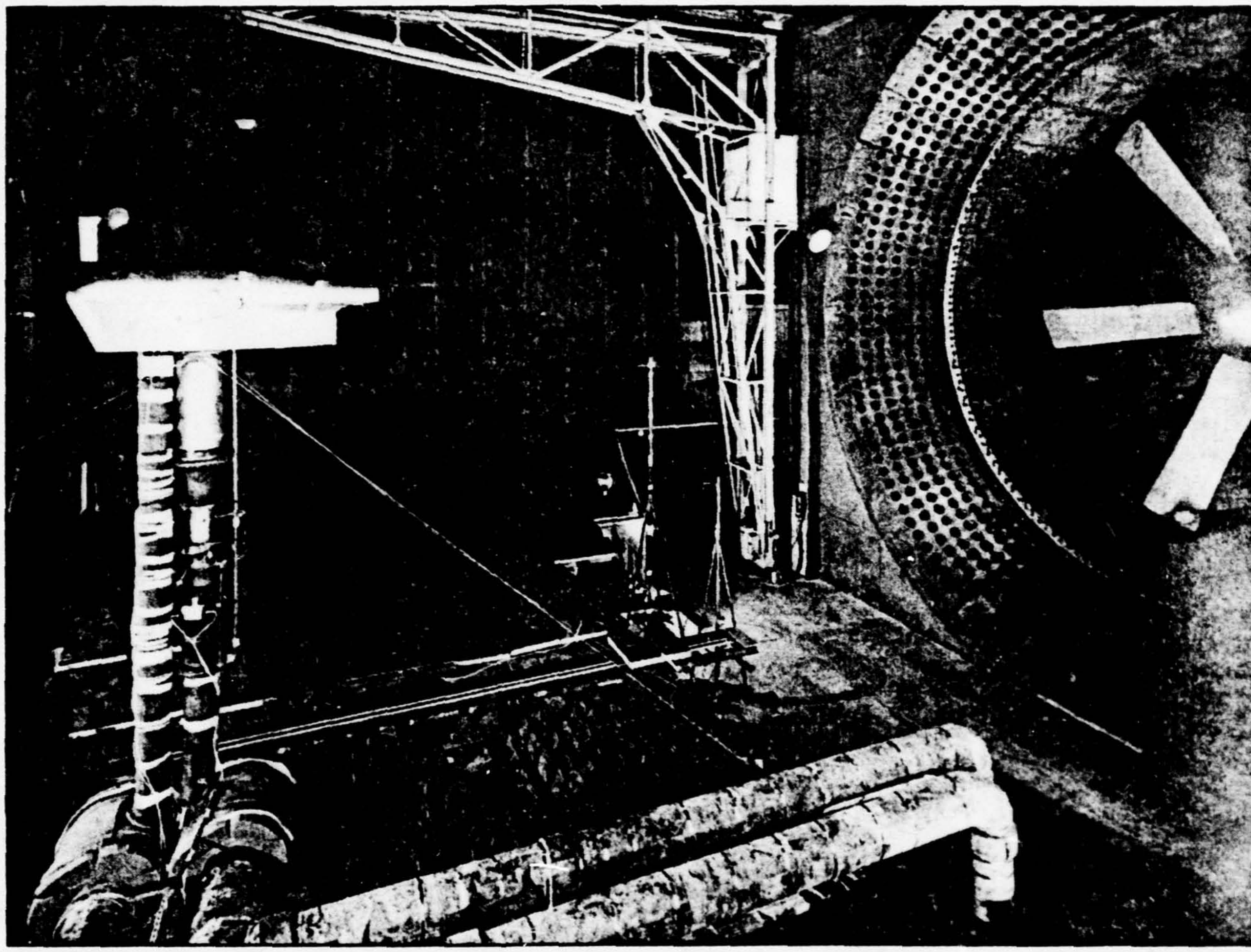


FIG.7 A HEATED JET INSTALLATION IN THE RAE WIND-TUNNEL (1975)

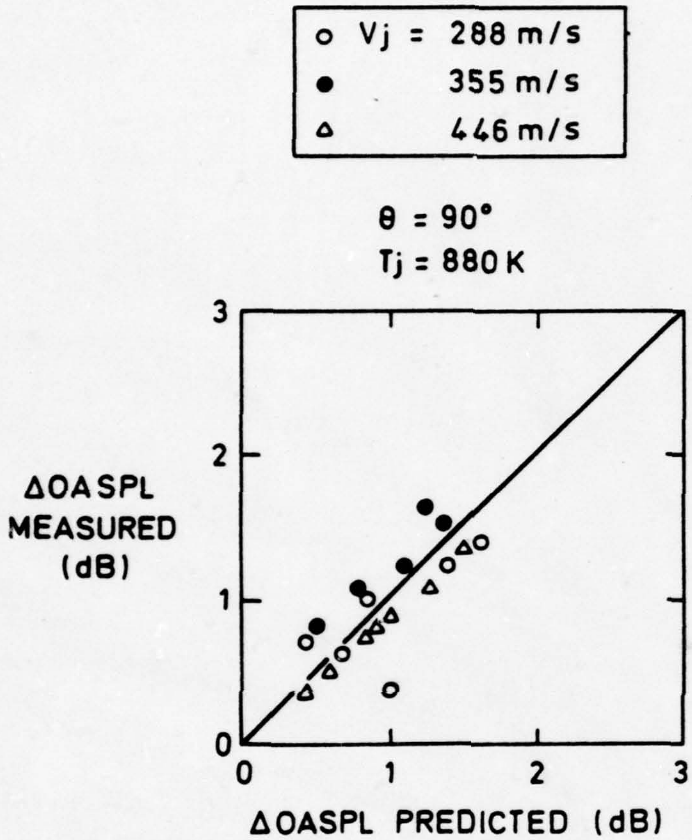



FIG. 8 NOISE REDUCTIONS IN FLIGHT FOR A HEATED JET

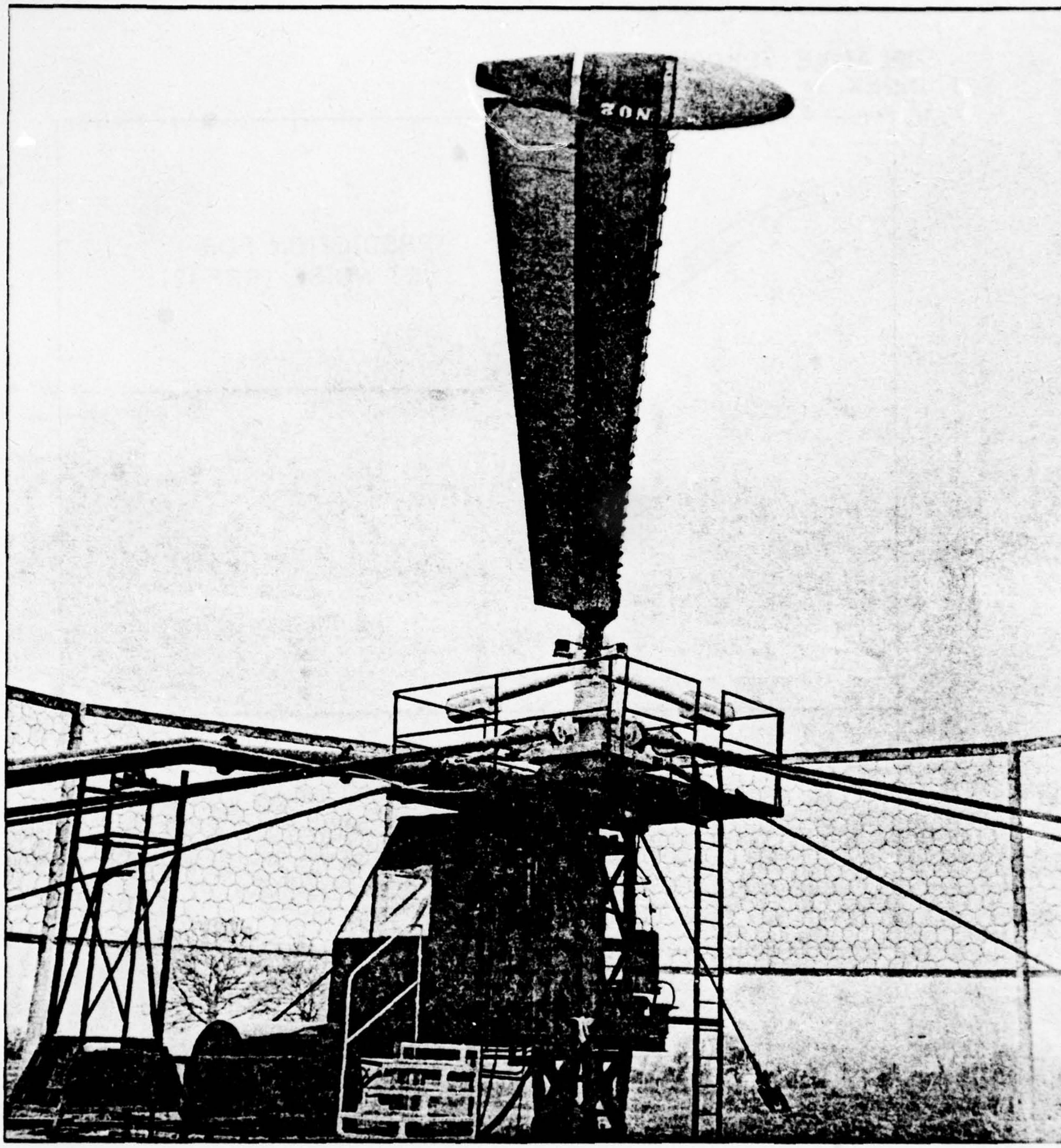


FIG.9 THE ROLLS-ROYCE SPINNING RIG

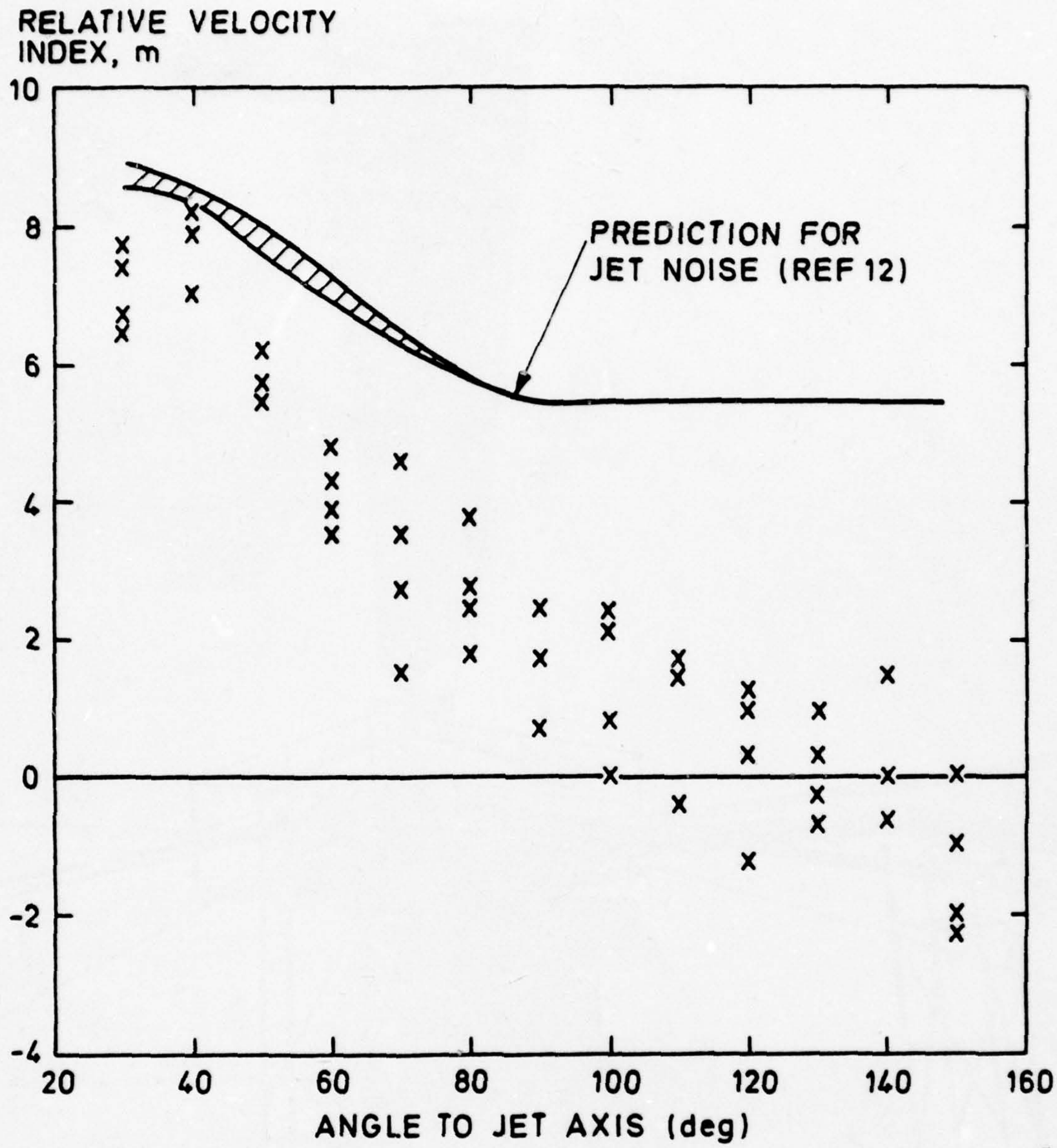



FIG. 10 VELOCITY EXPONENTS FOR HEATED JETS ON THE SPINNING RIG

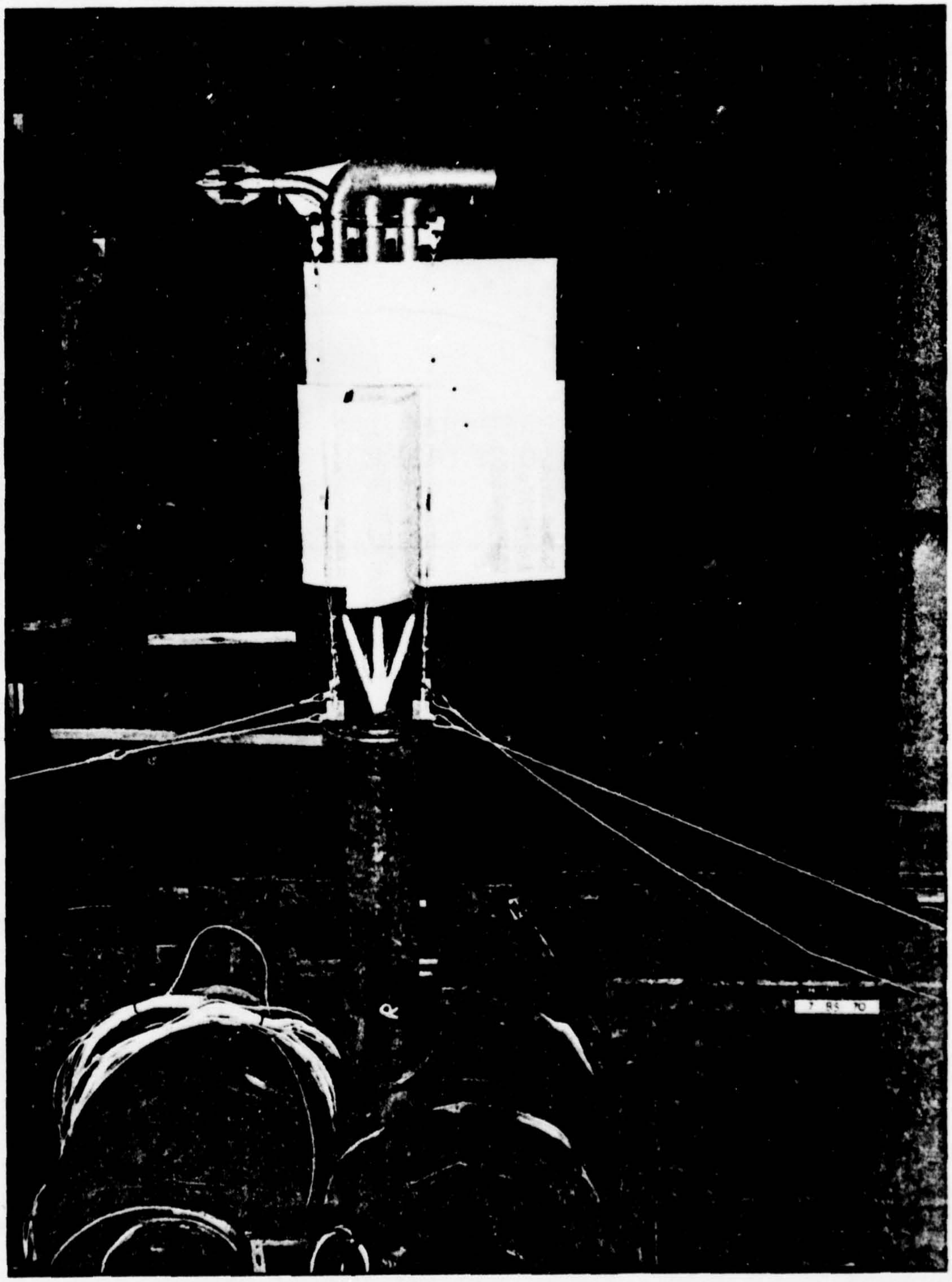


FIG.11 THE HSA NOZZLE INSTALLED IN THE RAE WIND-TUNNEL

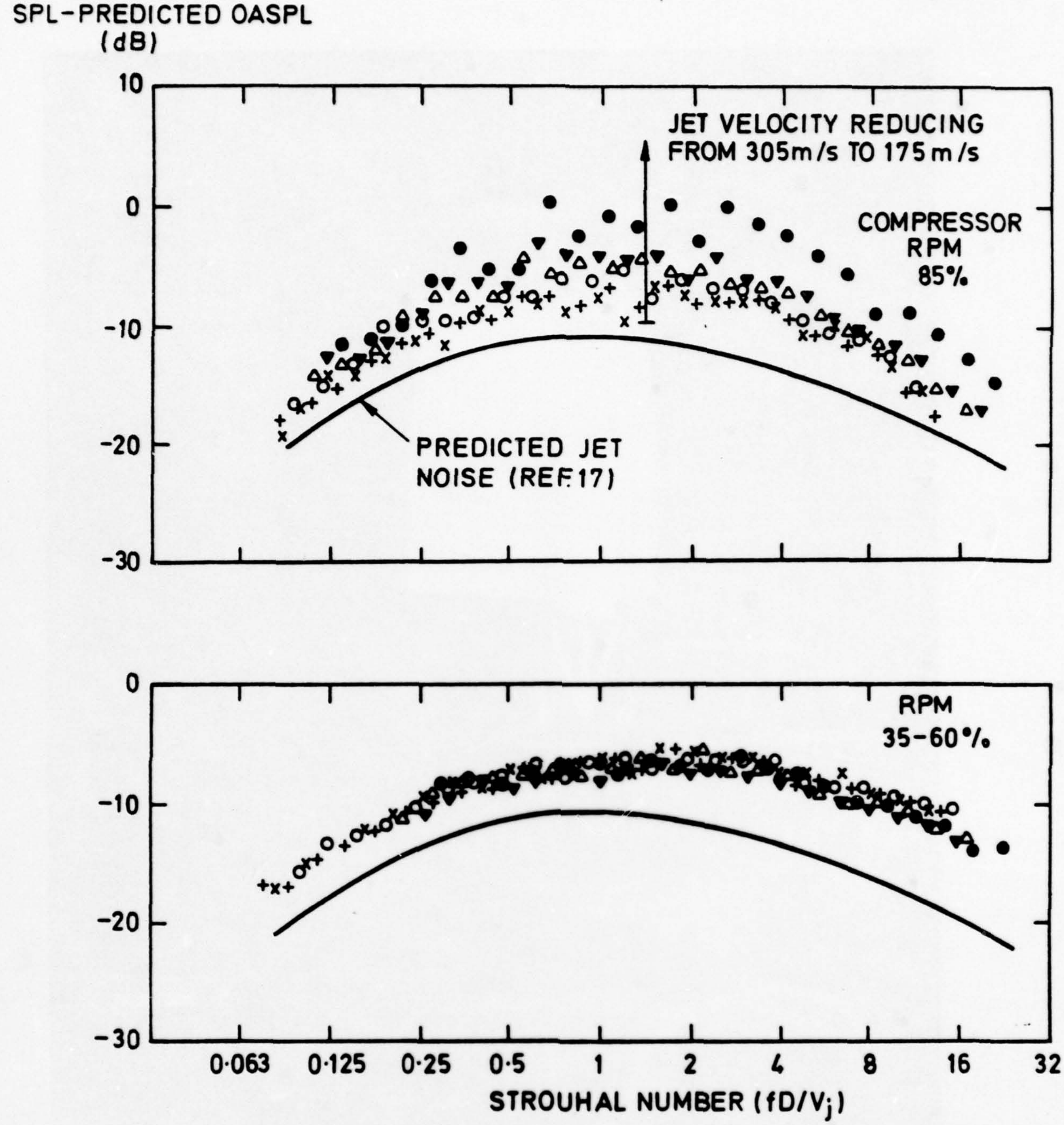



FIG. 12 STATIC SPECTRA AT 90° FROM THE HSA NOZZLE ON THE SPINNING RIG

124089

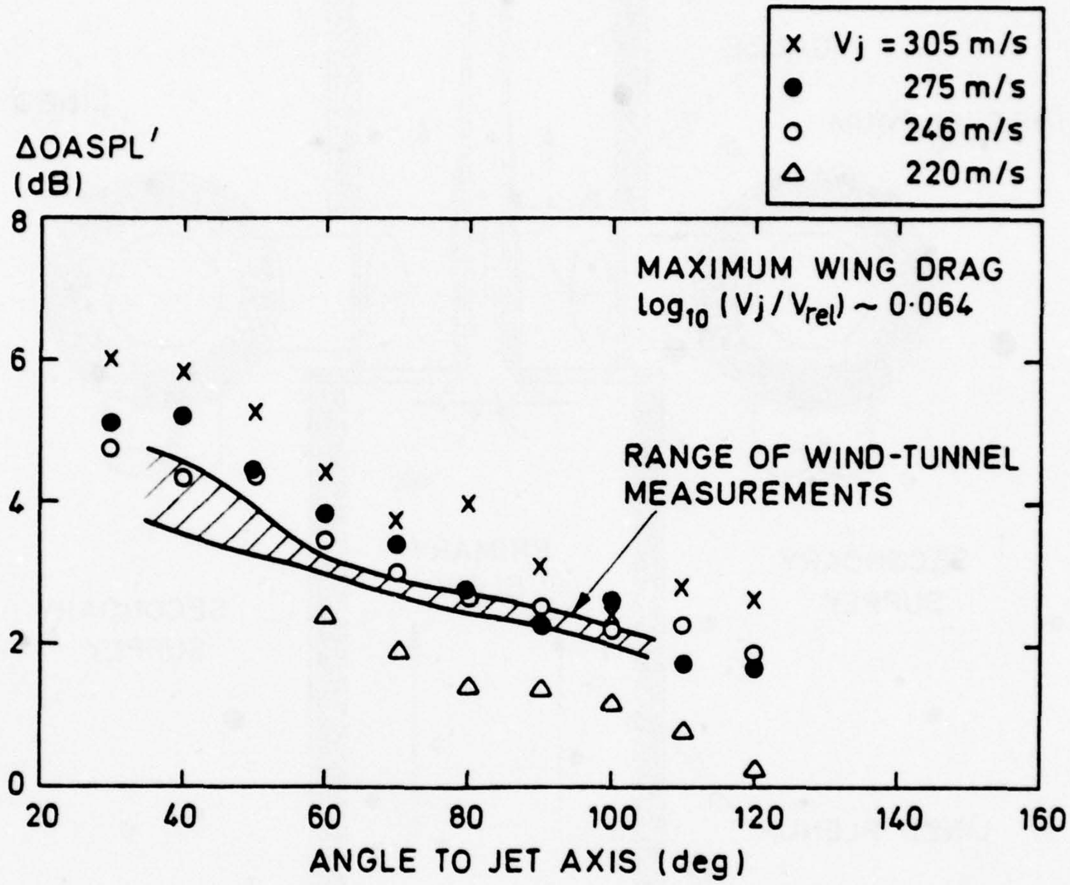



FIG. 13 A COMPARISON OF SPINNING RIG AND WIND-TUNNEL RESULTS FOR THE HSA NOZZLE

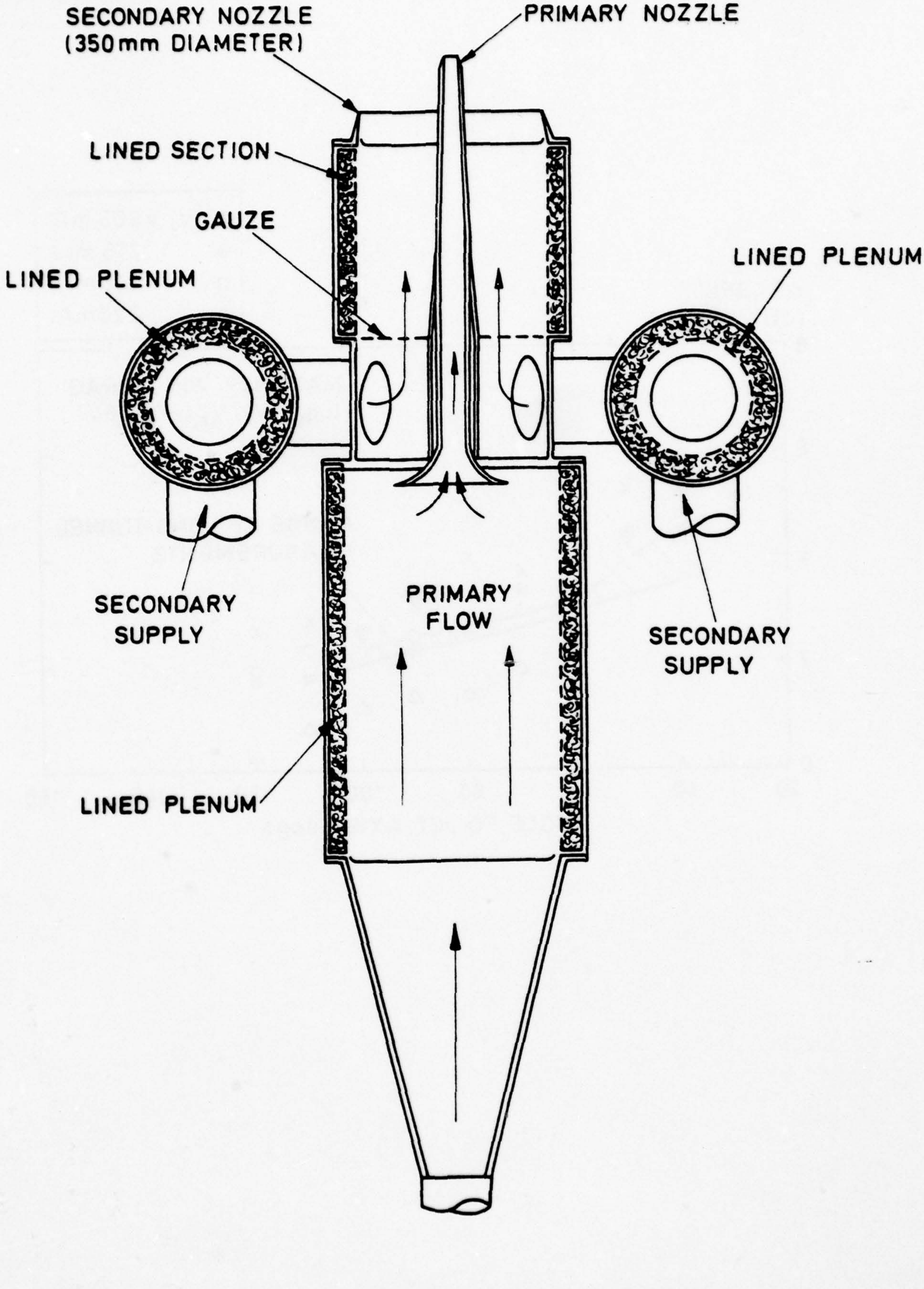



FIG. 14 A CROSS-SECTION OF THE FLIGHT SIMULATION RIG (1975)

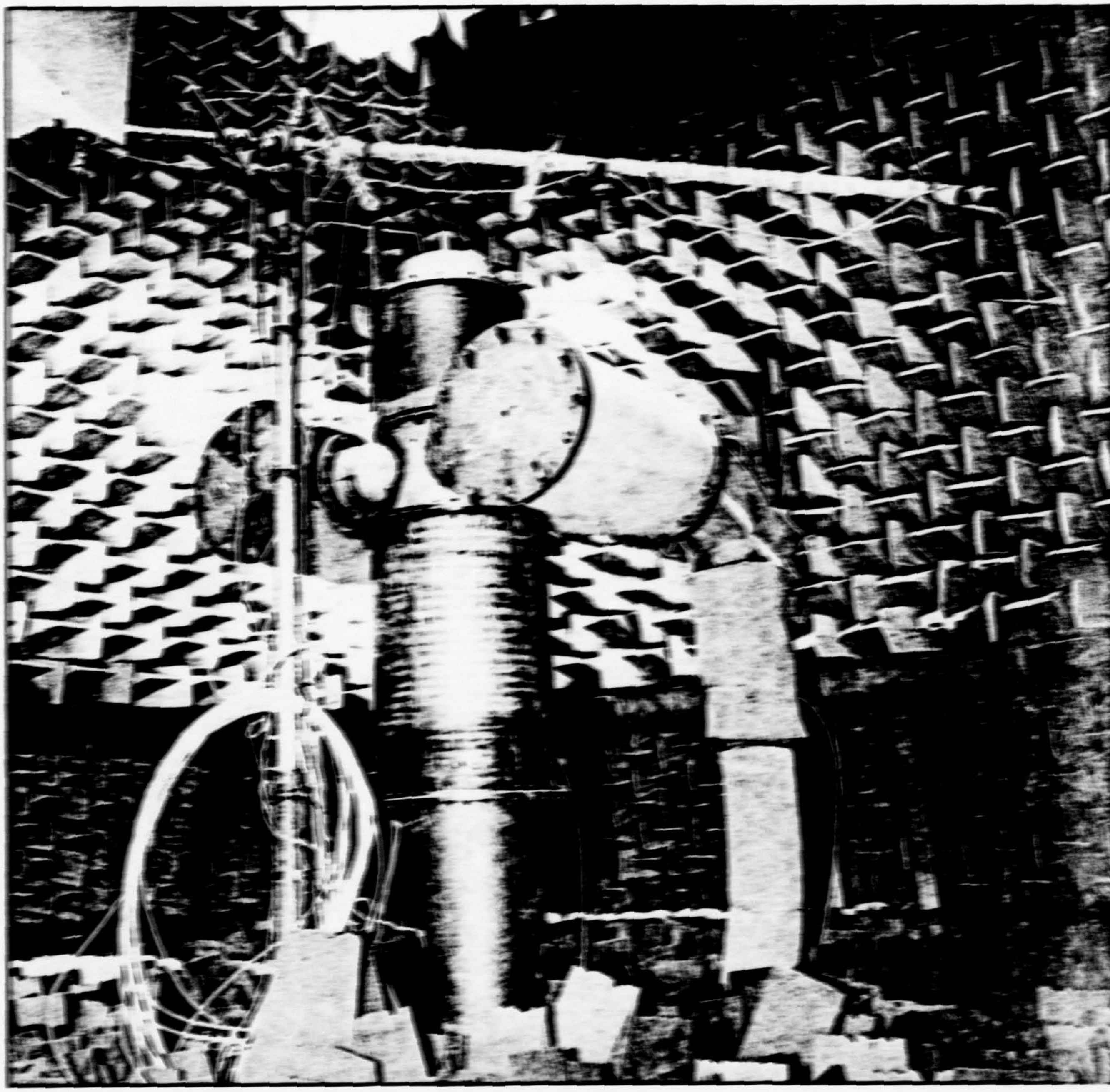


FIG.15 THE FLIGHT SIMULATION RIG IN
THE SMALL ANECHOIC CHAMBER

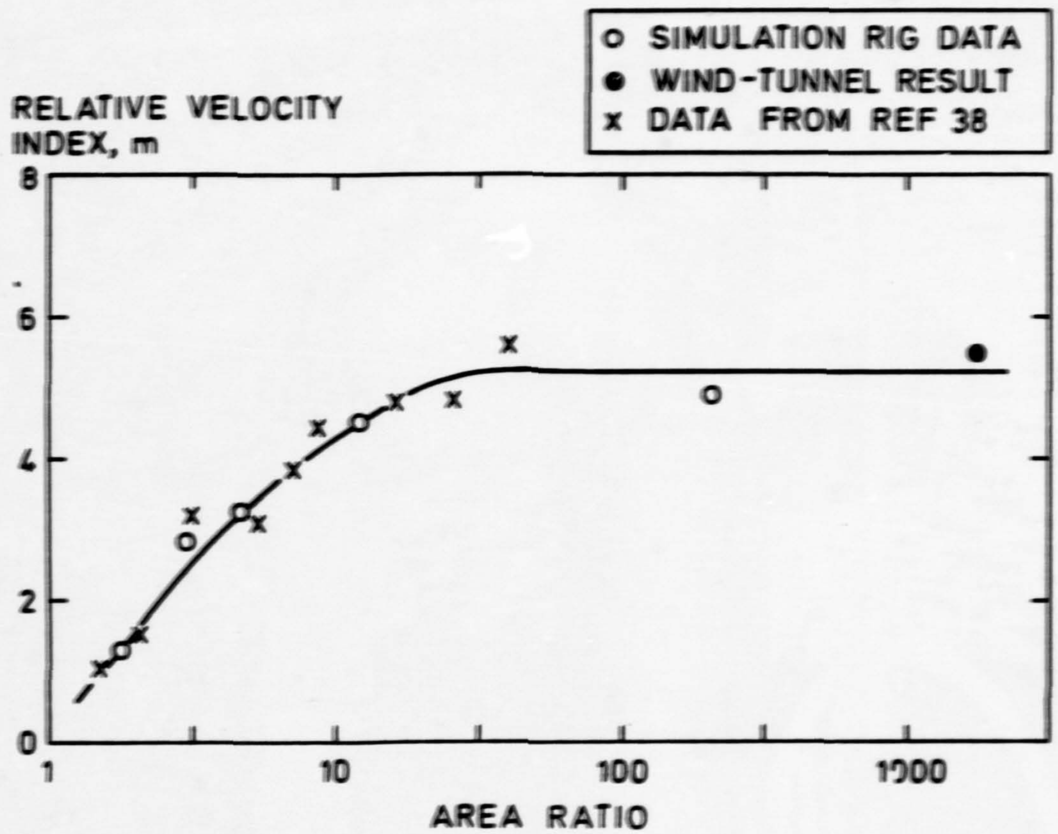



FIG. 16 THE DEPENDENCE OF THE RELATIVE VELOCITY INDEX AT 90° ON AREA RATIO

124092

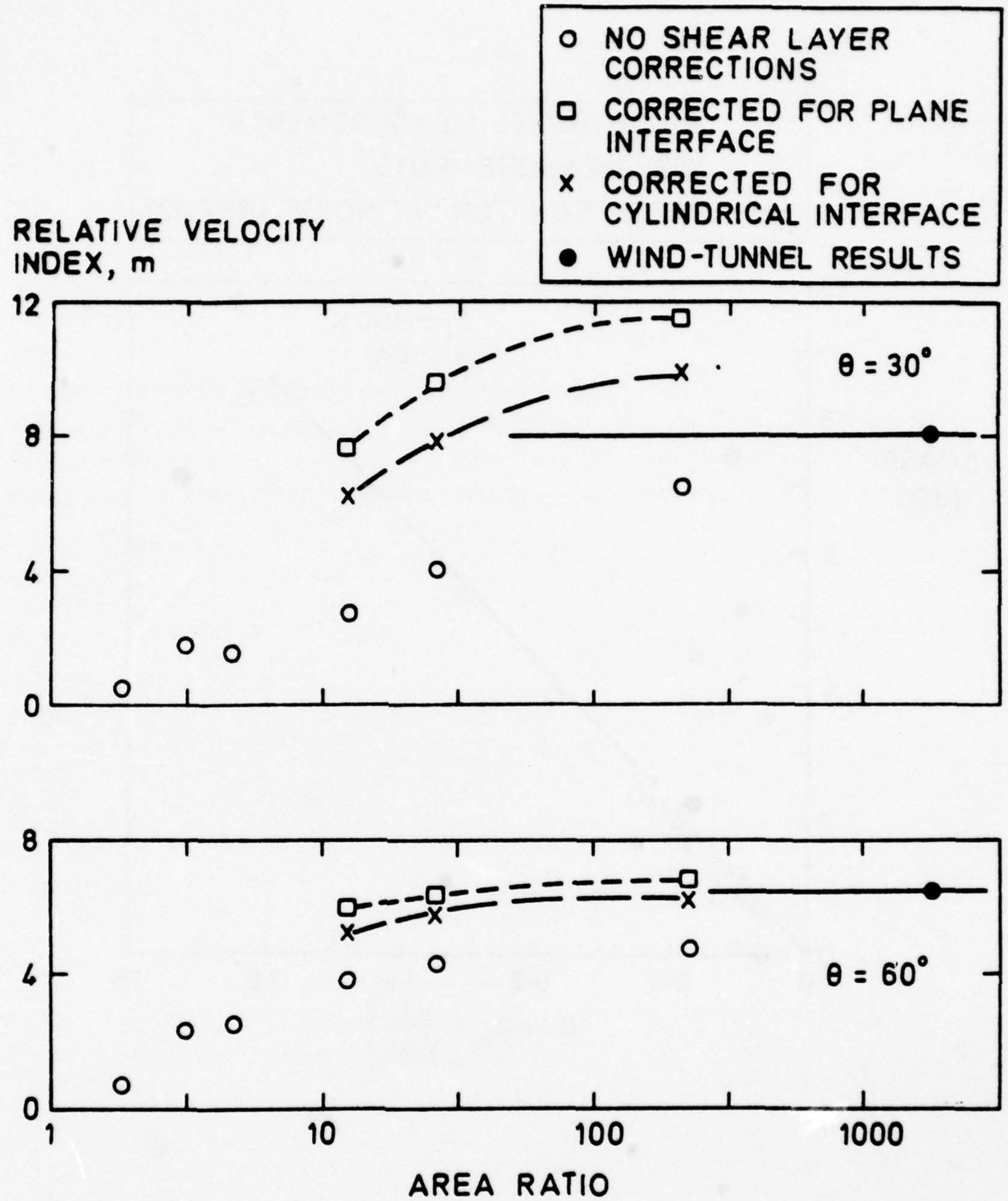



FIG. 17 THE EFFECT OF SHEAR LAYER CORRECTIONS ON REAR ARC DATA

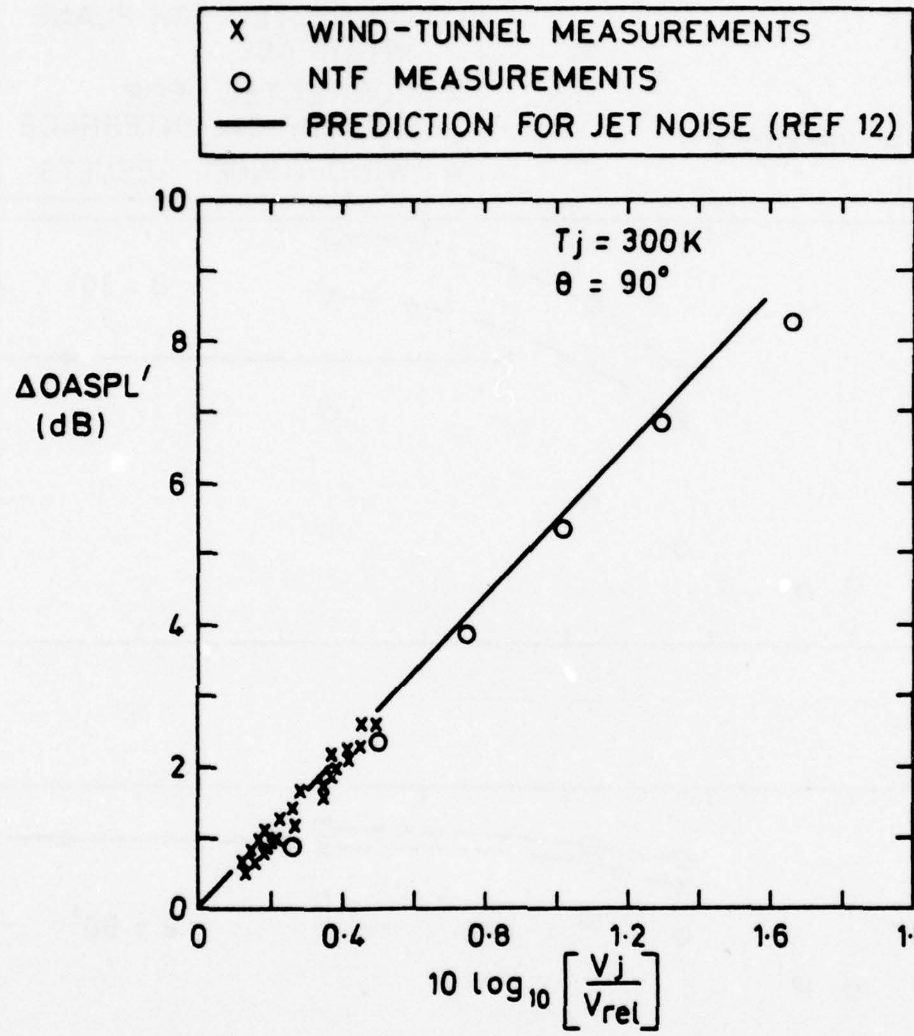



FIG. 18 A COMPARISON OF WIND TUNNEL AND NTF RESULTS FOR JET NOISE IN FLIGHT

124094

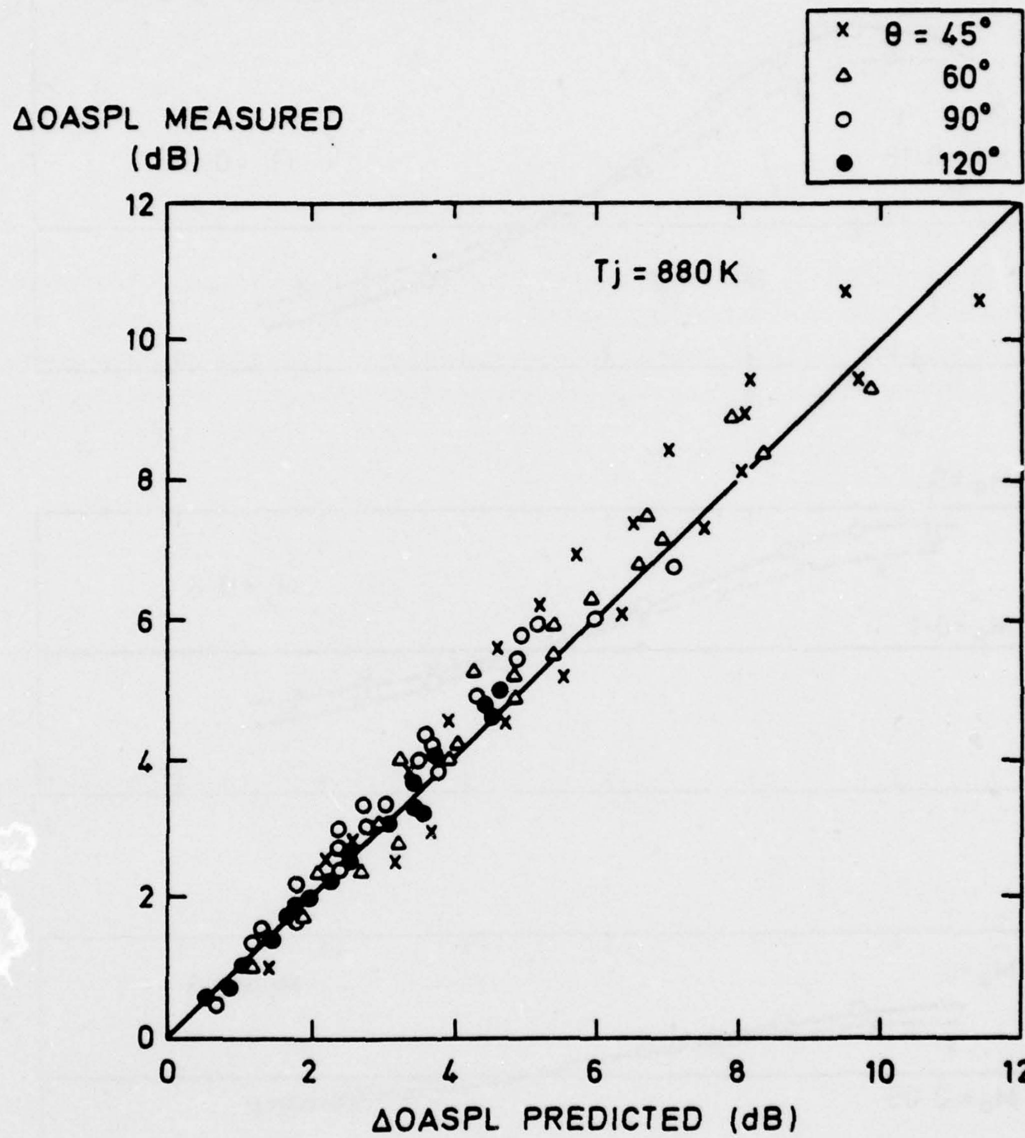



FIG. 19 A COMPARISON BETWEEN MEASURED AND PREDICTED CHANGES IN OASPL FOR HEATED JETS

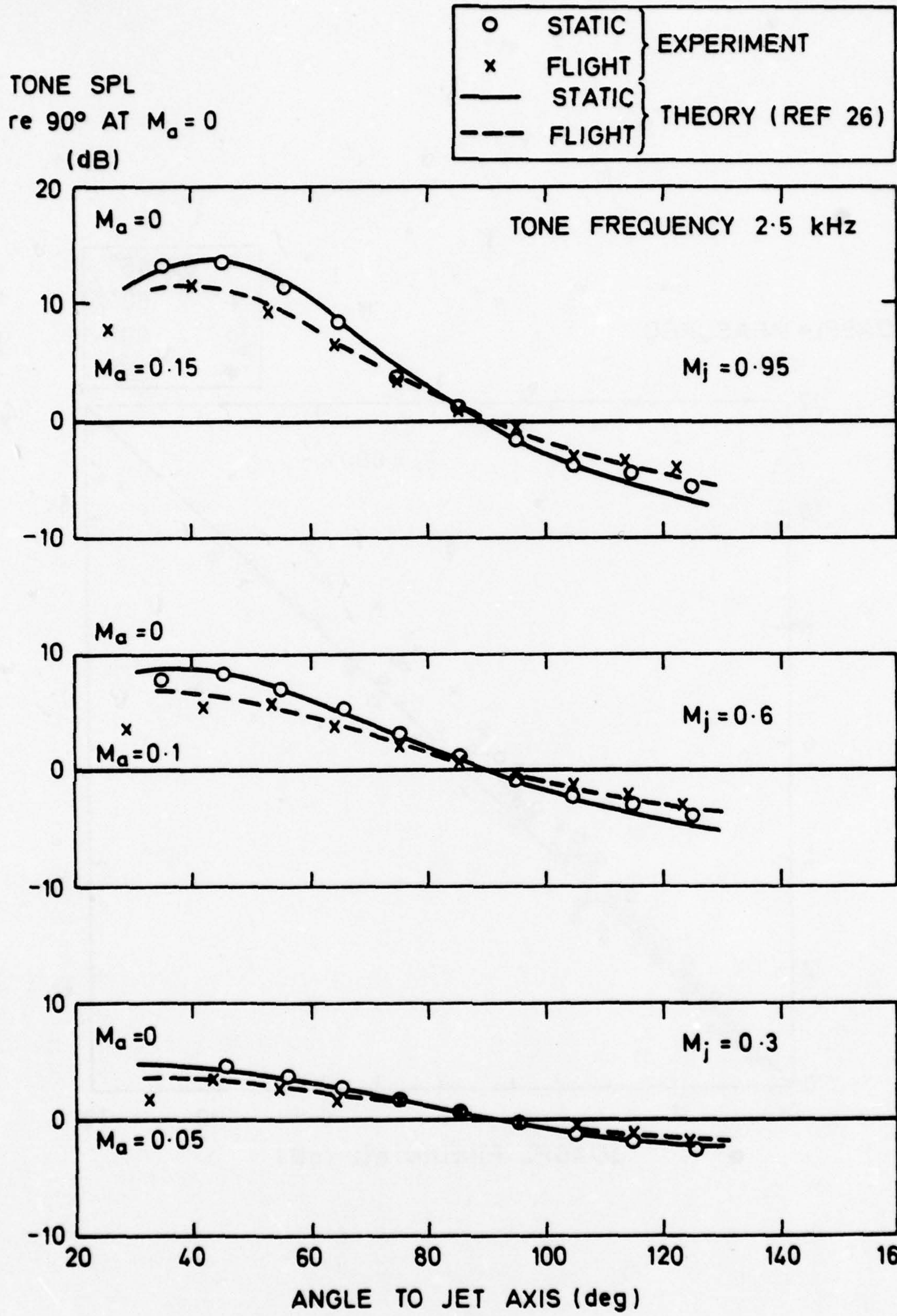



FIG. 20 THEORETICAL AND EXPERIMENTAL FLIGHT EFFECTS ON INTERNAL NOISE

124096

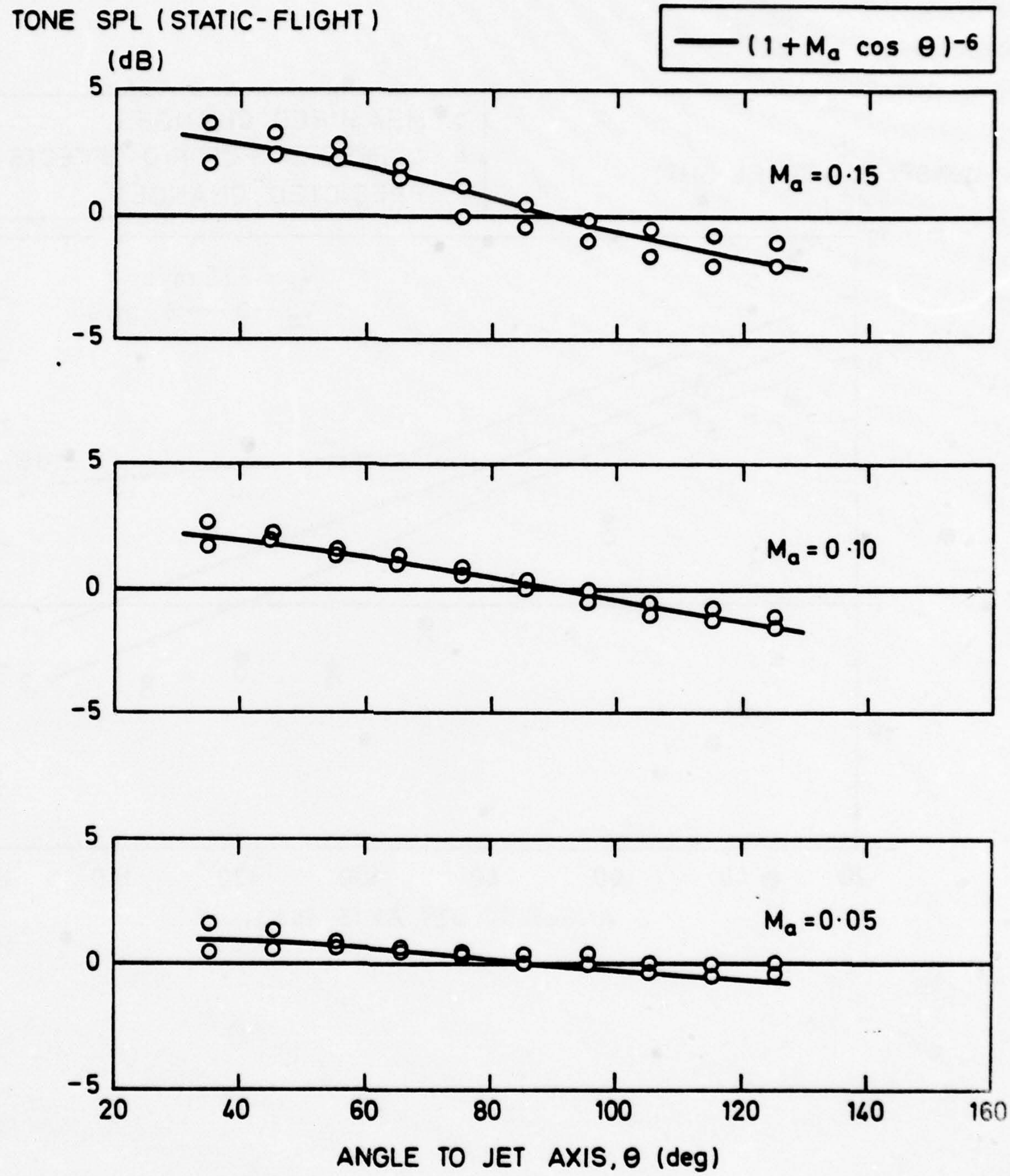



FIG. 21 A CORRELATION OF STATIC-TO-FLIGHT CHANGES OF INTERNAL NOISE

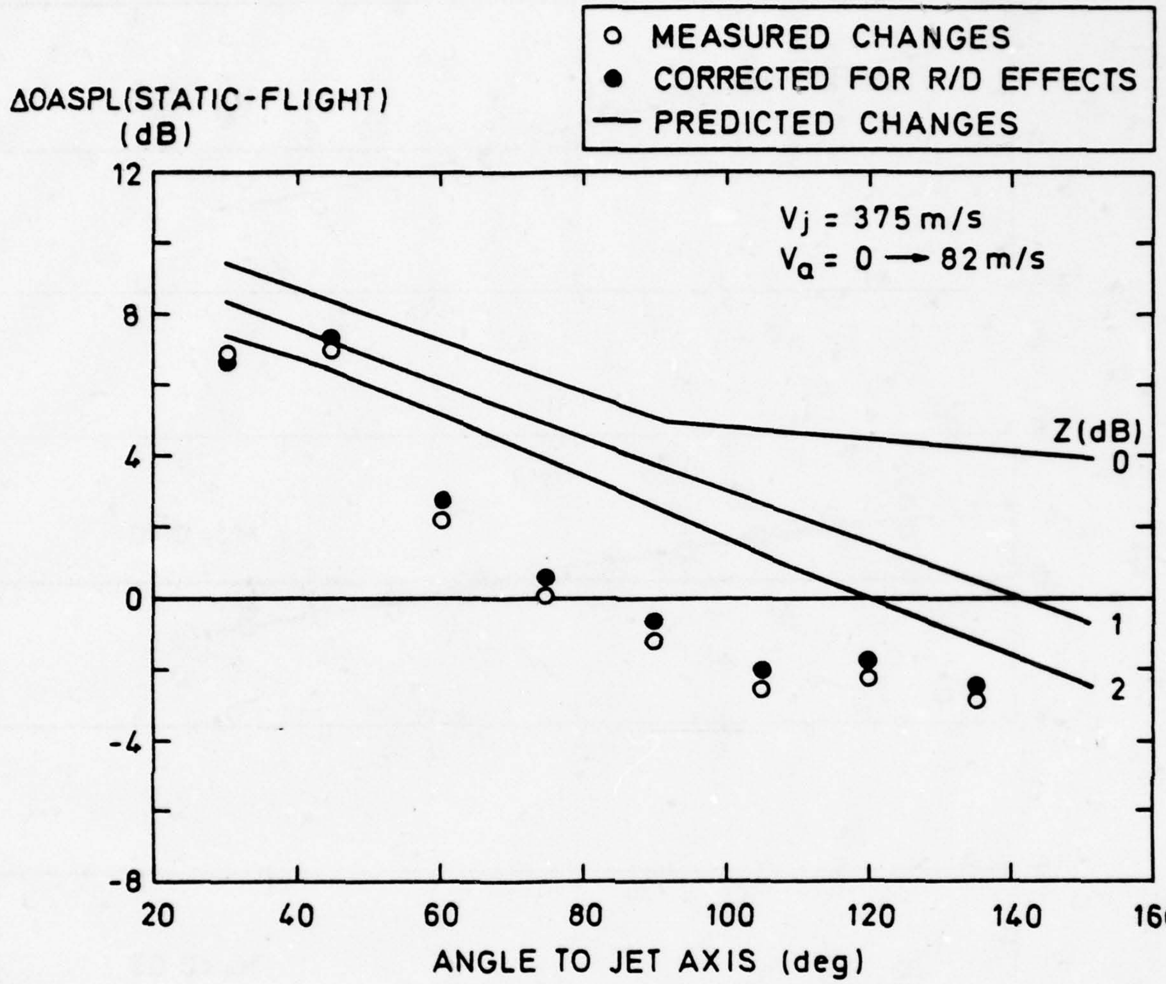



FIG. 22 STATIC-TO-FLIGHT DATA FOR THE VIPER 601/HS125 (1976)

124098

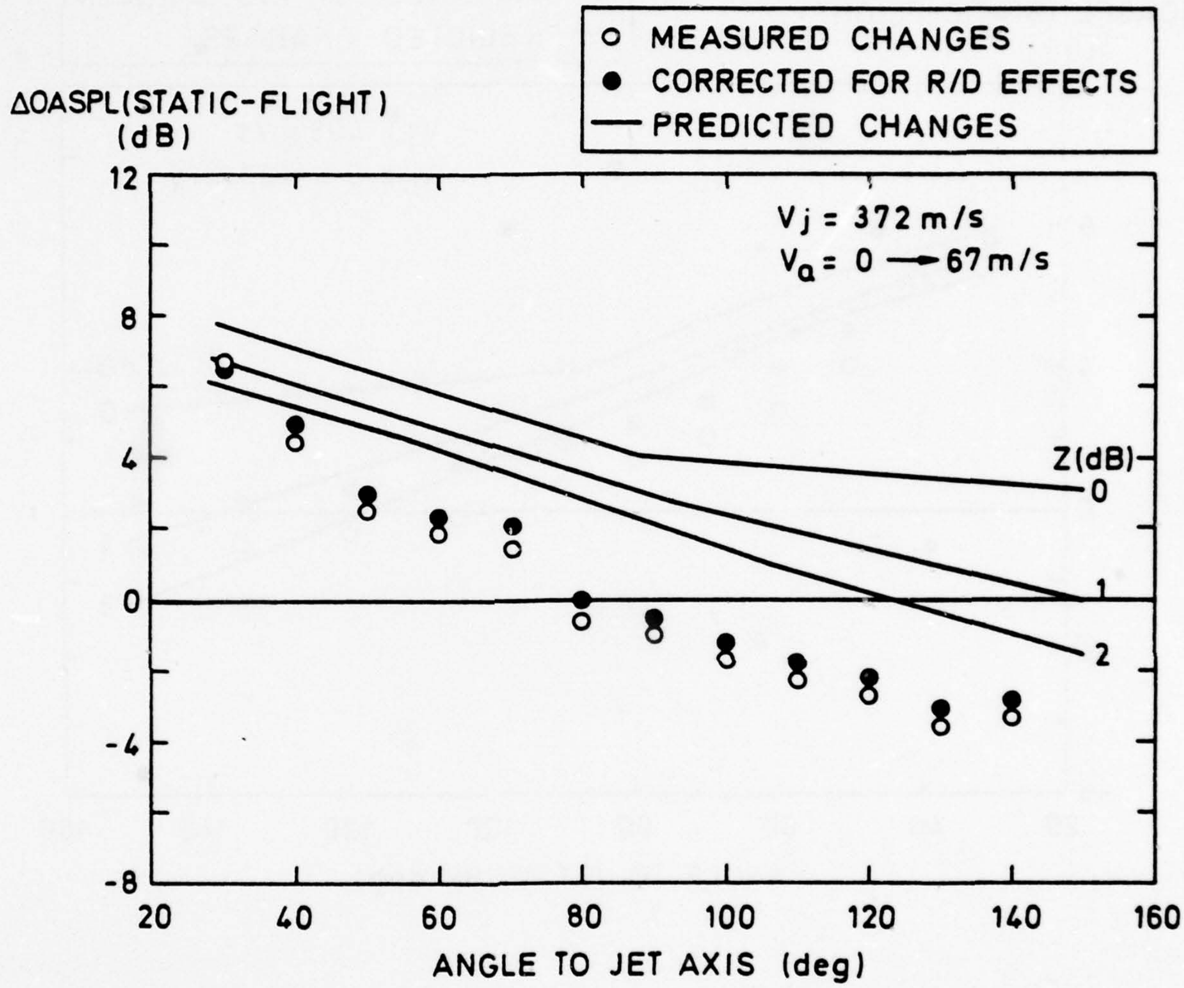



FIG. 23 STATIC-TO-FLIGHT DATA FOR THE VIPER 11/JET PROVOST (1976)

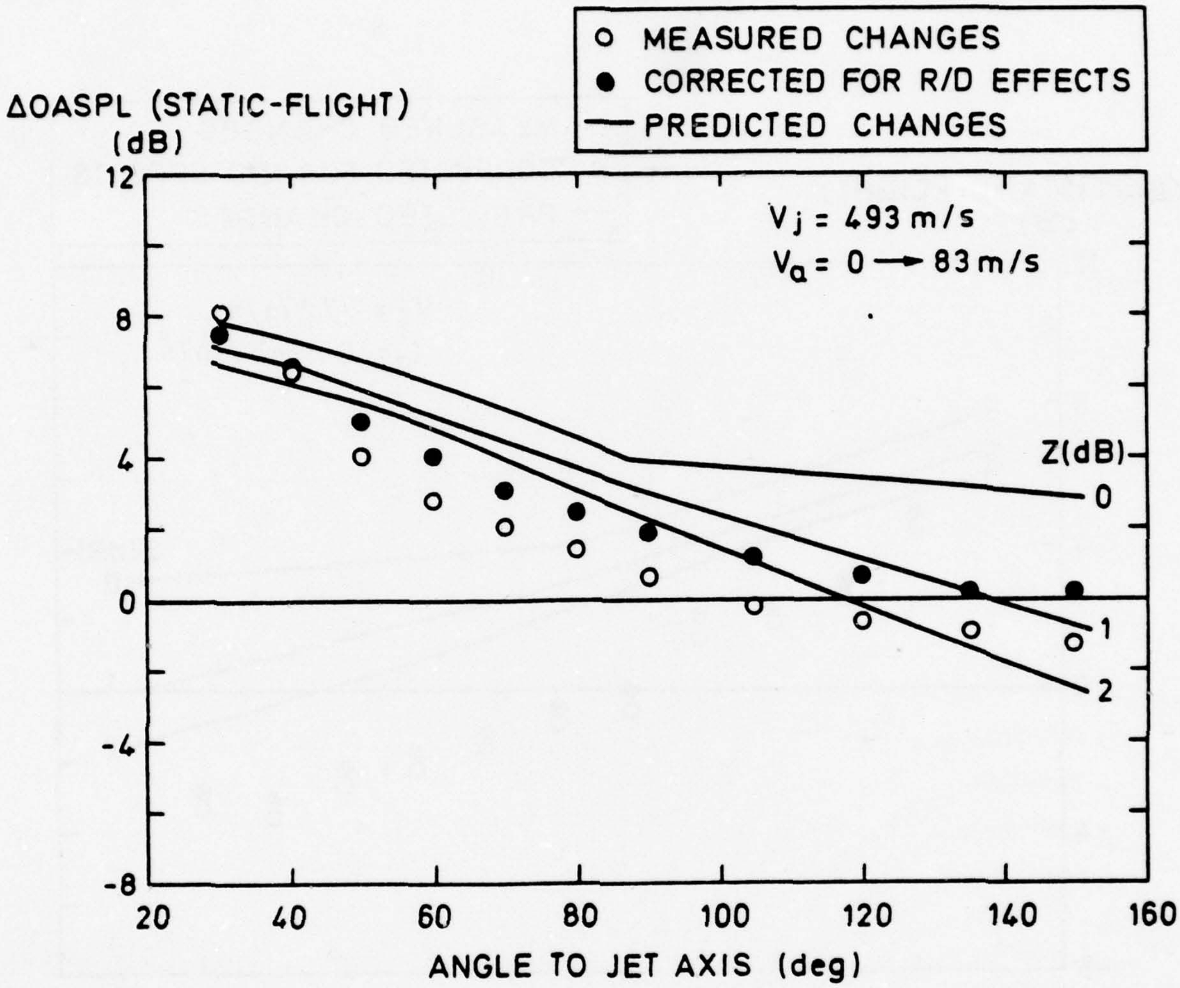



FIG. 24 STATIC-TO-FLIGHT DATA FOR THE JT8D/B727 (1976)

124100

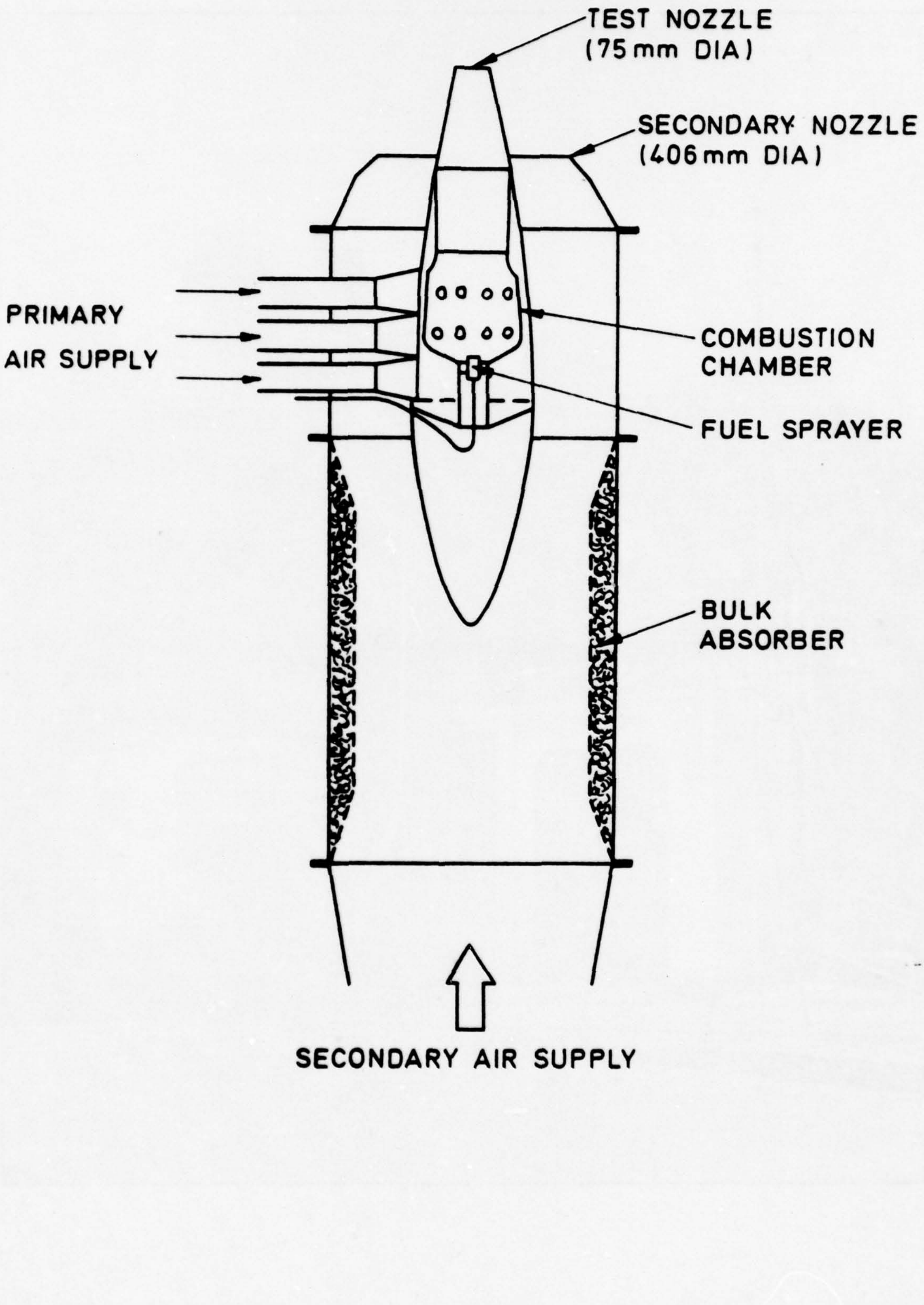



FIG. 25 THE SPINNING RIG SIMULATOR

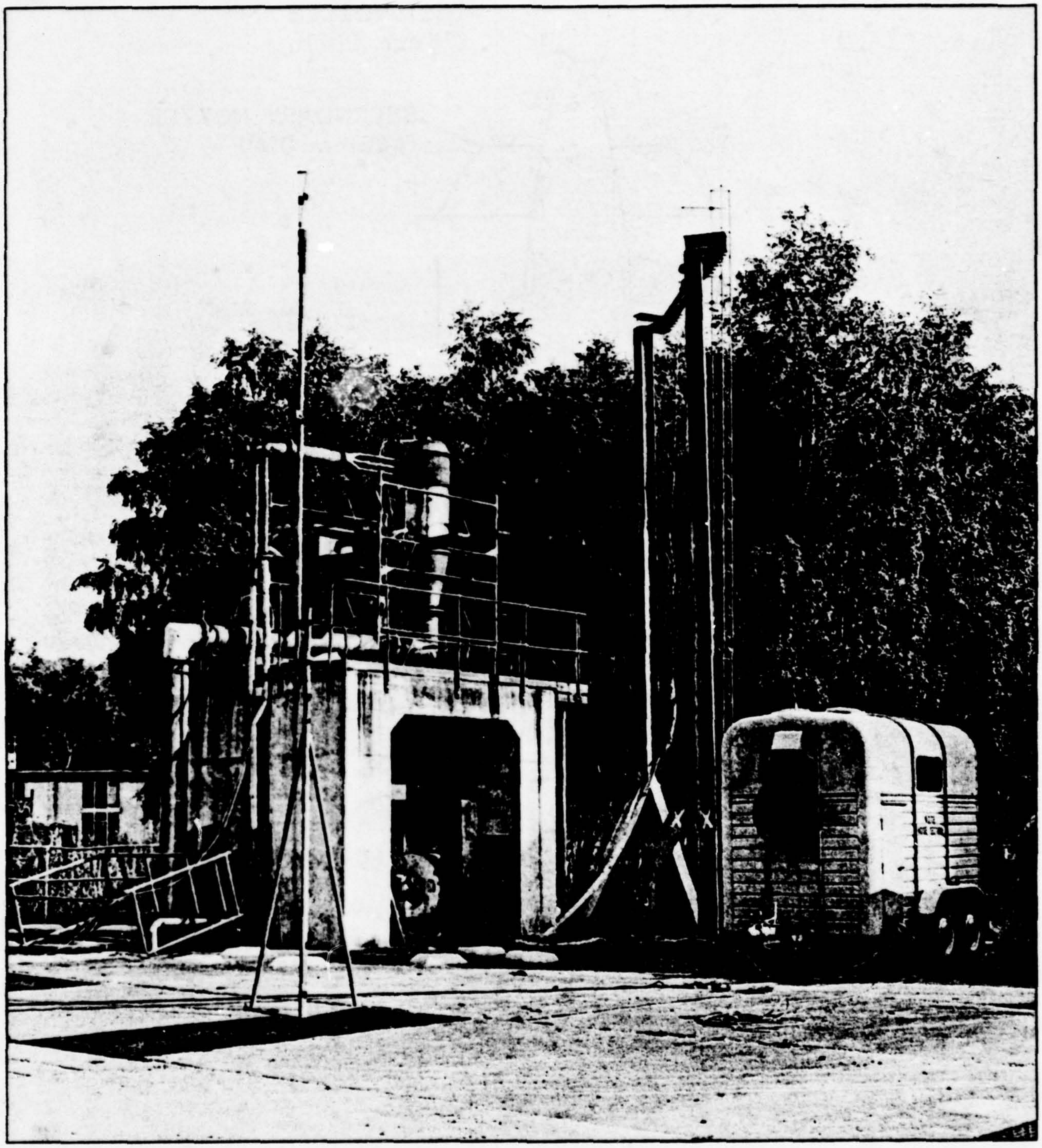
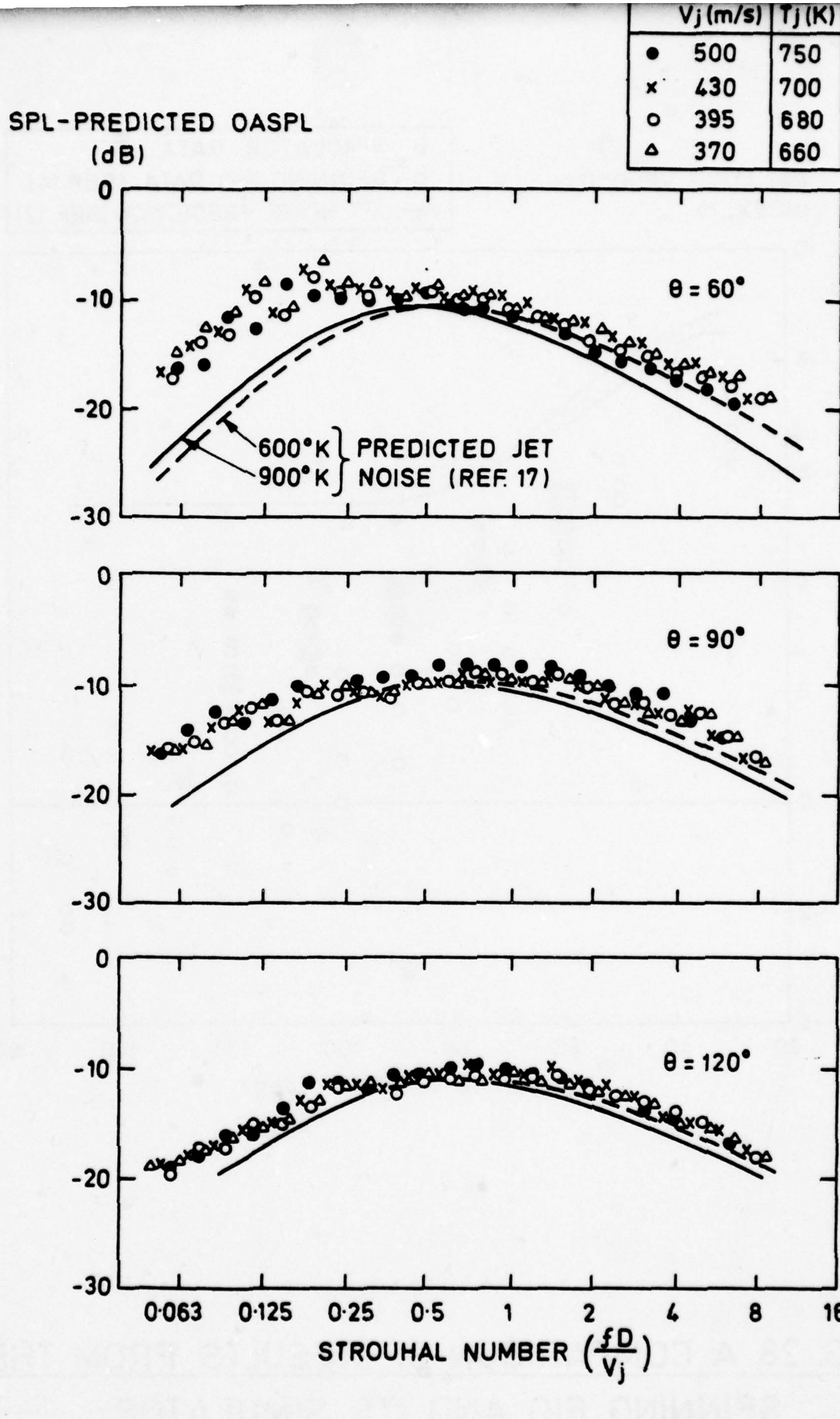


FIG.26 THE TEST ENVIRONMENT OF
THE SPINNING RIG SIMULATOR

124101




## FIG. 27 STATIC SPECTRA FROM THE SPINNING RIG SIMULATOR

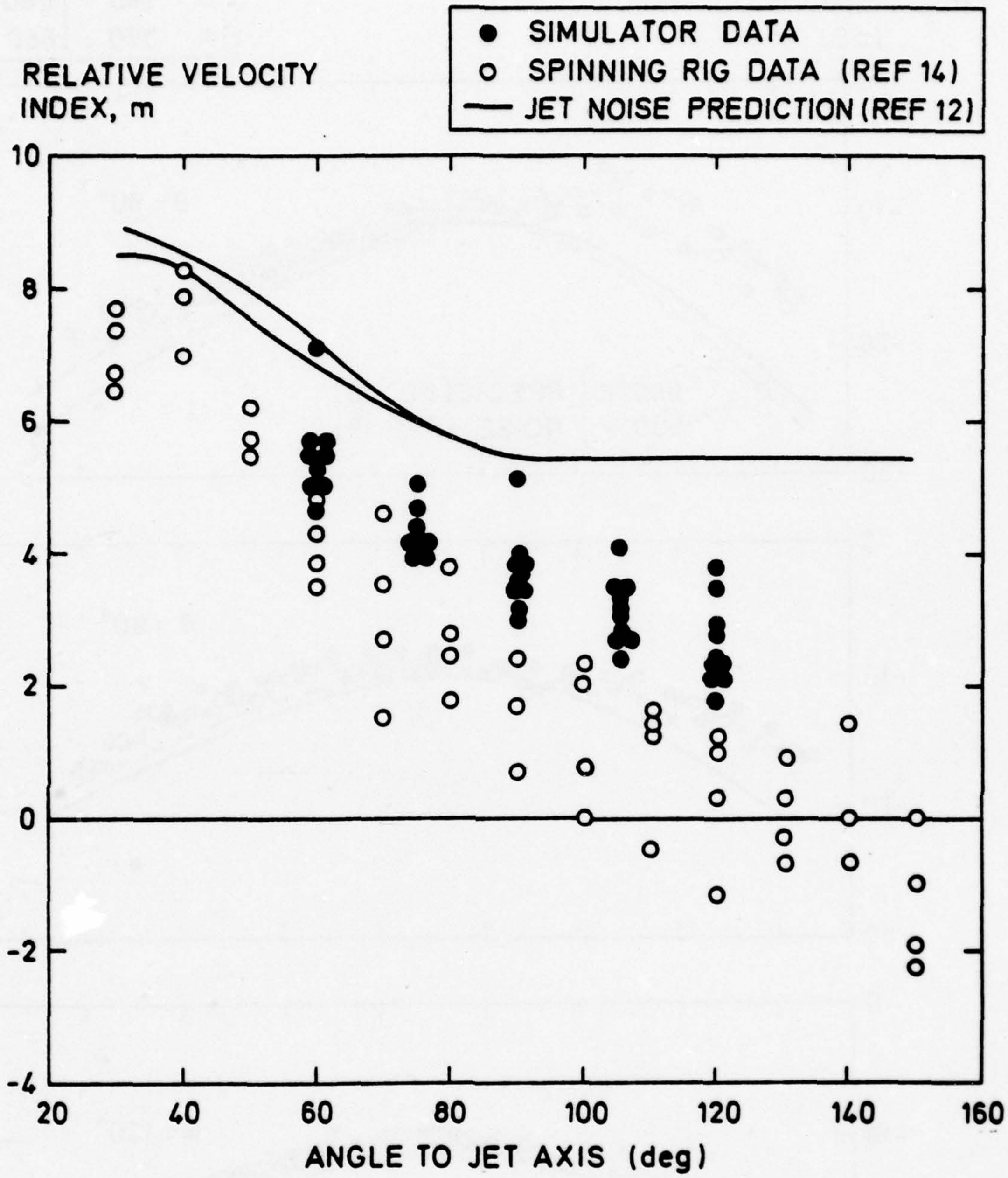



FIG. 28 A COMPARISON OF RESULTS FROM THE SPINNING RIG AND ITS SIMULATOR

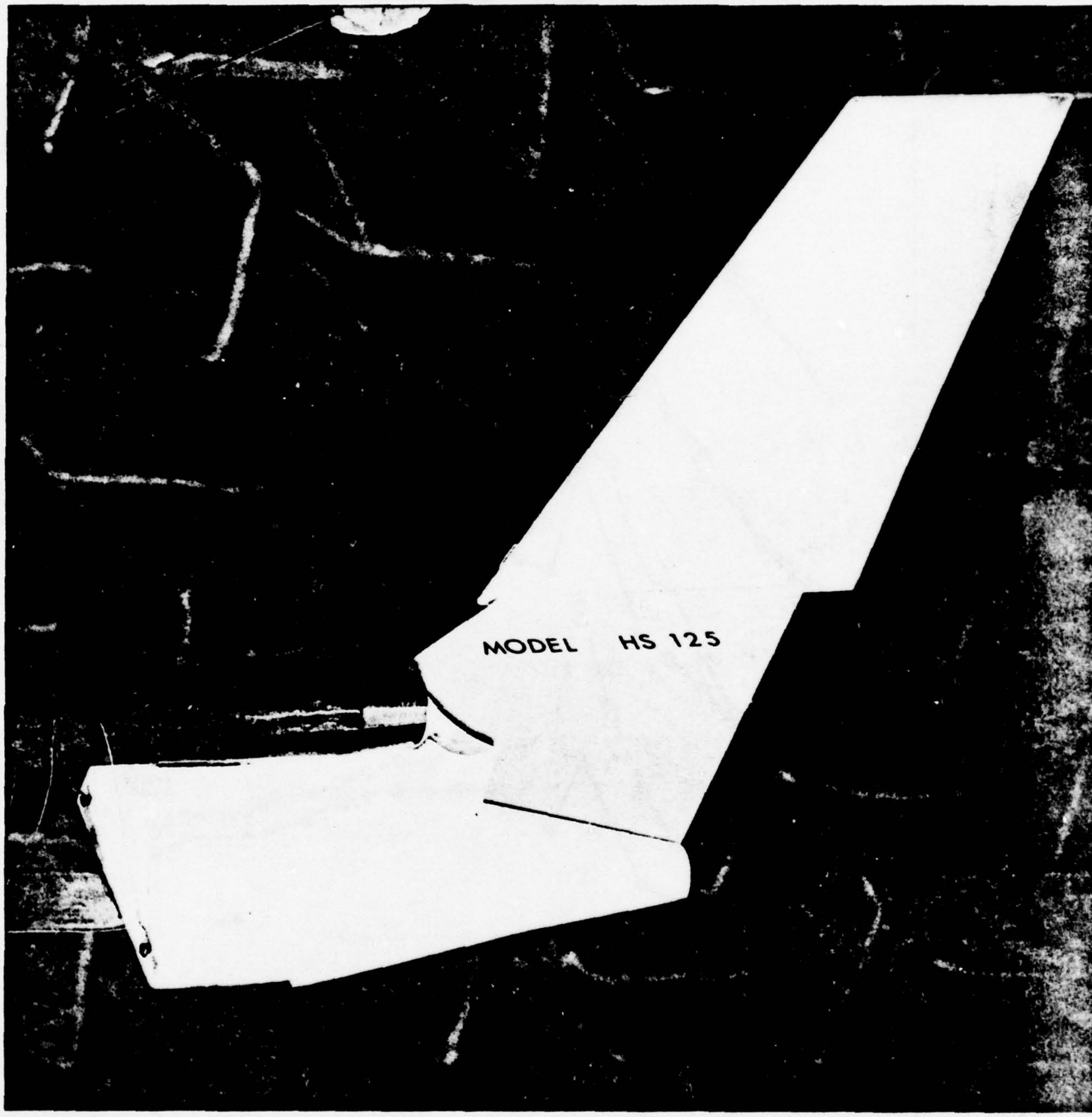



FIG.29 A MODEL OF THE HS125 AIRCRAFT USED FOR STATIC TESTS

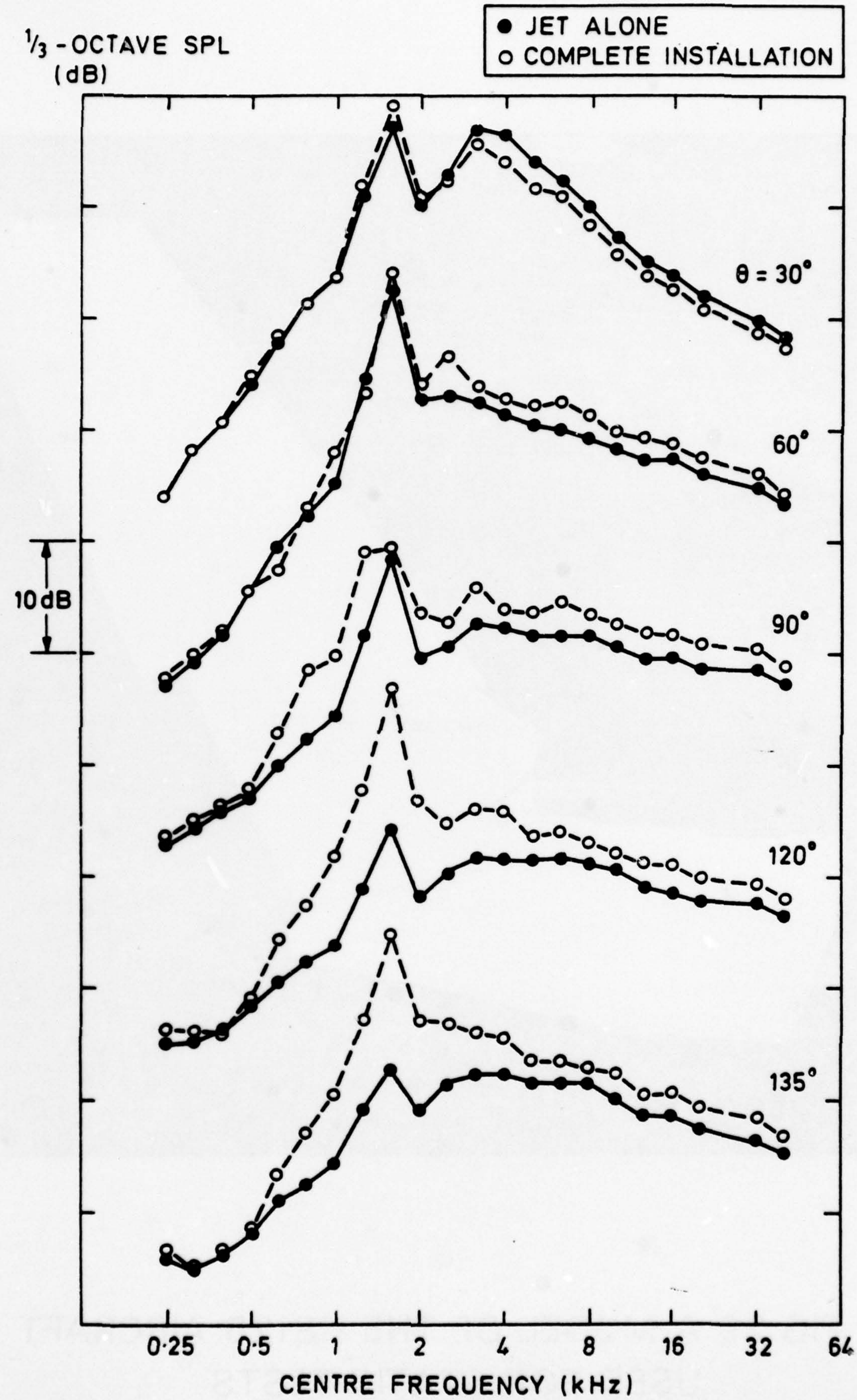



FIG. 30 INSTALLATION EFFECTS MEASURED USING AN HS 125 MODEL

124104

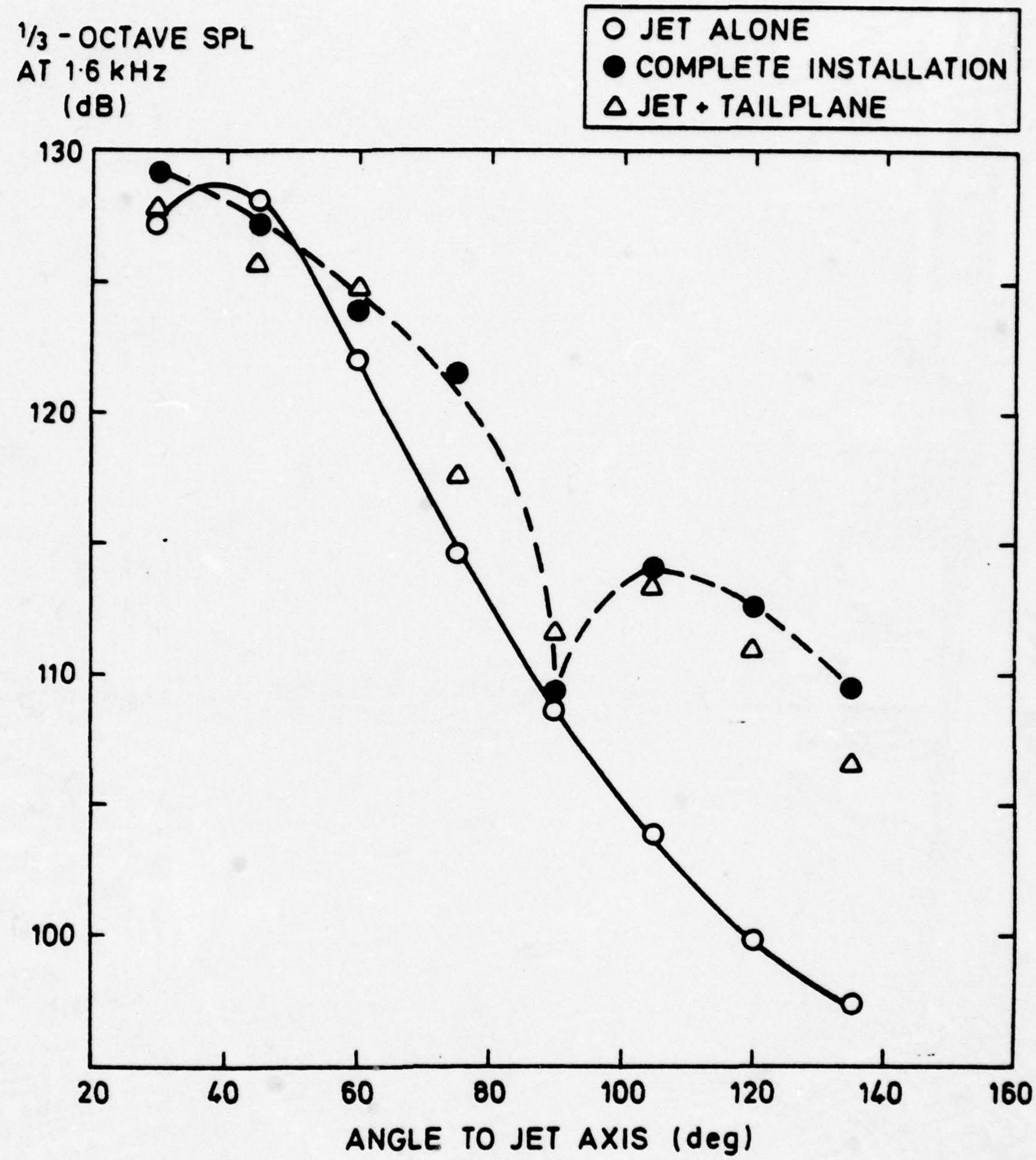



FIG. 31 POLAR DIRECTIVITY OF THE INTERNAL NOISE TONE WITH AND WITHOUT THE HS 125 MODEL

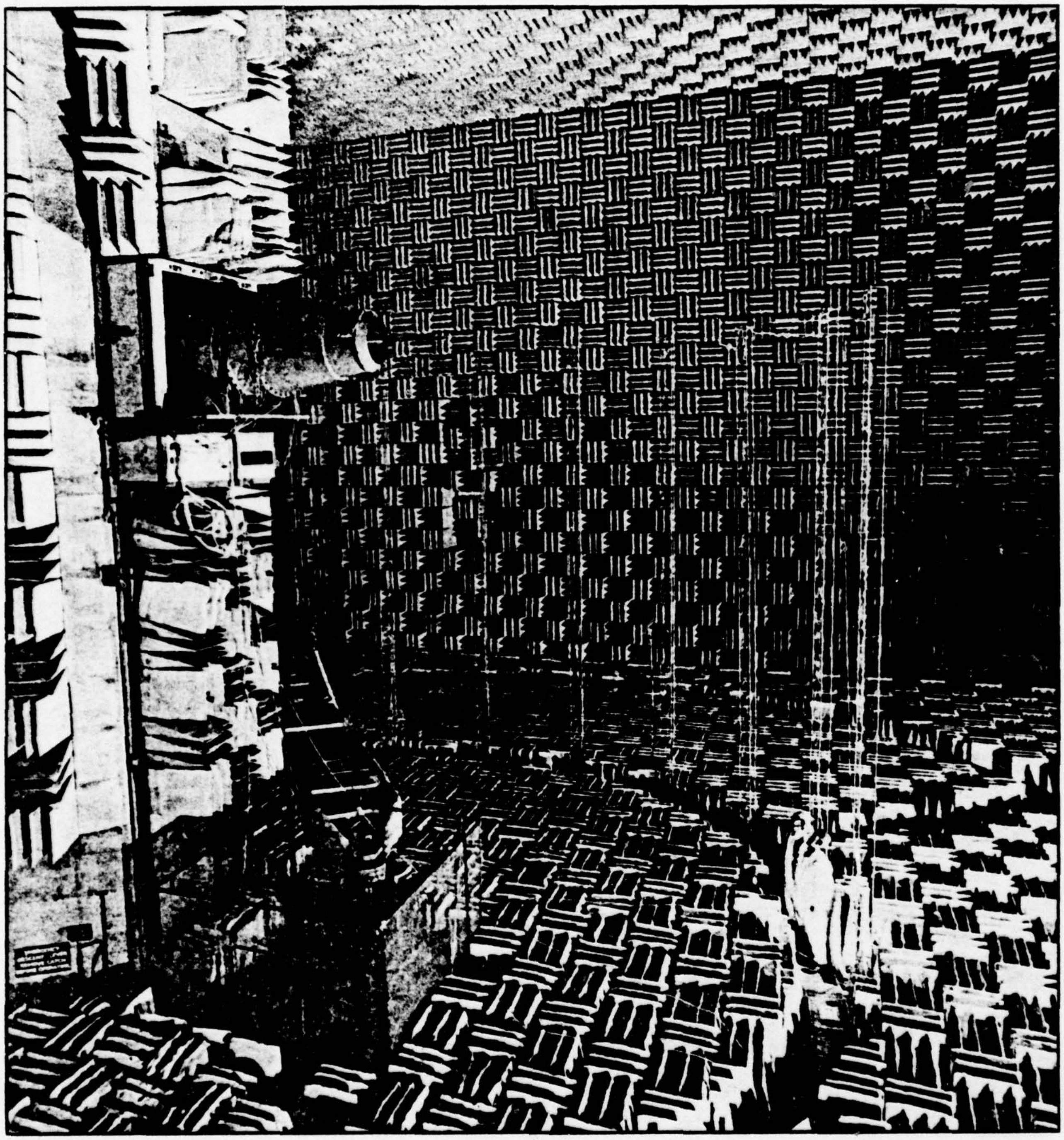


FIG.32 A GENERAL VIEW OF THE NTF ANECHOIC CHAMBER

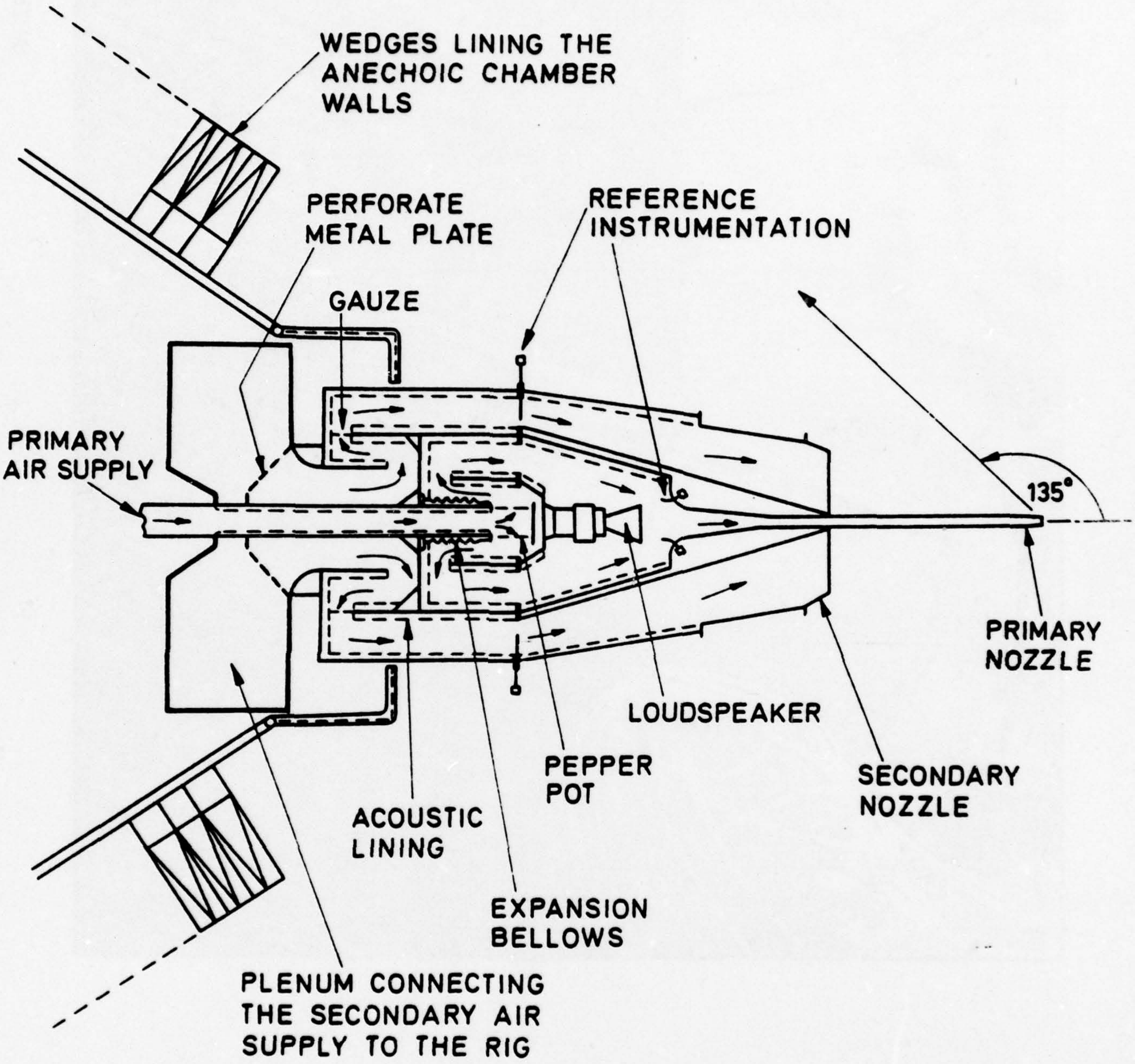



FIG. 33 A CROSS-SECTION OF THE FLIGHT SIMULATION RIG (1976)

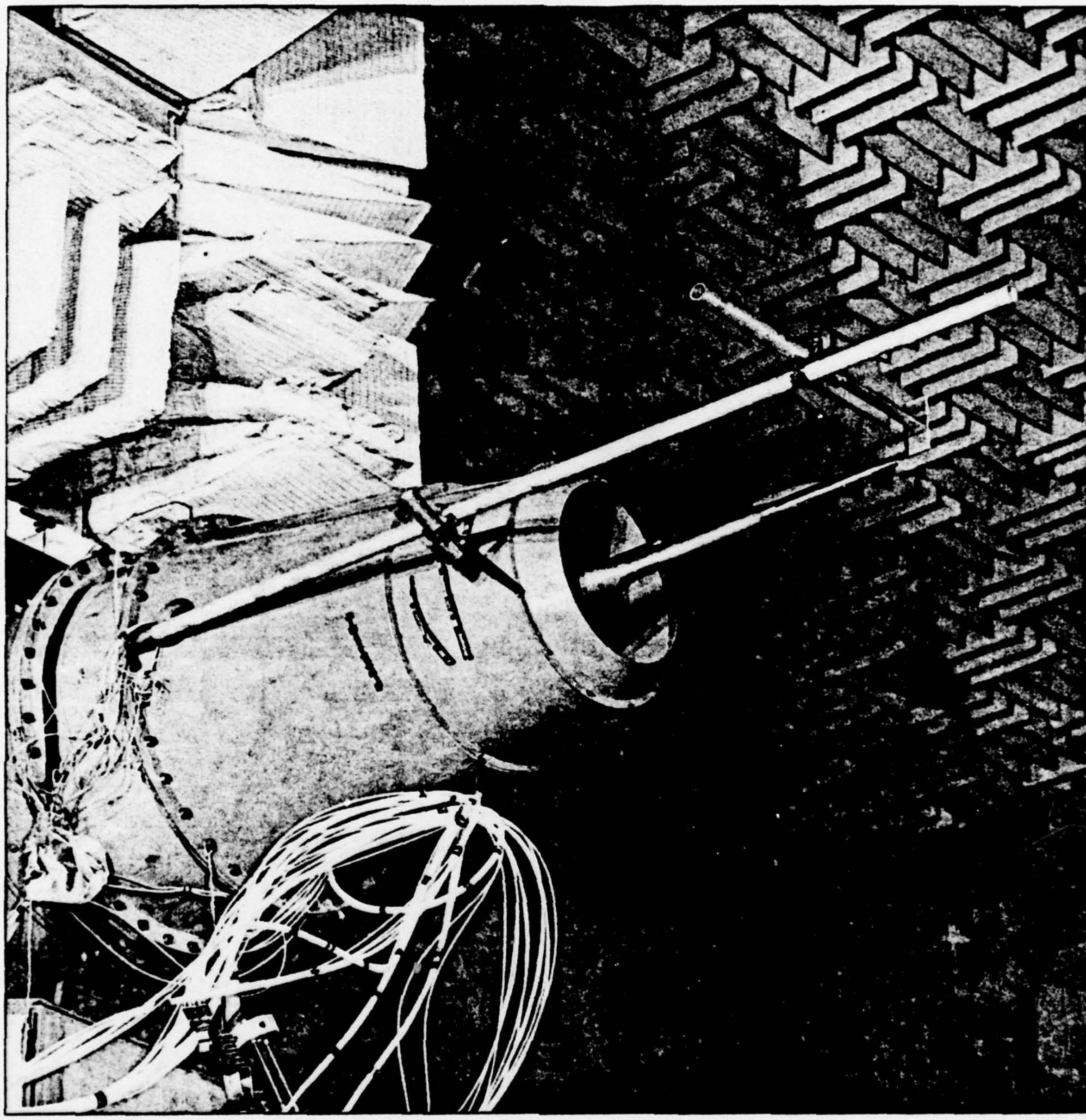


FIG.34 A TAILPLANE MOUNTED FOR FLIGHT SIMULATION TESTS

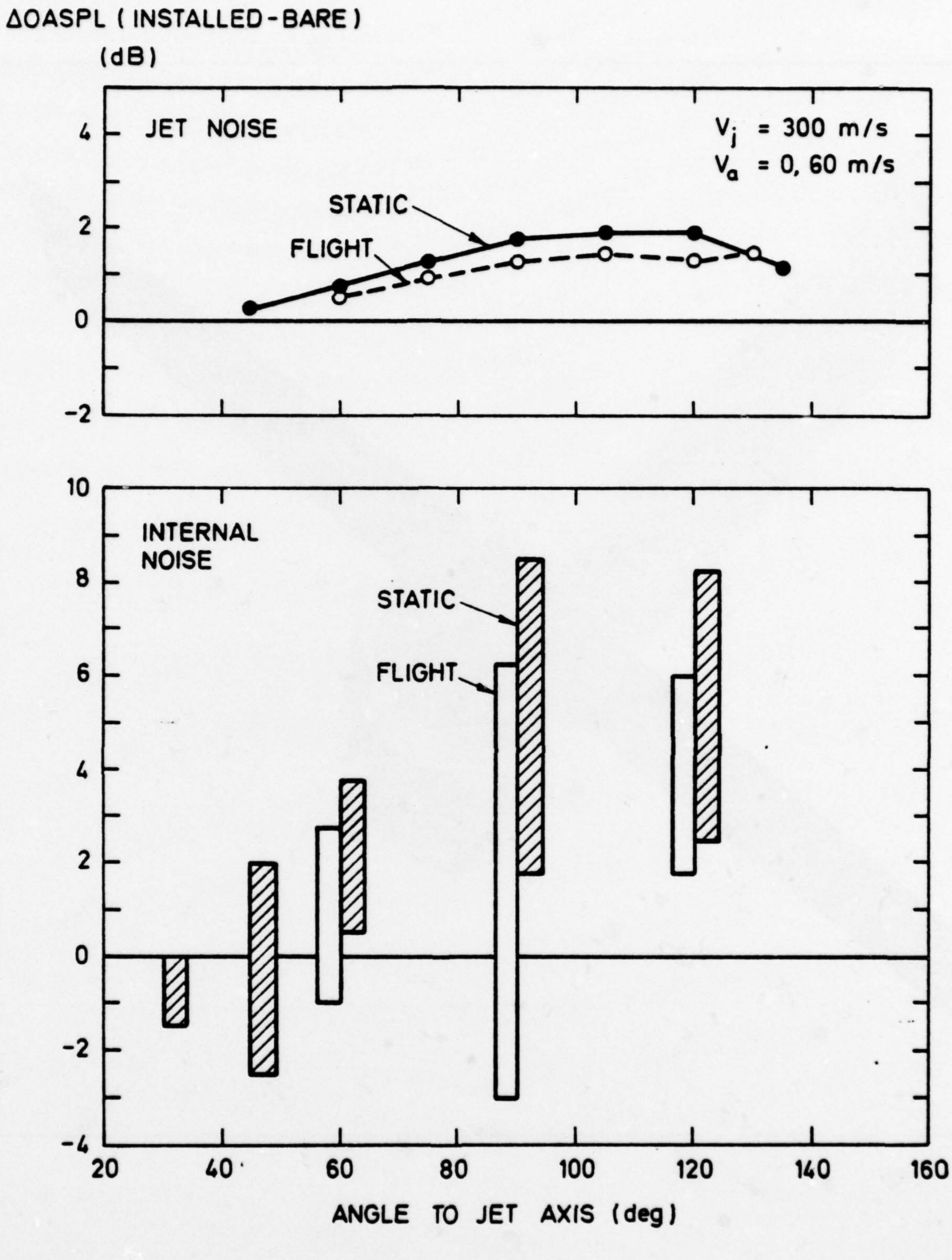



FIG. 35 INSTALLATION EFFECTS FOR AN HS 125 TYPE OF TAILPLANE

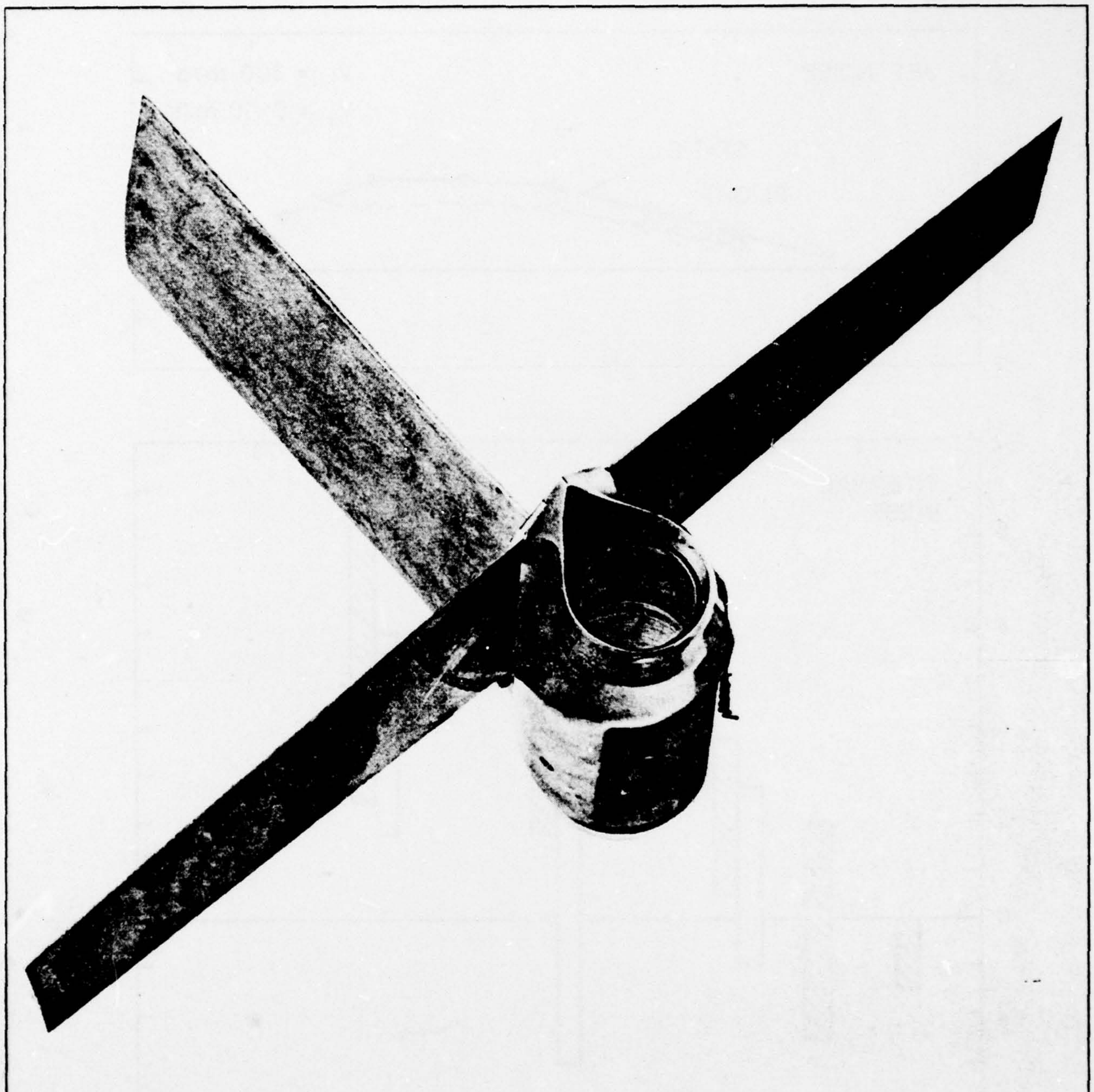


FIG.36 THE MODEL OF THE REAR FUSELAGE OF THE JET PROVOST AIRCRAFT

1244107

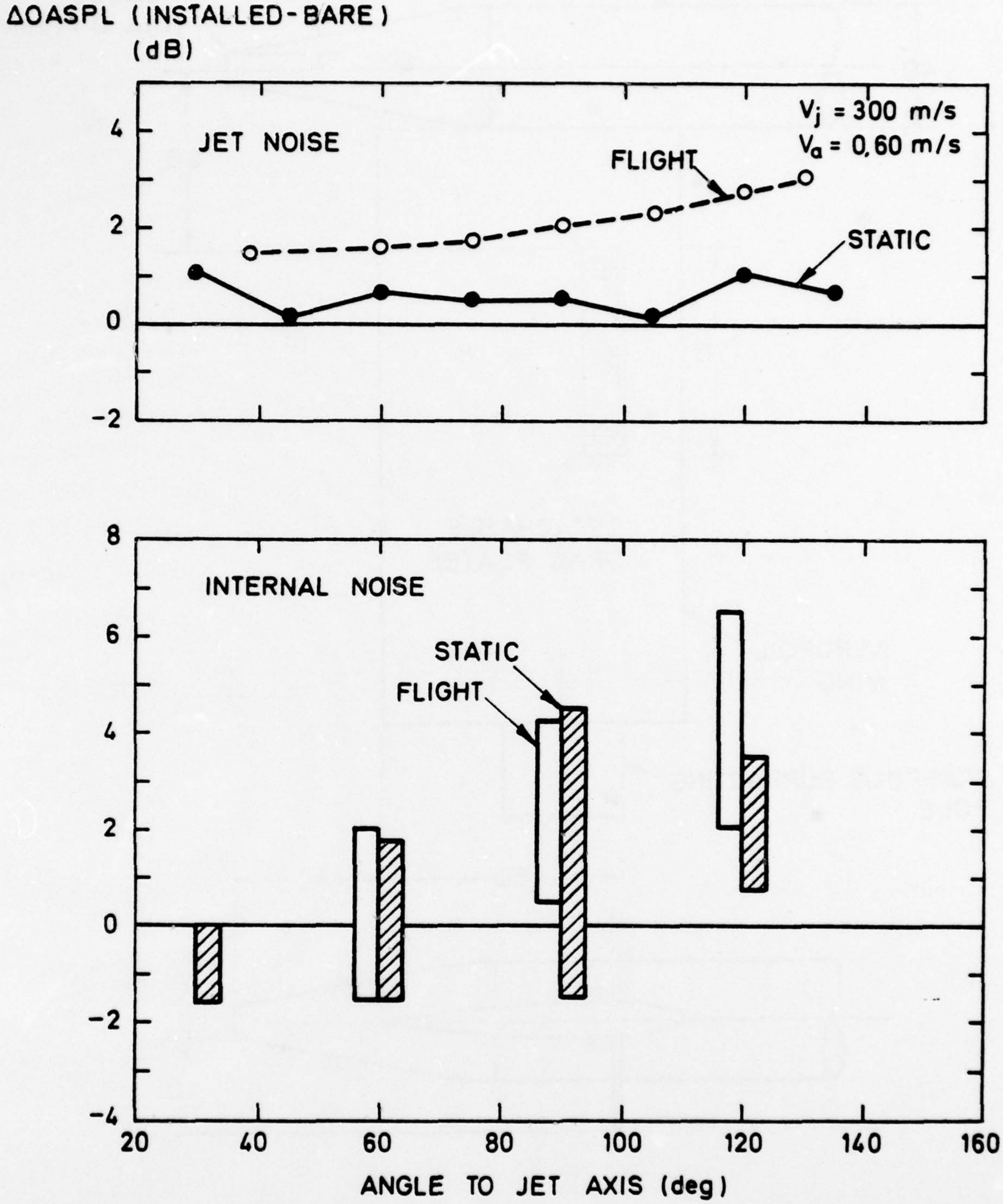



FIG. 37 INSTALLATION EFFECTS FOR THE JET PROVOST MODEL

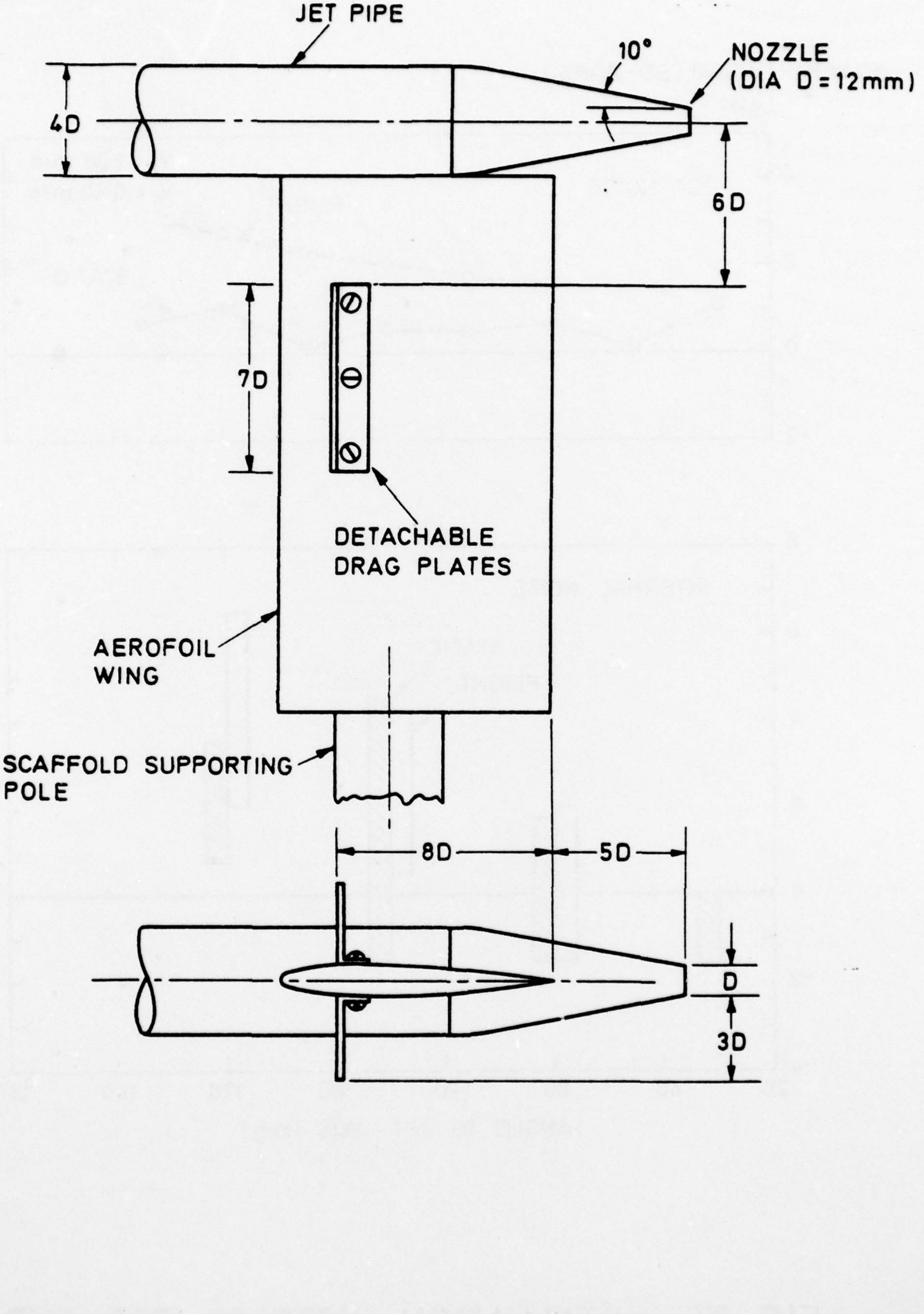



FIG. 38 A DIAGRAM OF THE SPINNING RIG MODEL

124109

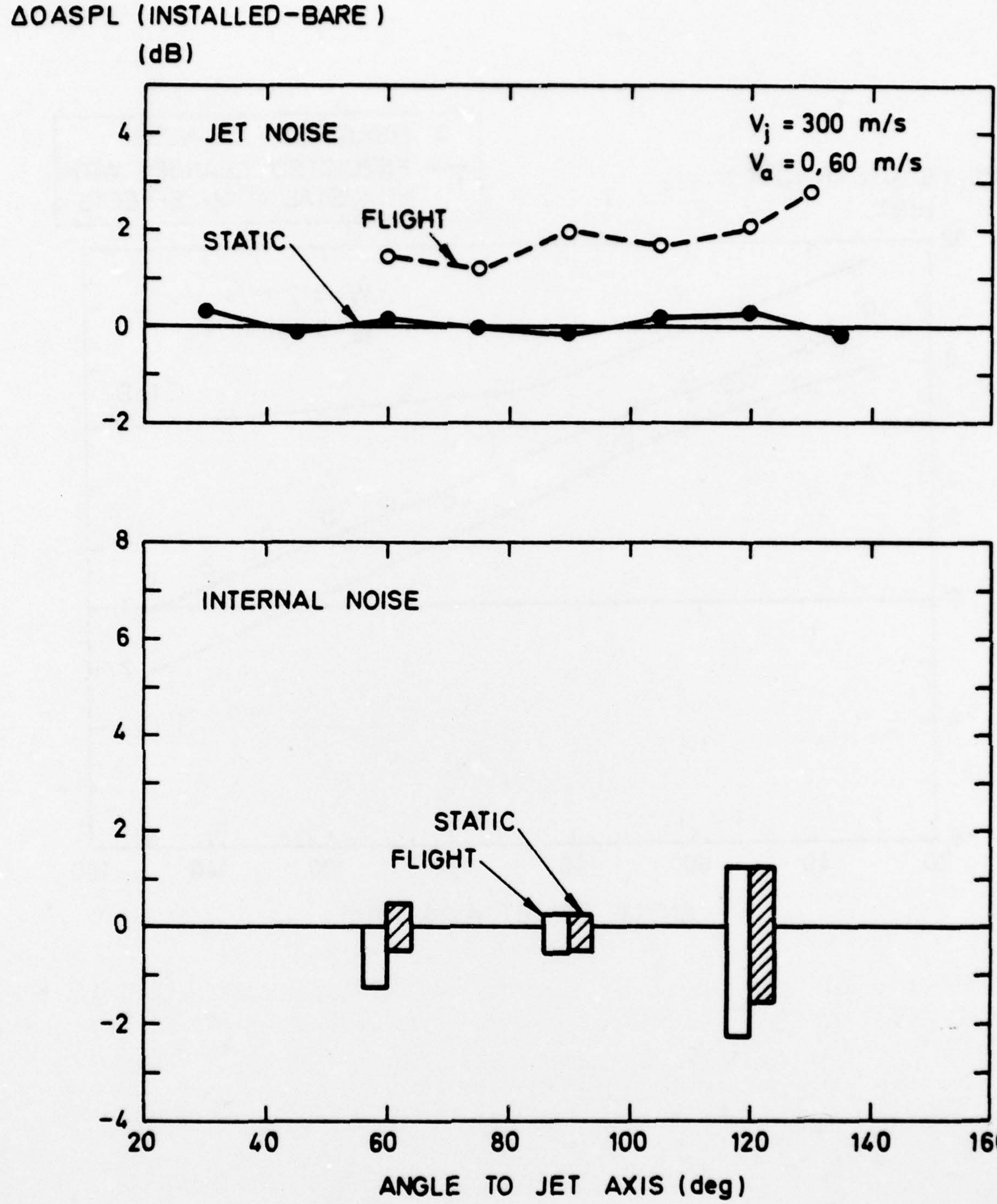



FIG. 39 INSTALLATION EFFECTS FOR THE SPINNING RIG MODEL AT MAXIMUM DRAG

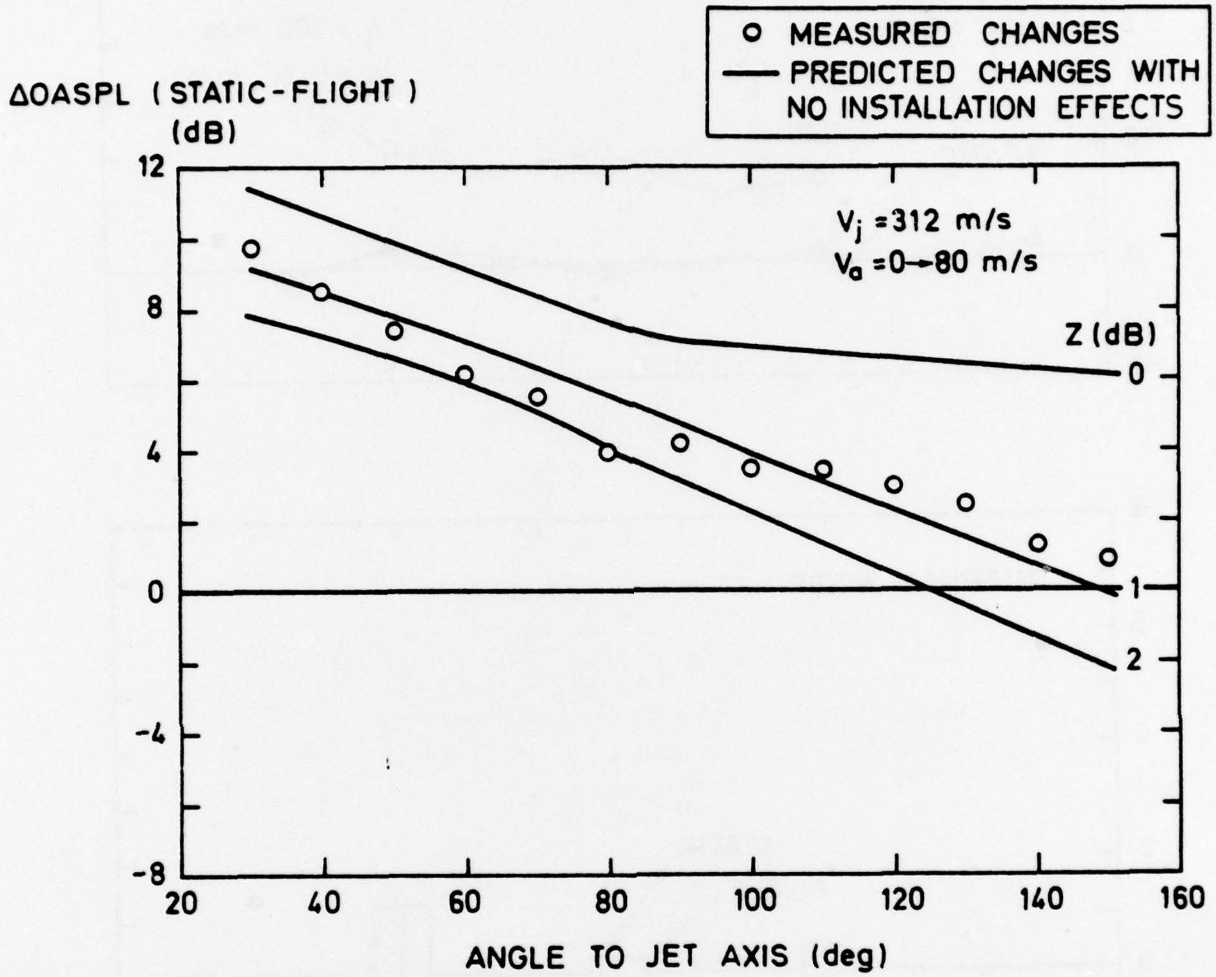



FIG. 40 STATIC-TO-FLIGHT DATA FOR THE SPINNING RIG AT MINIMUM DRAG

1241111

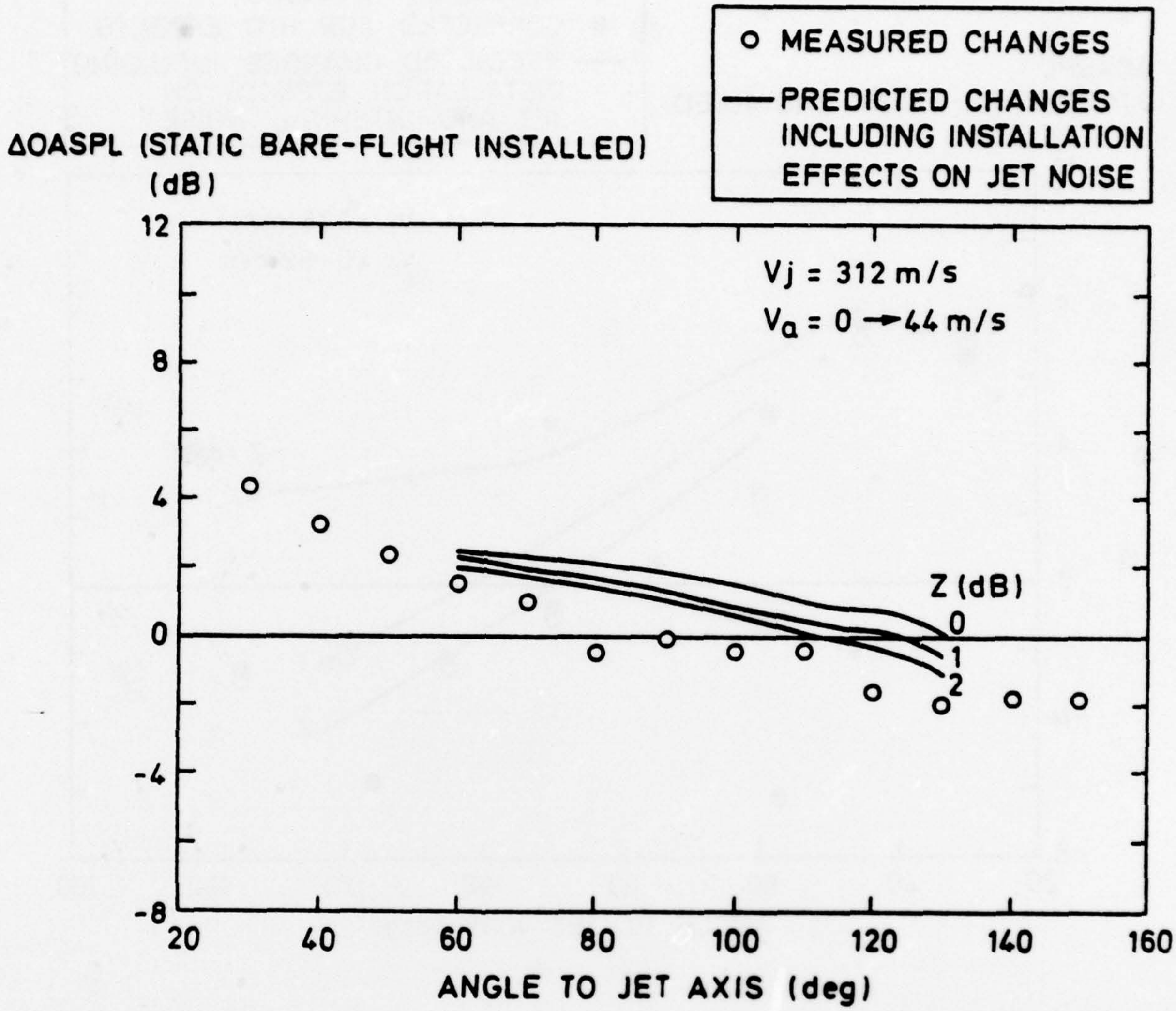



FIG. 41 STATIC-TO-FLIGHT DATA FOR THE SPINNING RIG AT MAXIMUM DRAG

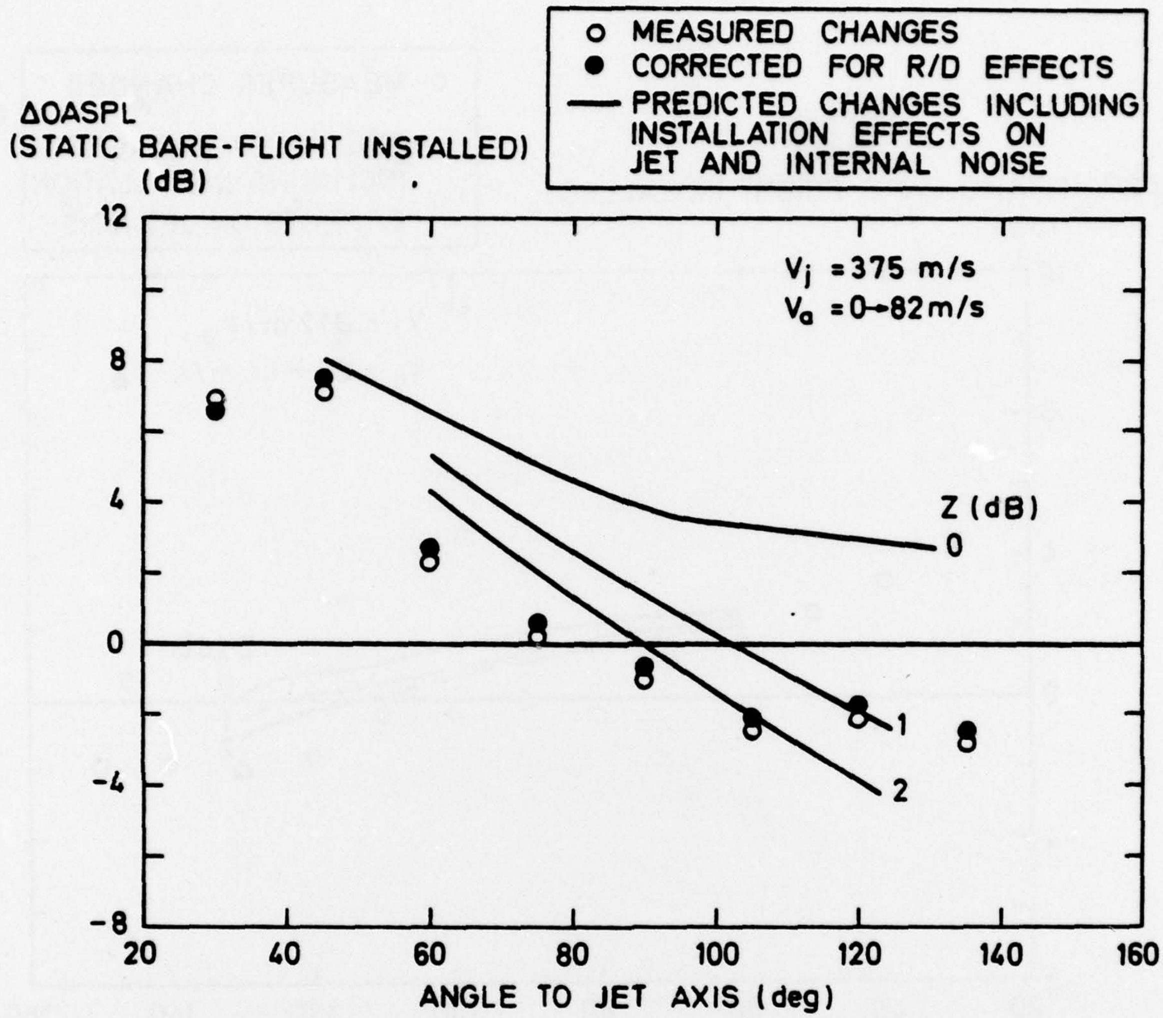



FIG. 42 STATIC-TO-FLIGHT DATA FOR THE VIPER 601/HS 125

124113

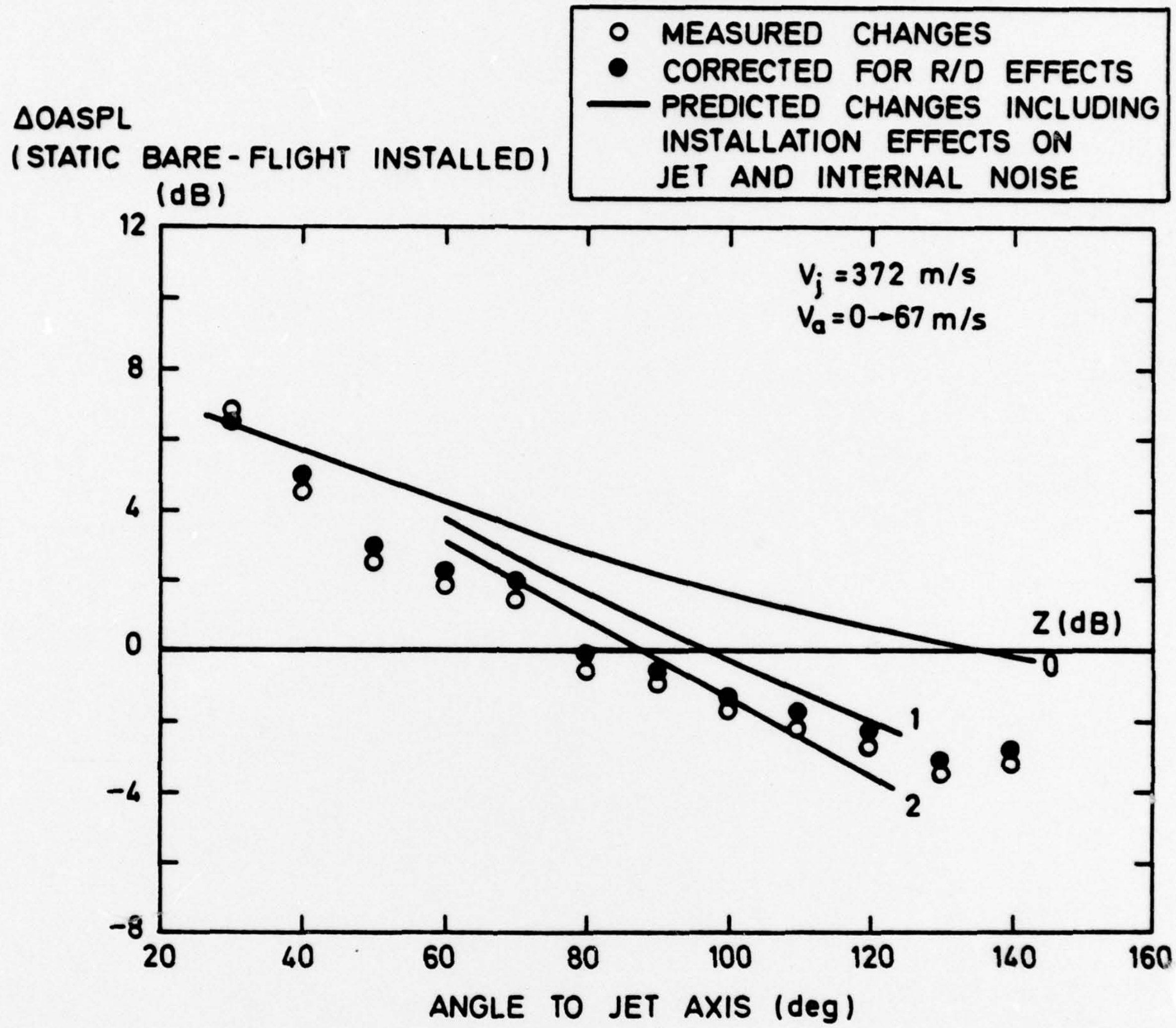



FIG. 43 STATIC-TO-FLIGHT DATA FOR THE VIPER 11/JET PROVOST

## ADVANCE DISTRIBUTION

MOD

CER
DCERC
DGRC/DCS (RAF)
DGEng (PE)
DEngT
DEngD
DRIC (3)

NGTE: Director
DD(Ops)
DD(R&D)
DD(N)
Mr. A. R. Howell
Hd AA Dept
Hd CIT Dept
Hd ER Dept
Hd ET Dept
Hd MS Dept
Hd PDR Dept
Hd TM Dept
Hd XR Dept
NGTE West Drayton Supt NME
NGTE West Drayton Supt NEE
NGTE Cobham Supt
NGTE Haslar Supt
Mr. D. R. Higton
Mr. D. L. Martlew
Mr. T. J. Hargest
Mr. R. A. Pinker
Mr. C. J. Hart
Mr. R. C. K. Stevens
Mr. D. J. Way
Mr. B. A. Turner
Miss E. M. Francis
Mrs. I. M. Casey
Library (3)

DOI

D/RTS4
AD/RTS4B

Mr. R. J. Hill, Rolls Royce Ltd
Dr. B. Barry, Rolls Royce Ltd (3)
Mr. M. J. T. Smith, Rolls Royce Ltd
Dr. K. W. Bushell, Rolls Royce Ltd
Mr. R. Hawkins, Rolls Royce Ltd
Mr. J. R. Brooks, Rolls Royce Ltd
Mr. B. Schofield, Hawker Siddeley Aviation Ltd
Mr. J. A. Hay, British Aircraft Corporation Ltd
Mr. B. Furness, British Aircraft Corporation Ltd
Dr. J. E. Green, RAE
Dr. L. East, RAE
Prof. J. Williams, RAE
Prof. D. J. Crighton, Leeds University
Prof. J. E. Ffowcs Williams, Cambridge University
Dr. M. J. Fisher, Southampton University
Mr. R. Hoch, SNECMA, France
Mr. W. G. Cornell, General Electric Co, USA

ADVANCE DISTRIBUTION (cont'd)

Dr. A. B. Packman, Pratt and Whitney Aircraft Ltd, USA
Mr. R. P. Gerend, Boeing Co, USA
Dr. H. Plumblee, Lockheed-Georgia Co, USA
Dr. J. Merriman, Douglas Aircraft Corp, USA
Dr. U. H. von Glahn, NASA (Lewis)
Dr. H. G. Morgan, NASA (Langley)
Dr. G. Banerian, NASA (HQ)
ARC (Noise Research Committee), (20)
ARC (Applied Aerodynamics Committee), (3)
Garteur 5 Working Group Responsables, (3)

WDB/E3/SJG/93/31/43

**DETACHABLE ABSTRACT CARDS**

These cards are subject to the same Security Regulations as the parent document, and a record of their location should be made on the inside of the back cover.

National Gas Turbine Est. Report No. R78007 — 621.45.035.5
1978.8 — 534.836.2
Bryce, W. D.

A REVIEW OF THE RESEARCH AT NGTE CONCERNING THE EFFECTS OF FLIGHT ON ENGINE EXHAUST NOISE

The problem of explaining the changes of engine exhaust noise in going from static to flight conditions has puzzled research workers for some years. This paper reviews the various experimental research programmes at NGTE which have been carried out on this topic over the last five years. The step-by-step progress which has been made in the analysis of the problem is described and the results from some recent tests, hitherto unpublished, are presented. It is concluded that, together with the characteristics established for jet noise and internally-generated noise in flight, acoustic and aerodynamic effects arising from the installation of engines in aircraft constitute necessary, perhaps sufficient, features of the required explanation.

National Gas Turbine Est. Report No. R78007 — 621.45.035.5
1978.8 — 534.836.2
Bryce, W. D.

A REVIEW OF THE RESEARCH AT NGTE CONCERNING THE EFFECTS OF FLIGHT ON ENGINE EXHAUST NOISE

The problem of explaining the changes of engine exhaust noise in going from static to flight conditions has puzzled research workers for some years. This paper reviews the various experimental research programmes at NGTE which have been carried out on this topic over the last five years. The step-by-step progress which has been made in the analysis of the problem is described and the results from some recent tests, hitherto unpublished, are presented. It is concluded that, together with the characteristics established for jet noise and internally-generated noise in flight, acoustic and aerodynamic effects arising from the installation of engines in aircraft constitute necessary, perhaps sufficient, features of the required explanation.

National Gas Turbine Est. Report No. R78007 — 621.45.035.5
1978.8 — 534.836.2
Bryce, W. D.

A REVIEW OF THE RESEARCH AT NGTE CONCERNING THE EFFECTS OF FLIGHT ON ENGINE EXHAUST NOISE

The problem of explaining the changes of engine exhaust noise in going from static to flight conditions has puzzled research workers for some years. This paper reviews the various experimental research programmes at NGTE which have been carried out on this topic over the last five years. The step-by-step progress which has been made in the analysis of the problem is described and the results from some recent tests, hitherto unpublished, are presented. It is concluded that, together with the characteristics established for jet noise and internally-generated noise in flight, acoustic and aerodynamic effects arising from the installation of engines in aircraft constitute necessary, perhaps sufficient, features of the required explanation.

National Gas Turbine Est. Report No. R78007 — 621.45.035.5
1978.8 — 534.836.2
Bryce, W. D.

A REVIEW OF THE RESEARCH AT NGTE CONCERNING THE EFFECTS OF FLIGHT ON ENGINE EXHAUST NOISE

The problem of explaining the changes of engine exhaust noise in going from static to flight conditions has puzzled research workers for some years. This paper reviews the various experimental research programmes at NGTE which have been carried out on this topic over the last five years. The step-by-step progress which has been made in the analysis of the problem is described and the results from some recent tests, hitherto unpublished, are presented. It is concluded that, together with the characteristics established for jet noise and internally-generated noise in flight, acoustic and aerodynamic effects arising from the installation of engines in aircraft constitute necessary, perhaps sufficient, features of the required explanation.