von KARMAN INSTITUTE FOR FLUID DYNAMICS

DESIGN AND CALIBRATION OF FOUR PROBES FOR USE IN THE TRANSONIC TURBINE CASCADE TESTING

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LIST OF SYMBOLS

k	specific heat ratio
ℓ	reference length
M	Mach number
P	pressure
RE	Reynolds number
s	sensitivity of directional probe
V	flow velocity
α	incidence angle
η	blade efficiency
ν	kinematic viscosity

Subscripts

o	total
1	upstream
2	downstream
s	static
L	left
R	right
is	isentropic
REF	reference
PIT	pitot

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SUMMARY

The work described herein concerns the design and the testing of four probes for the investigation of the flow behind straight transonic turbine cascades. The probes have been designed and manufactured at VKI. The calibration tests were carried out at the DFVLR - AVA - Göttingen and at the von Karman Institute. The probes were investigated in the Mach number range $0.8 \leq M \leq 2.2$ for the range of incidence angles $-12^\circ \leq \alpha \leq +12^\circ$. Special attention is given to the calibration in the transonic domain. The influence of Reynolds numbers on the probe calibrations is studied at $M = 1.64$ and 2.2.

INTRODUCTION

Contrary to measurements in subsonic flow the total pressure measured with a pitot tube in supersonic flow includes the shock losses in front of the pitot probe. This shock is assumed to be normal in the vicinity of the opening of the pitot probe. The shock strength is of course a function of the Mach number and therefore the static pressure has to be known in order to evaluate the true total pressure in the outlet flow. Hence, an error in the static pressure influences directly the total pressure.

The blade performance of turbine cascades is characterized by the ratio of total pressure downstream of the cascade P_{02} to the total pressure upstream of the cascades P_{01} or by the blade efficiency :

$$\eta = \frac{V_2^2}{V_{2,is}^2} = \frac{1 - \left(\frac{P_{s2}}{P_{02}}\right)^{\frac{K}{K-1}}}{1 - \left(\frac{P_{s2}}{P_{01}}\right)^{\frac{K}{K-1}}}$$

If we assume for example that the static pressure in the outlet plane of a shock free two-dimensional nozzle is consistently measured too low by 1 % of the real dynamic pressure $(P_{02} - P_{s2})$, then the nozzle efficiency would increase linearly from $\eta = 100$ % at $M_2 = 1$ to $\eta = 101$ % at $M_2 = 2.0$, while P_{02}/P_{01} would increase in a parabolic way from $\eta = 100$ % at $M_2 = 1.0$ to $\eta = 103.2$ % at $M_2 = 2.0$.

Apart from measuring errors which can be directly attributed to errors in the readings of the pitot pressure and static pressure, the most frequent ones are due to the fact that the pitot pressure and static pressure are measured in two different field points with non-identical flow conditions.

The strong pressure variations in the outlet flow field of transonic turbine cascades require in fact that the total, static and directional pressure be measured in the same field point. This is obviously not achievable and has to be replaced by the requirement of the probe head being very small compared to the cascade dimensions. If the flow is two-dimensional, it is possible to measure the total, static and directional pressure on the same stream surface, which allows to use 2 or 3 separated pressure tubes aligned parallel to each other with all measuring holes lying on a line normal to the flow direction. In any way, the success of obtaining reliable cascade data is very closely linked to the ability of reducing the probe dimensions. Miniaturizing of the probes is also mandatory in order to limit an alteration of the outlet flow field at transonic Mach numbers by the presence of the probe. Furthermore, the probe parts ahead of the measuring holes have to be kept to a minimum.

The aim of this note is not the presentation of new probe concepts but rather a comparison of the characteristics of various probe designs which have already found applications in cascade testing and which are susceptible to present an adequate answer to the particular problem of transonic turbine cascade testing. An effort has been made in view of reducing the probe dimensions to a minimum size.

2. PROBE DESIGNS

The design of a probe for the use in the outlet flow field of transonic turbine cascades is, in most cases, a compromise between the need of reducing the probe dimensions, the requirement of short response times and good probe characteristics. The following probe characteristics are desirable :

1. The pitot pressure does not need any correction in the whole Mach number and incidence range.
2. The correction of the static pressure is accessible to theoretical considerations in order to limit the calibration work.
3. The directional probe is sensitive to flow angle variations and has a linear calibration curve over a wide range of incidence angles.

Four probes have been designed and manufactured at VKI (Fig. 1). The predominant factor in all four designs was the choice of the static pressure probe and the position of the static pressure holes with respect to the pitot tube opening. According to their characteristic features, the probes are called :

1. NEEDLE-probe,
2. CONE-probe,
3. TRUNCATED-CONE-probe,
4. WEDGE-probe (AVA).

The NEEDLE-probe consists of a long needle static pressure probe and separated from it, a combined total-directional probe. The length between the cone head of the static pressure tube (cone angle 15°) and the measuring holes are $12 \times d$ ($d = 1.5$ mm) while the length between the measuring holes and the probe stem amounts to $15 \times d$. The two tubes of the directional probe lie on both sides of the pitot tube, their openings are cut under an angle of 35° with respect to the tube axis. All measuring holes of the needle probe lie on a line normal to the flow direction.

The CONE-probe measures the static pressure on a 30° cone by means of 4 measuring holes (4 × 90°) at 1.3 mm from the cone head. The total-directional probe is the same as for the needle probe. The pressure holes on the cone line 0.6 mm behind the openings of the total-directional probe.

The TRUNCATED-CONE-probe consists of a combined total-static pressure probe and, separated from it, a directional probe. The combined total-static pressure tube is made out of two co-axial tubes : the inner pitot tube and the outer static pressure tube with the truncated cone of 25° cone angle. The static pressure is measured on the cone by 6 × 60° holes at 1,5 mm from the tip. The openings of the directional tubes are lined up with that of the pitot tube. The directional tubes are cut under an angle of 40° with respect to the tube axis.

The WEDGE-probe has originally been developed at the AVA-Göttingen (Ref. 1). The probe shown in figure 1 is a somewhat modified version with reduced dimensions. Contrary to the other probes, the wedge-probe incorporates the holes for the pitot, static and directional pressure in one unit only. The pitot tube is situated in the center of the wedge and exceeds the wedge edge by 0.1 mm. The directional holes lie on the upper and lower side of the wedge at a distance of 1.3 mm behind the wedge edge. The static pressure is measured on both sides of the wedge behind a step which is situated at 1.1 mm behind the wedge edge.

It should be noted that the directional elements of each probe can of course also be used in a zero balancing mode for the determination of the static pressure.

3. CALIBRATION TESTS IN THE TRANSONIC WIND TUNNEL OF THE DFVLR/AVA GÖTTINGEN

The main body of the calibration work was carried out at the DFVLR/AVA under contract for VKI. The tests were made in the large transonic wind tunnel (test section of 1 m × 1 m). This tunnel was chosen because of the possibility of varying the tunnel Mach number continuously in the range of interest, i.e., $0.8 < M < 2.2$ and because the large test section would allow to test all 4 probes simultaneously.

3.1 Test set up and calibration procedure

The AVA transonic wind tunnel is a closed loop wind tunnel with continuous operation. The tunnel has a transonic test section with perforated walls for the Mach number range $0.8 < M < 1.2$ and a supersonic test section at the nozzle exit for the Mach number range $1.2 < M < 2.21$. The dimensions for both test sections are 1 m × 1 m. The figures 2a and 2b show a schematic sketch and a photograph of the probe holder with the 4 VKI probes and an additional AVA probe mounted in the center of the probe holder. Some schlieren pictures (Fig. 2c) illustrate the shock patterns at a Mach number of $M = 1.41$.

Because of certain anomalies in the tets results, it was later deemed necessary to repeat the calibration with each probe separately. Figure 3a shows the probe holder with one single probe and Figure 3b the set up in the wind tunnel.

The tests were run in the transonic Mach number range $(0.8 < M < 1.2)$ at a stagnation pressure $P_0 \simeq 1$ ata and in the supersonic range $(M > 1.2)$ at $P_0 \simeq 0.8$ ata. The Reynolds number in the test section based on a reference length of 1 m is of the order of 0.75×10^7 to 1.4×10^7. The relation between the Reynolds number and the Mach number is presented in Fig. 4. The reference values of the total and static pressures in the test section for a given nozzle set up, i.e., at a given Mach number, are known from previous calibration tests of the empty test section.

3.2 Test results

3.2.1 Significance of blockage effect of probe and probe holder for the simultaneous calibration of several probes

As mentioned before, two test series have been run :
1. a simultaneous calibration of all probes mounted together in the test section (referred to as "common calibration" in figures 6 and 8) and
2. a calibration of each probe mounted separately in the test section (referred to as "single calibration" in figures 6 and 8). The necessity of the second test series became apparent after a quick critical check of the test results of the "common calibration". It was found that :

1. The calibration curves for the AVA-probe showed considerable differences in the transonic domain in comparison with previous calibration results.
2. The calibration curve for the static pressure of the NEEDLE probe indicates excessive errors in the transonic range (up to 22 % of the dynamic pressure at an angle of attack $\alpha = 0$) and still unexpected high errors in the supersonic Mach number range (3 % of dynamic head at $M = 2.2$ for $\alpha = 0$).

From a detailed investigation performed at the AVA, it was concluded that the simultaneous calibration of all probes was not a suitable test procedure. As possible error sources, one must consider :

1. interference effects between the probes,
2. slight vibration of the probes due to an insufficient rigidity of the probe holder,
3. blockage effect of probes and probe holder.

The last point is of particular importance in the transonic domain. It is obvious that the variation of the flow field in the environment of the probes due to the blockage effect of probes and probe holder is much stronger and reaches much further upstream than in the case of the calibration of a single probe. Furthermore, it is evident that the blockage effect for given dimensions of a probe and the probe holder depend on the dimensions of the tets section. Two questions then arise :

1. what is the appropriate environment for the probes during the calibration procedure (size of test section) ?
2. do we have to measure the reference values for the total and static presure inside or outside of the influence field of probe and probe holder ?

These questions need an adequate answer for the sake of testing turbine and compressor cascade at transonic outlet flow Mach numbers.

The test results of the "common calibration" are not presented in detail. The main results will, however, be compared with those of the "single calibration" in order to underline the significance of the probe blockage effect on the test results.

3.2.2 Single probe calibration

The results of the single probe calibration are shown in figures 5 to 9. The data are presented in the following form :

Total pressure probe : $$\frac{(P_0)_{REF} - (P_0)_{PROBE}}{(P_0 - P_s)_{REF}} = f(\alpha)$$

Static pressure probe : $$\frac{(P_s)_{REF} - (P_s)_{PROBE}}{(P_0 - P_s)_{REF}} = f(\alpha)$$

Directional probe : $$\frac{P_L - P_R}{(P_0 - P_s)_{REF}} = f(\alpha)$$

Sensitivity of directional probe : $S = \frac{P_L - P_R}{(P_0 - P_s)_{REF}}$ per degree incidence angle

with the tunnel Mach number M_{REF} as free parameter and

$\left.\begin{matrix}(P_0)_{REF} \\ (P_s)_{REF}\end{matrix}\right\}$ real total and static pressure in the test section

$\left.\begin{matrix}(P_{pit})_{PROBE} \\ (P_s)_{PROBE}\end{matrix}\right\}$ measured total and static pressure in the test section by probe to be calibrated. In supersonic flow P_{pit} represents the total pressure behind the bow wave (normal shock) in front of the probe head

$\left.\begin{matrix}P_L \\ P_R\end{matrix}\right\}$ directional pressures

α flow angle with respect to probe axis

The calibration covered the incidence angle range of $-12° < \alpha < +12°$ and the Mach number range $0.8 < M < 2.2$.

Total pressure corrections (Figs. 5 and 6): The measured total pressure of the 4 probes is practically independent of the variation of the incidence angle covered in the tests in the whole Mach number range. The only exception is the wedge probe at an incidence angle of 12° in the Mach number range $0.8 < M < 1.33$ which shows a slight pressure drop. The pitot tubes measure the correct total pressure at subsonic Mach numbers. The difference between P_{pit} and $(P_0)_{REF}$ at supersonic Mach numbers follows very closely the normal shock relations up to $M = 1.8$ (Fig. 6). For Mach numbers $M > 1.8$, the measured values start to fall below the theoretical curve which indicates that the shock losses are somewhat less than those corresponding to a normal shock.

Static pressure corrections (Figs. 7 and 8): The shape of the calibration curve and the magnitude of the deviation of the measured static pressure from the reference static pressure vary significantly for the various probe designs. The calibration curves for the NEEDLE-probe and WEDGE-probe are symmetric to the zero incidence angle axis and have a simple parabolic shape. The curves for the TRUNCATED-CONE-probe are in general symmetric to the zero incidence angle axis, but their shape can only be approximated by a higher order equation. The asymmetry of the CONE-probe calibration curves might be caused by a slight asymmetric position of the 4 pressure holes on the cone envelope or by imperfections of the cone nose.

The error of the static pressure measurements at zero incidence is plotted in figure 8a in function of the Mach number. This figure also includes the results of the simultaneous probe calibration. The test results for the single probe calibration outside of the transonic range, i.e., $M > 1.2$, are very encouraging. The tests confirm in fact that the NEEDLE-probe needs only very little correction (maximal error of 1 % in the range $1.2 < M < 2.2$) and that the curves for the CONE-probe and TRUNCATED - CONE-probe follow very closely the theoretical value of the static pressure on a 30° and 25° cone. A comparison of the theoretical and experimental curves is shown in figure 8b. The difference for the 25° cone amounts to about 0.6 to 0.8 % in the Mach number range $1.3 \leq M \leq 2.1$ while for the 30° cone differences of 0.3 to 0.6 % are recorded. The higher differences for the 25° cone have to be attributed to the blunt nose. The relation of the static pressure error versus Mach number is not directly accessible to theoretical considerations in the case of the wedge probe, however, the smooth behaviour of the measured calibration curve will be helpful for future calibrations of similar probes. It should be noted that the measuring points for $M = 1.63$, which all lie far off the curves, are obviously wrong, as this phenomenon occurs systematically for all probes.

As mentioned earlier, the directional element of each probe might also be used for measuring the static pressure. In this case, we use

$$P_{s,probe} = \frac{P_L + P_R}{2}$$

Figure 8c represents the case where the directional tubes of the NEEDLE-probe are used to measured the static pressure at zero angle of attack. It is obvious that the insensitivity in the Mach number range M = 1.0 to 1.3 excludes the use of such a probe in this domain. However, for M > 1.4, the static pressure correction factor depends not only strongly on the Mach number, but moreover, it is a linear function of the Mach number.

The curves for the simultaneous probe calibration deviate in the range M > 1.2 in general by 1 % to 2 % from the single probe calibration. Possible reasons are interference effects and vibration of probe holder as already mentioned .

The transonic regime 0.8 < M < 1.2 is characterized by very high static pressure errors for all probes. The influence of the different blockage effects for the single anf common calibration is clearly demonstrated. In the case of the NEEDLE-probe, the different blockage effect is expressed by a reduction of the static pressure error from -22% to -16% at M = 1.05 and a reduction from -14% to -7% at M = 0.8. The remaining error is, however, still much too high in order to attribute it simply to the NEEDLE-probe. If the static pressure tube of the NEEDLE-probe indicates errors in the transonic domain significantly different from those in the subsonic domain, these differences are due either to small normal shocks formed on the static pressure tube itself somewhere ahead of the measuring holes or to the interference of the bow wave, generated by the pitot tube, with the static pressure tube ahead of the measuring holes. However, normally for slender bodies like those considered here, these effects should occur only for M > 0.9 - 0.95.

It must therefore be concluded that also in the case of the single probe calibration, the high errors recorded for the NEEDLE-probe in the range 0.8 < M < 1.1 are due to strong upstream effects of the probe holder. The fact that M_{REF} is based on measurements with an empty test section entails that the static pressure measured by the NEEDLE-probe is compared to a reference static pressure obtained in a different flow field. Hence, the blockage effect of the probe holder has to be reduced further or the reference static pressure has to be measured within the influence field of the probe holder. These conclusions are of course also applicable for the other probes.

Directional pressure coefficient: The variation of the directional pressure coefficient in function of the incidence angle and the free stream Mach number is plotted in figure 9.

The two main requirements for a directional probe are :
1) a good sensitivity and
2) a linear relationship between the directional pressure coefficient and the Mach number.
Both characteristics depend mainly on the included wedge angle (or equivalent wedge angle for a side by side arrangement of single tubes). If the directional probe is a combination of single tubes (NEEDLE-probe, CONE-probe, TRUNCATED-CONE-probe) both the sensitivity and the linearity depend furthermore on the alignment of the holes with respect to the stream surface and the arrangement of the tubes to each other (tube P_L and tube P_R side by side or separated by a pitot tube).

The best linearity is obtained with the directional elements of the NEEDLE-probe and TRUNCATED-CONE-probe. The calibration curves for both cases can be approximated with good accuracy by a straight line in the angle range of ± 10°. The sensitivity of these probes, expressed by the slope of the curves in figures 9a and 9c is plotted in figure 9e. Both curves show a strong Mach number dependence in the range $M = 0.8$ to 1.6 (almost linear relationship). This dependence is, however, greatly reduced for $M > 1.6$. The difference between both curves is mainly due to the difference of the equivalent wedge angle (70° for NEEDLE-probe, 80° for TRUNCATED-CONE-probe).

The directional element of the CONE-probe is the same as for the NEEDLE-probe, however, a non-alignment of the openings of the directional tubes with respect to the stream surface produces a slight S-shape of the calibration curves (Fig. 9b).

The irregularities of the calibration curves for the WEDGE-probe (Fig. 9d) are difficult to explain. The range of incidence angles in which all curves can be approximated with a sufficient accuracy by a straight line is limited to $\alpha = \pm 6°$ to 8°.

The variation of the zero error (defined by the intersection of the calibration curves with x-axis) for a change in M_{REF} is probably due to a lack of accuracy in the geometric setting of the probes.

4. TESTS WITH THE NEEDLE-PROBE AT TRANSONIC MACH NUMBERS IN THE VKI HIGH SPEED CASCADE TUNNEL C-2

Based on the conclusions concerning the calibration results in the transonic domain as obtained in the AVA transonic wind tunnel, an additional test series was run in the VKI high speed cascade tunnel C-2 to study more closely the characteristics of the NEEDLE-probe in this range. The use of this tunnel presents the advantage of calibrating the probe in an environment which is very similar to the outlet section of transonic turbine cascades tested in the same tunnel.

4.1 Test set up and calibration procedure

The C-2 tunnel was equipped for these tests with a convergent nozzle which is followed by a sudden area enlargement. The test section dimensions at the nozzle exit are 135 mm x 50 mm and behind the enlargement 195 mm x 50 mm (Fig. 10). The Mach number behind the nozzle exit depends on the settling chamber pressure and the distance of the measuring plane with respect to the nozzle exit.

The NEEDLE-probe was tested in the Mach number range $0.5 < M < 1.05$ at zero incidence. The reference static pressure in the test section was measured by a pressure tapping on the tunnel side wall, in presence of the NEEDLE-probe. The quality of the side wall pressure measurements was checked before by comparing them with the measurements of a single AGARD needle probe in the center of the test section. Figure 10 shows the arrangement of the probes in the test section. The reference total pressure was measured by a pitot tube placed just upstream of the nozzle exit. The relation between the settling chamber pressure and the reference total pressure in the test section was measured once for all before starting the calibration tests.

4.2 Test results

The comparison of the reference wall static pressure with the AGARD needle measurements at mid-span is presented in figure 11. The difference between both measurements is very small. A maximum deviation of 0.7 % of the dynamic head is recorded at M = 1.05.

A comparison of the side wall pressure distribution in the measuring plane with and without probe in the test section shows a negligible blockage effect of the single AGARD needle probe while the presence of the NEEDLE-probe alters considerably the flow field for M > 0.9. The reason is that the shaft of the AGARD probe is about twice as far behind the measuring plane as the shaft of the NEEDLE-probe.

The reference static pressure was measured on the same side wall on which the NEEDLE-probe was mounted (Fig. 10). Therefore, the wall pressure is influenced in the same way by the probe shaft as the needle static tube in the free stream.

The calibration results are presented in figure 12 which also shows, for comparison purposes, the calibration curve obtained in the AVA transonic wind tunnel. The static pressure errors obtained at VKI are considerably smaller than those at AVA. The VKI values recorded at M = 0.8 and 1.0 are -1.2 % and -3 % instead of -7 % and -13 % found at AVA. However, a comparison of the static pressure measured by the NEEDLE-probe and the wall pressure measured without the presence of any probe in the test section, showed very similar results as those obtained at AVA. One should therefore insist on the fact that the differences in figure 12 are due to the differences in the reference static pressure, i.e., whether the reference static pressure is measured in the presence or the absence of the probe to be calibrated.

4.3 Investigation of the bow wave generated by a pitot tube at M = 1.06

In order to study more closely the strength of the pitot tube bow wave at the intersection point with the needle static pressure tube of the NEEDLE-probe a test series was run in which the bow wave of a pitot tube of 2 mm diameter was traversed at a distance of 16 mm by a single AGARD needle probe with a tube diameter of 1.5 mm. The AGARD probe was introduced through the side wall, the pitot probe from the bottom of the tunnel. Both probes were placed at mid-stream (Fig. 13). The wall pressure distribution was measured parallel to the AGARD needle probe. The results are presented in figure 14.

Both the AGARD probe and the side wall pressure tappings measure the Mach number ahead of the shock as M = 1.06. The shape and position of the bow wave as taken from schlieren photographs at M = 1.06 are drawn to scale in figure 14. In the case of zero displacement of the AGARD needle probe (i.e., static pressure measuring holes aligned with pitot probe opening) the bow wave would intersect with the needle tube at a distance of 3.0 mm ahead of the measuring holes. In that case, the Mach number measured with the AGARD probe behind the bow wave is $M_{AGARD} = 1.0$. In order to correct the measurements behind the bow wave to the undisturbed flow conditions ahead of it, the static pressure read by the AGARD probe needs a correction of 7 % of the dynamic head $(P_0 - P_s)_{REF}$. The side wall pressure tappings which are approximately twice as far from the pitot probe than the AGARD needle probe are much less influenced by the bow wave. The Mach number changes only from M = 1.06 ahead of the shock to M = 1.04 behind the shock.

The fact that there is a non-negligible influence of the bow wave on the wall presure measurements indicates that the reference wall static pressure for the calibration tests in figure 12 also does not correspond to the undisturbed flow conditions ahead of the bow wave. The influence of the bow wave on the wall pressure measurements is, however, not necessarily the same in both cases because of the difference in the frontal area of the shock generators.

The test results allow to conclude that an error of the static pressure measurement of 7 % at M = 1.06 presents a maximum value for the NEEDLE-probe; the real value should lie between 5 % and 7 %.

5. INFLUENCE OF RE-NUMBER ON CONE-PROBE, TRUNCATED-CONE-PROBE AND WEGDE-PROBE AT M = 1.64 and 2.2

(VKI SUPERSONIC WIND TUNNEL S-3)

The calibration tests in the closed loop AVA transonic wind tunnel were carried out for the transonic Mach number range at an absolute total pressure of P_0 = 1 atm and for the supersonic Mach number range at P_0 = 0.8 atm. (Fig. 4). However, the probes are intended to be used in the VKI high speed cascade tunnels which are of the blowdown type with exhaust to atmosphere. These tunnels are operated for transonic turbine cascade testing with settling chamber pressure of the order of 2 to 4 atm. An additional test series was therefore performed in the VKI supersonic wind tunnel S-3 in order to investigate possible Re-number effects on the probe calibrations. The tests were limited to high supersonic Mach numbers (M = 1.64 and 2.2) because of the rather small dimensions of the S-3 tunnel. This test series did not include the calibration of the NEEDLE-probe.

5.1 Test set up and calibration procedure

The supersonic wind tunnel S-3 (Fig. 15) is, like the high speed cascade tunnels, of the blowdown type facility with exhaust to atmosphere. The inlet duct consists of a straight fixed lower nozzle block and a contoured interchangeable upper nozzle block. Two contoured nozzle blocks for M = 1.64 and 2.2 were used for this test series. The test section measures 60 mm × 50 mm. A variable supersonic diffuser downstream of the test section allowed to obtain a fully developed supersonic flow in the test section for both nozzle configurations at an absolute pressure in the settling chamber as low as P_0 = 2 atm. The tests were performed in the range of P_0 = 2 to 4 atm.

The reference static pressure in the test section was measured by an AGARD needle probe and the reference pitot pressure by a single pitot tube with an outer to inner diameter ratio

$\frac{D}{d}$ = 3. The stems of the reference probes as well as those of the probes to be calibrated did in no case alter the flow conditions in the measuring plane. Each probe was put separately into the tunnel. The repeatability of the test conditions was checked by a pressure tapping on the lower nozzle block in the measuring plane.

5.2 Test results

The test results in figure 16 present only the data for zero incidence angle. The graph shows both VKI and AVA data. In case that the VKI and AVA results were not obtained at the same Mach number, the AVA data in figure 16 present interpolated values from the calibration curves in figure 7.

It is very difficult to draw any definite conclusions about the influence of the Re-number on the various probes. The problem lies in the fact that no comparative data are available between the VKI and AVA results for the same Re-numbers . Hence, we are unable to properly eliminate the differences which are inherent to the use of two different calibration tunnels, two different measuring systems, etc. Nevertheless, the tests indicate that

1) the CONE-probe and the TRUNCATED-CONE-probe are not at all or only very little influenced by a change in Reynolds number in the investigated Mach number range;
2) the WEDGE-probe is very sensitive to a Re-variation at M = 1.64 At M = 2.2 the Re-effect is trongly reduced but seems still to exist.

It should be noted that the present VKI data of the WEDGE-probe (open circles) are confirmed by 2 data points (open triangles) from earlier VKI tests with a very similar wedge probe.

Obviously, these tests are only of very restricted value. More testing is needed in order to cover a wider range of Re-numbers and Mach numbers.

6. CONCLUSIONS

- The pitot pressure readings of all probes follow very closely the normal shock relations in the supersonic domain up to $M = 1.8$. For $M > 1.8$, the measured bow wave losses are smaller than those corresponding to a normal shock. The deviation increases with increasing Mach number.
The pitot pressure of all probes is independent of an incidence angle variation for the range of ± 10°.

- In the supersonic Mach number range, the NEEDLE-probe needs at zero incidence less than 1 % correction for the static pressure. The static pressure measured with the CONE- and TRUNACTED-CONE-probe follows at zero incidence the theoretical values within 0.3 to 0.8 %. The WEDGE-probe (AVA) requires very high corrections but all the calibration curves are of simple parabolic shape.

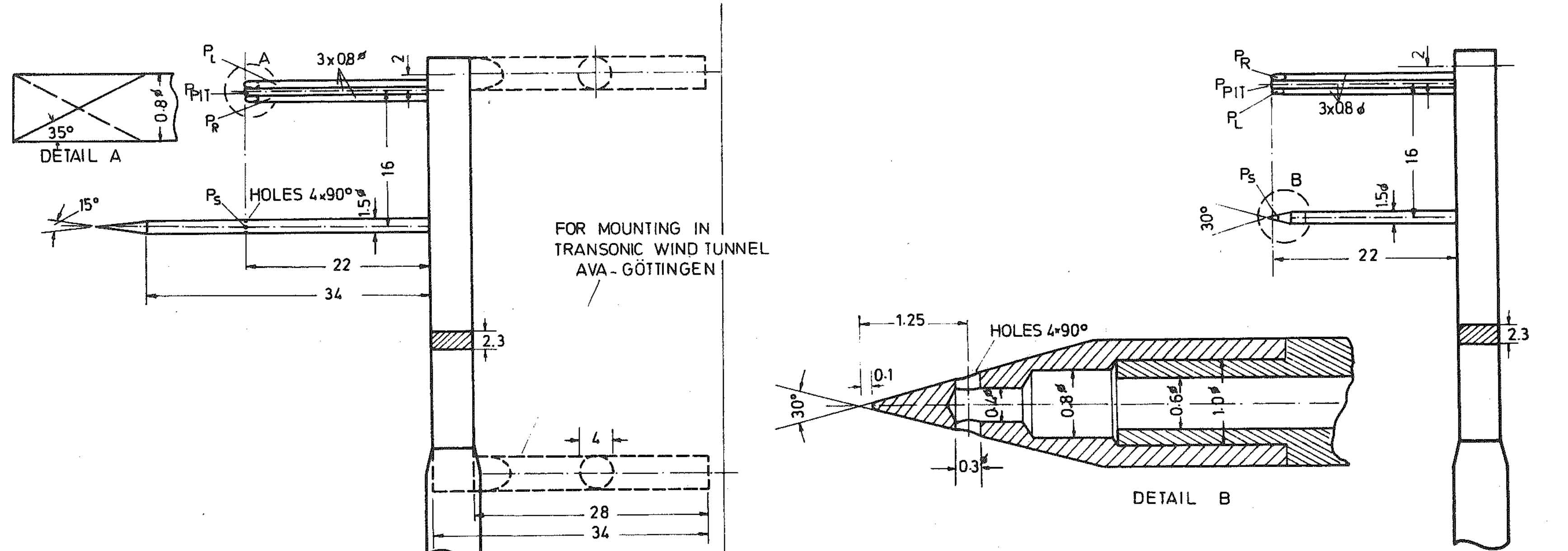
- The calibration in the transonic regime requires much more attention. This problem is not only the problem itself of performing measurements in the transonic domain, but it has to be seen in connection with the final purpose of the calibration, i.e., the measurement of the performance of a transonic turbine cascade at transonic outlet Mach numbers with a relatively big probe at a relative short distance from the trailing edge plane. In fact, the blockage effect of the probe stem and probe holder can be compared to the effect of a local back pressure valve which might not only modify the outlet flow field but also the complete passage flow. Hence, it would not only be advisable to calibrate the probes in a tunnel of similar size as the cascade tunnel in order to simulate the same blockage effect, but also to measure the reference pressures in presence of the probe to be calibrated, i.e., within the modified flow field, because this is the one which is also going to exist at the cascade exit.

- The principle used for the directional probes of the NEEDLE-probe, CONE-probe and TRUNCATED-CONE-probe give in general satisfactory results in the incidence angle range of ± 10°; however, the linearity of the curves depends strongly on a precise alignment of measuring holes with respect to the stream surface. The relatively small wedge angle of the WEDGE-probe limits the linear range to ± 6° to 8°.

- Contrary to the CONE-probe and TRUNCATED-CONE-probe, the WEDGE-probe characteristics are Re-number dependent.

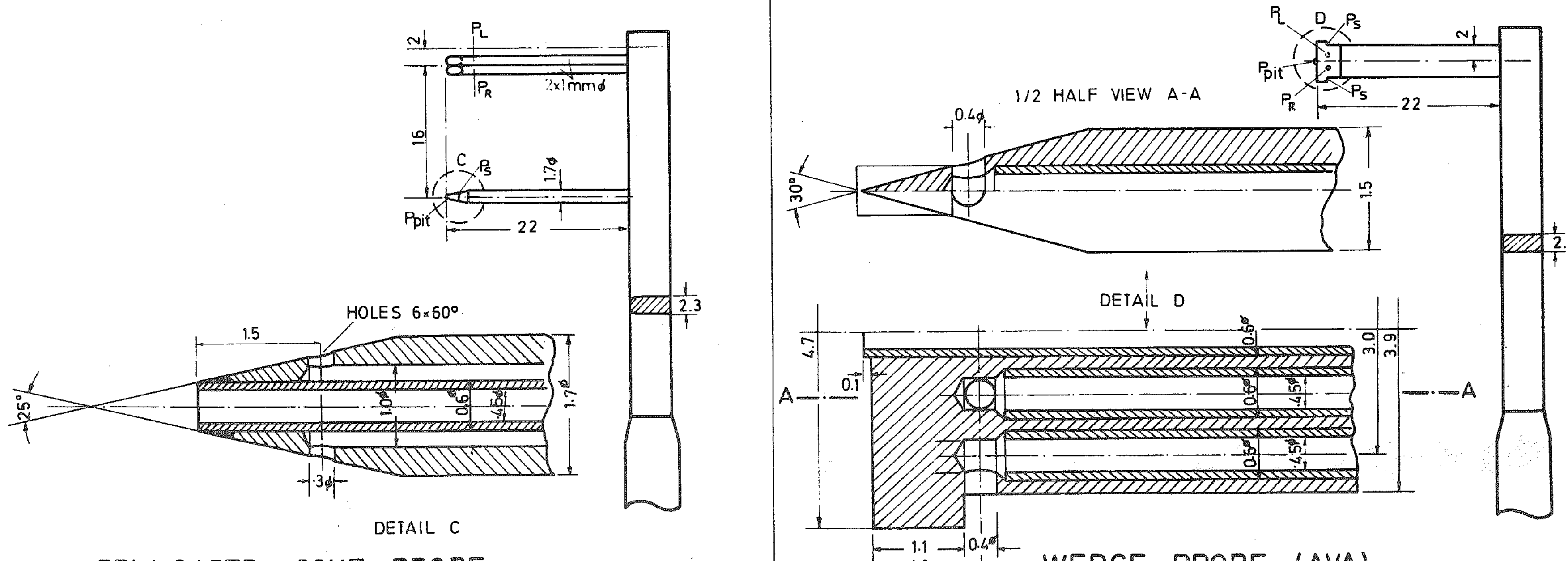
REFERENCES

1. AMECKE, J. and LAWACZECK, O.: Aufbau und Eichung einer neuentwickelten Keilsonde für ebene Nachlaufmessungen, insbesondere im transsonischen Geschwindigkeitsbereich. DLR - Forschungsbericht 70-69, 1970.



NEEDLE PROBE

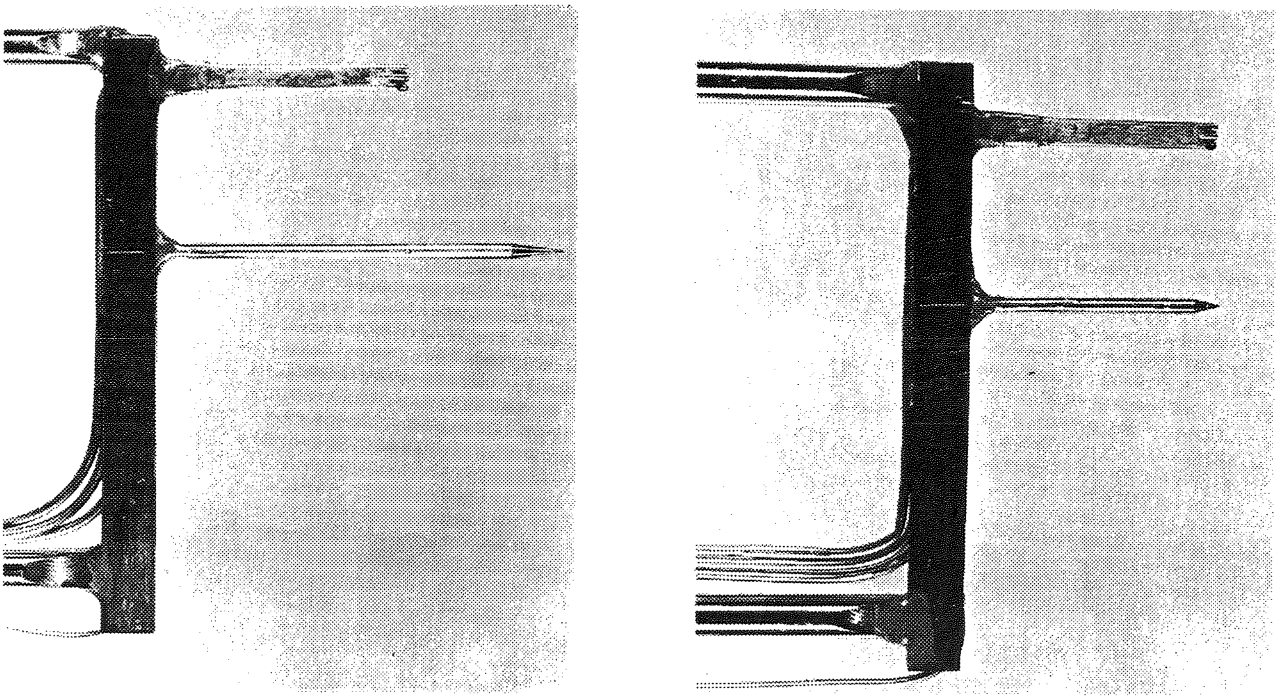
CONE PROBE



TRUNCATED CONE PROBE

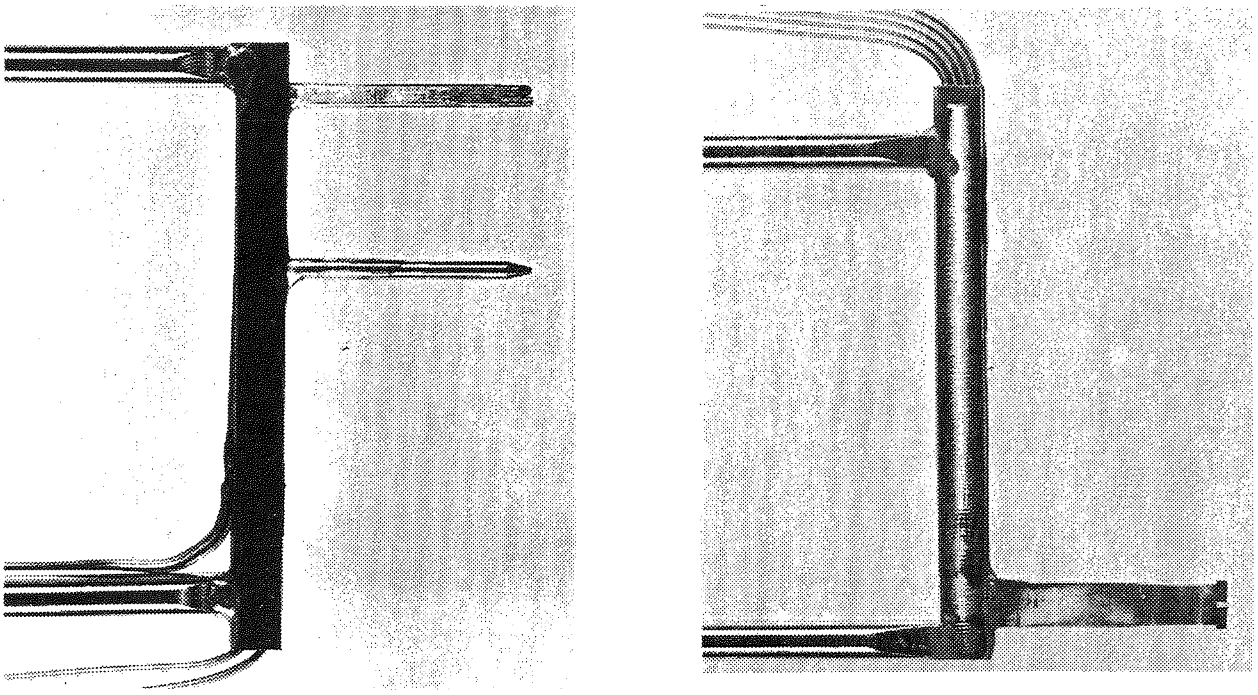
WEDGE PROBE (AVA)

FIG. 1



NEEDLE PROBE

CONE PROBE



TRUNCATED CONE PROBE

WEDGE PROBE(AVA)

FIG 1-b

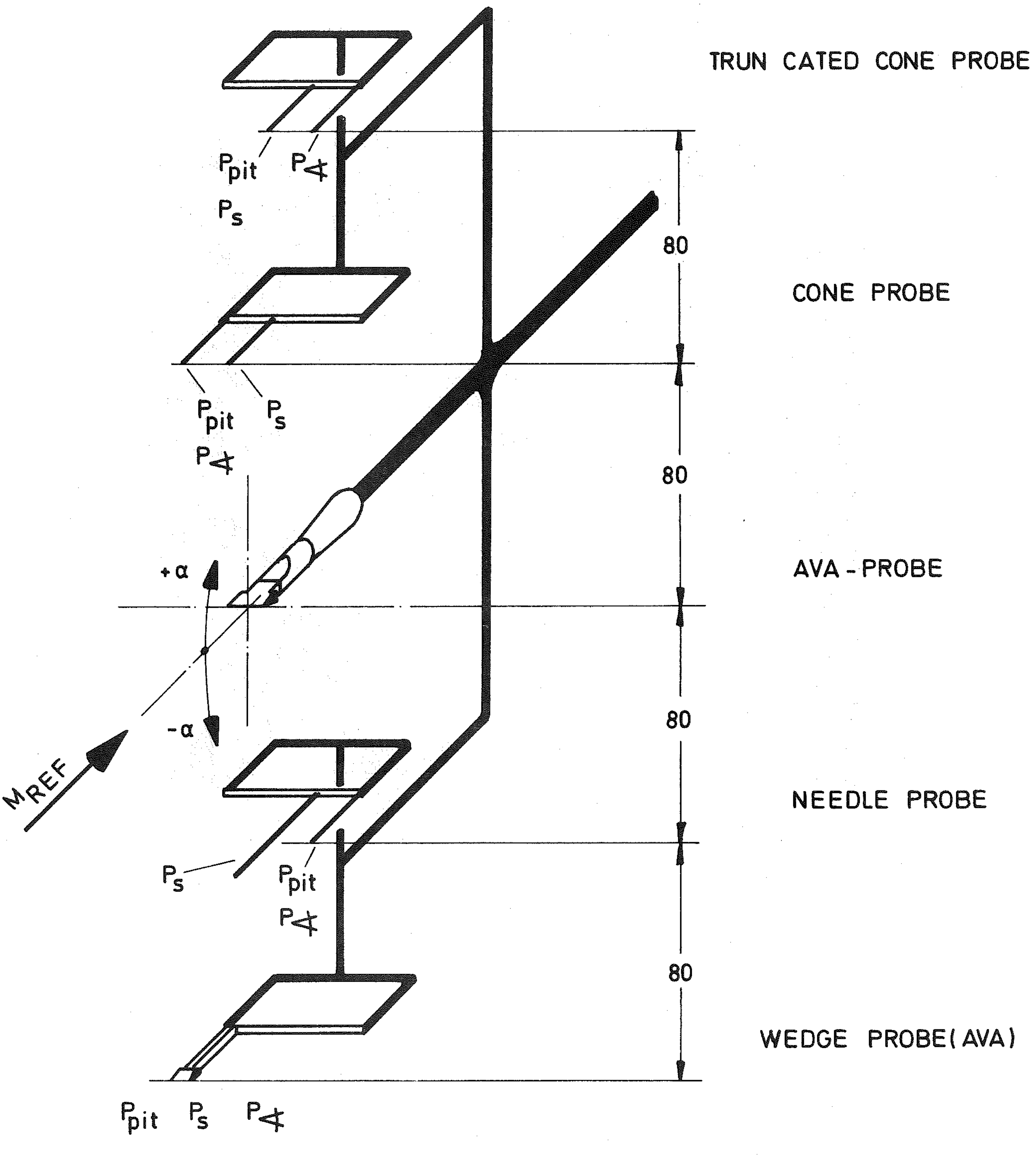
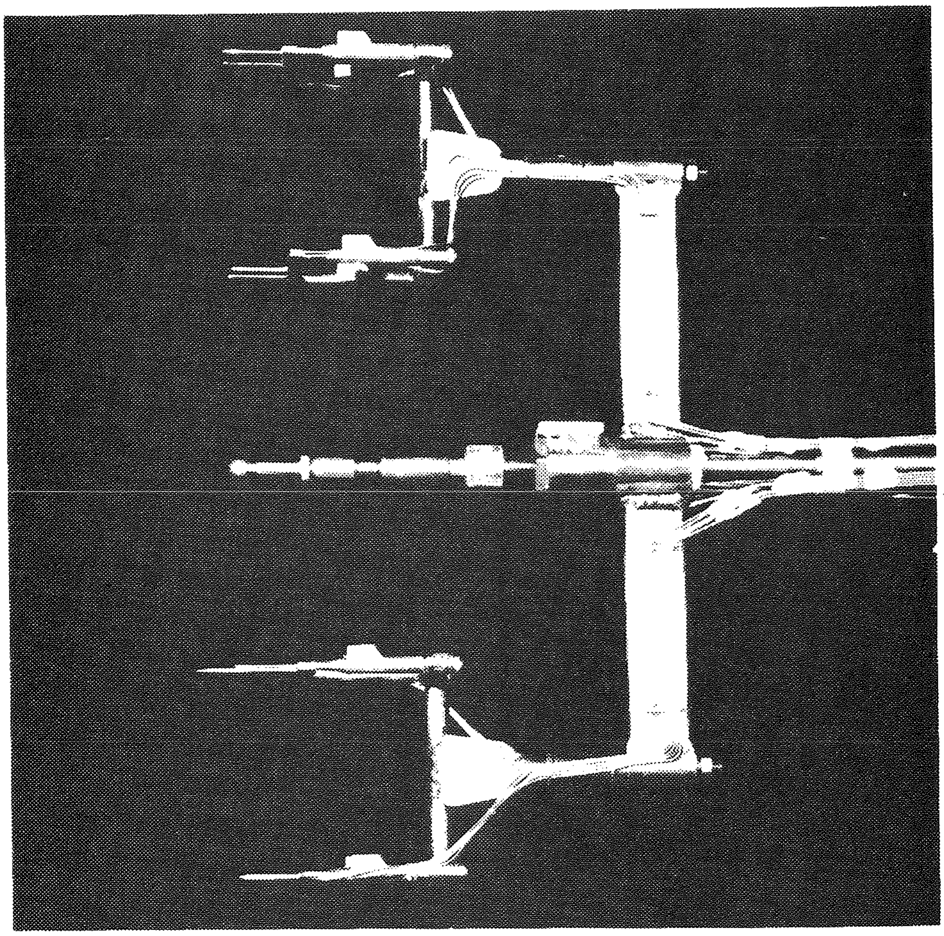
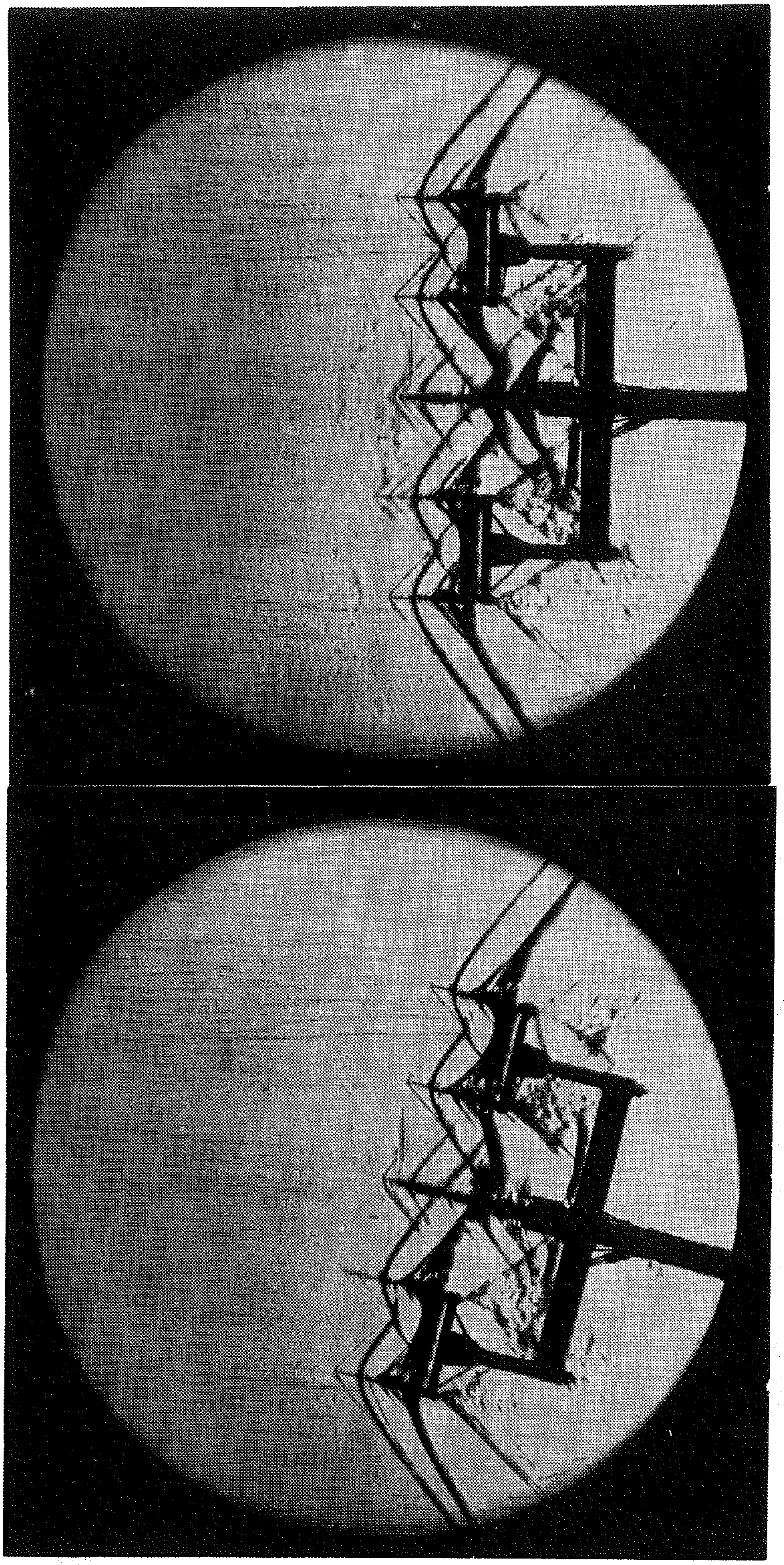

TRUN CATED CONE PROBE
CONE PROBE
AVA - PROBE
NEEDLE PROBE
WEDGE PROBE(AVA)
80
80
80
80
P_{pit}
$P_{\sphericalangle}$
P_s
P_{pit}
P_s
$P_{\sphericalangle}$
+α
-α
M_{REF}
P_s
P_{pit}
$P_{\sphericalangle}$
P_{pit}
P_s
$P_{\sphericalangle}$

FIG. 2-a



PROBE HOLDER FOR SIMULTANEOUSLY CALIBRATION OF 5 PROBES.

FIG. 2-b



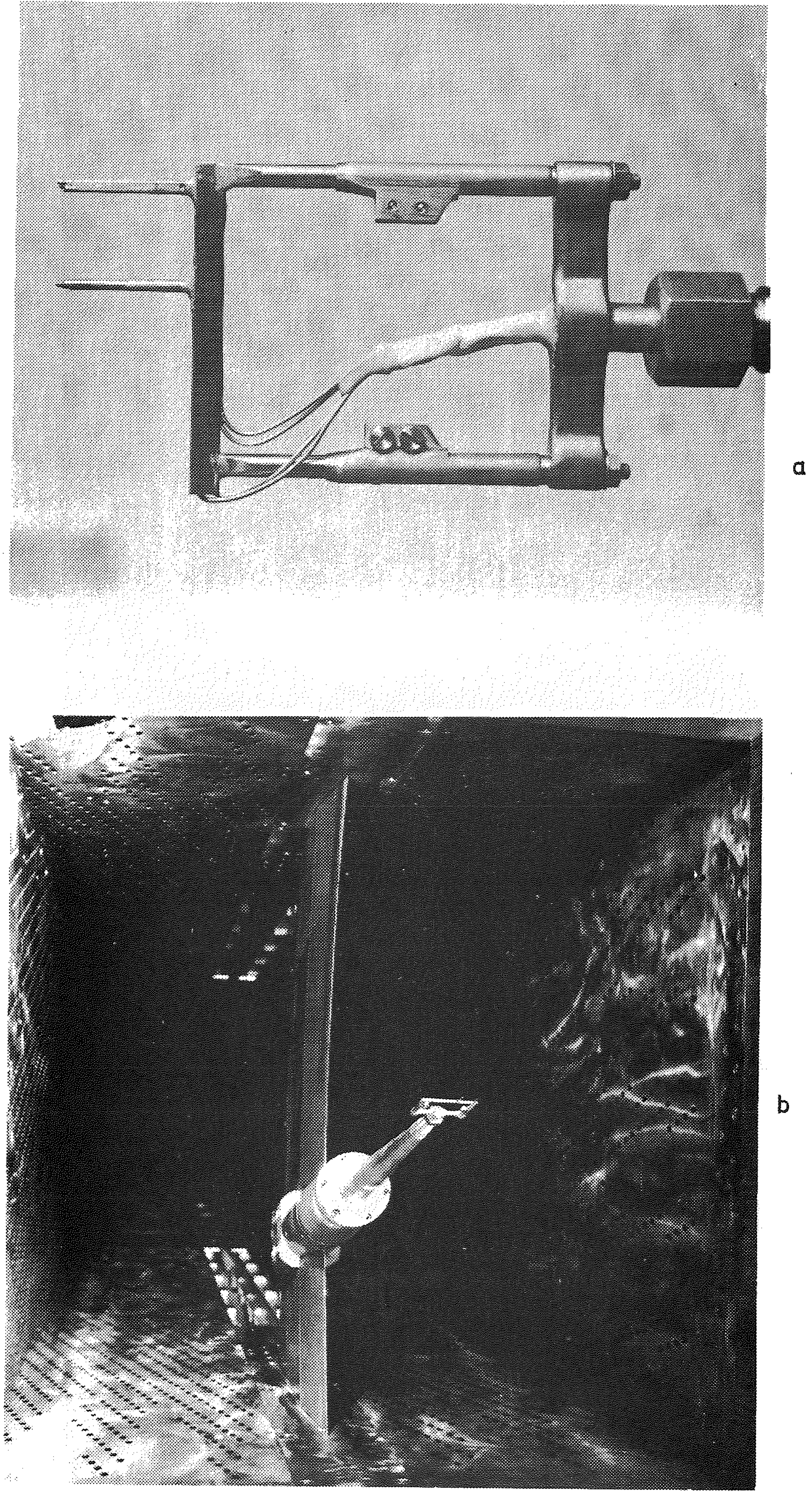
α = 0°

α = +12°

$M_{REF} = 1.41$

TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN

FIG.2-c



TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN

FIG. 3

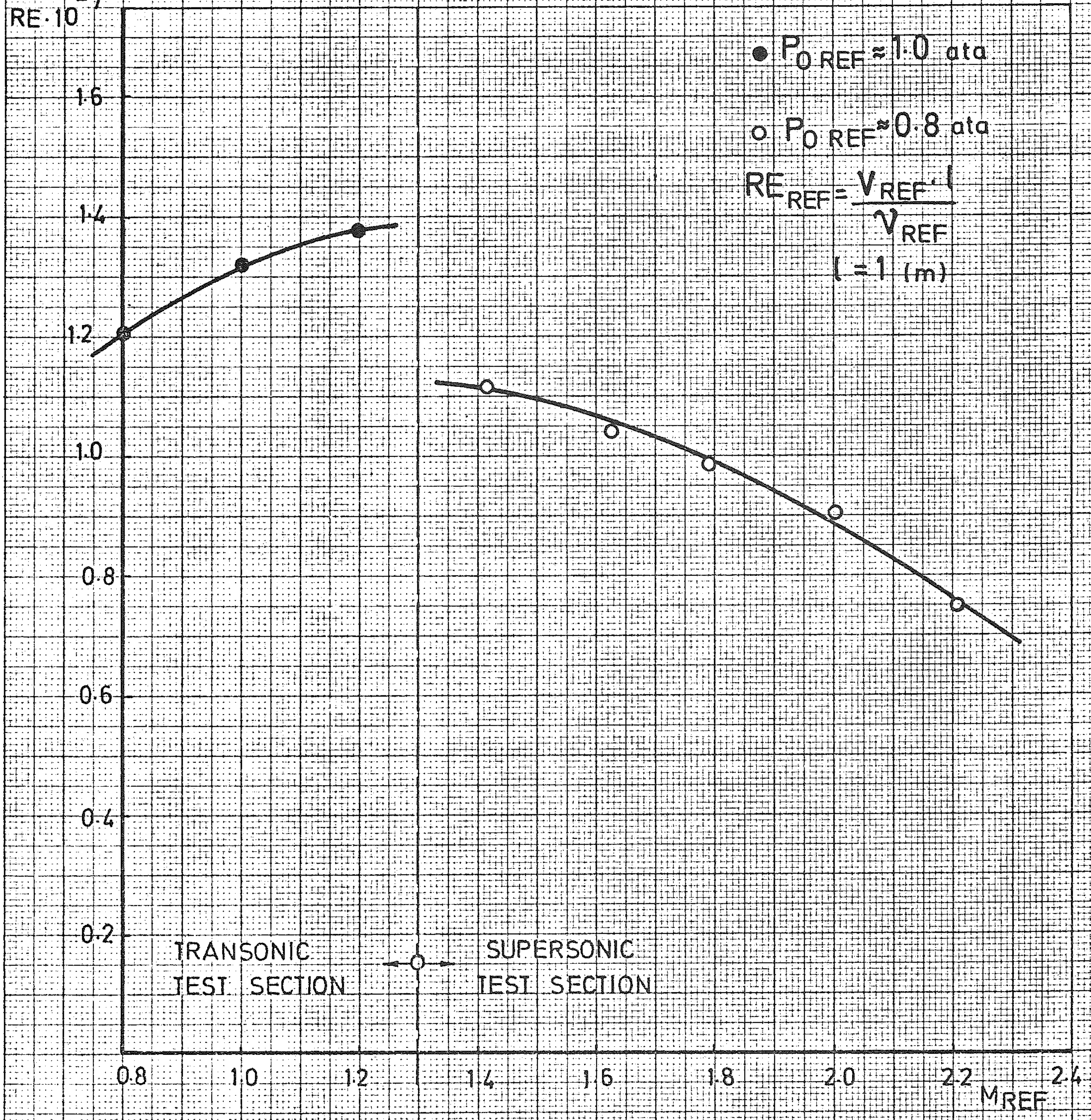

RE·10^-7
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
● P_0 REF ≈ 1.0 ata
○ P_0 REF ≈ 0.8 ata
RE_REF = V_REF · l / ν_REF
l = 1 (m)
TRANSONIC TEST SECTION
SUPERSONIC TEST SECTION
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
M_REF

FIG. 4

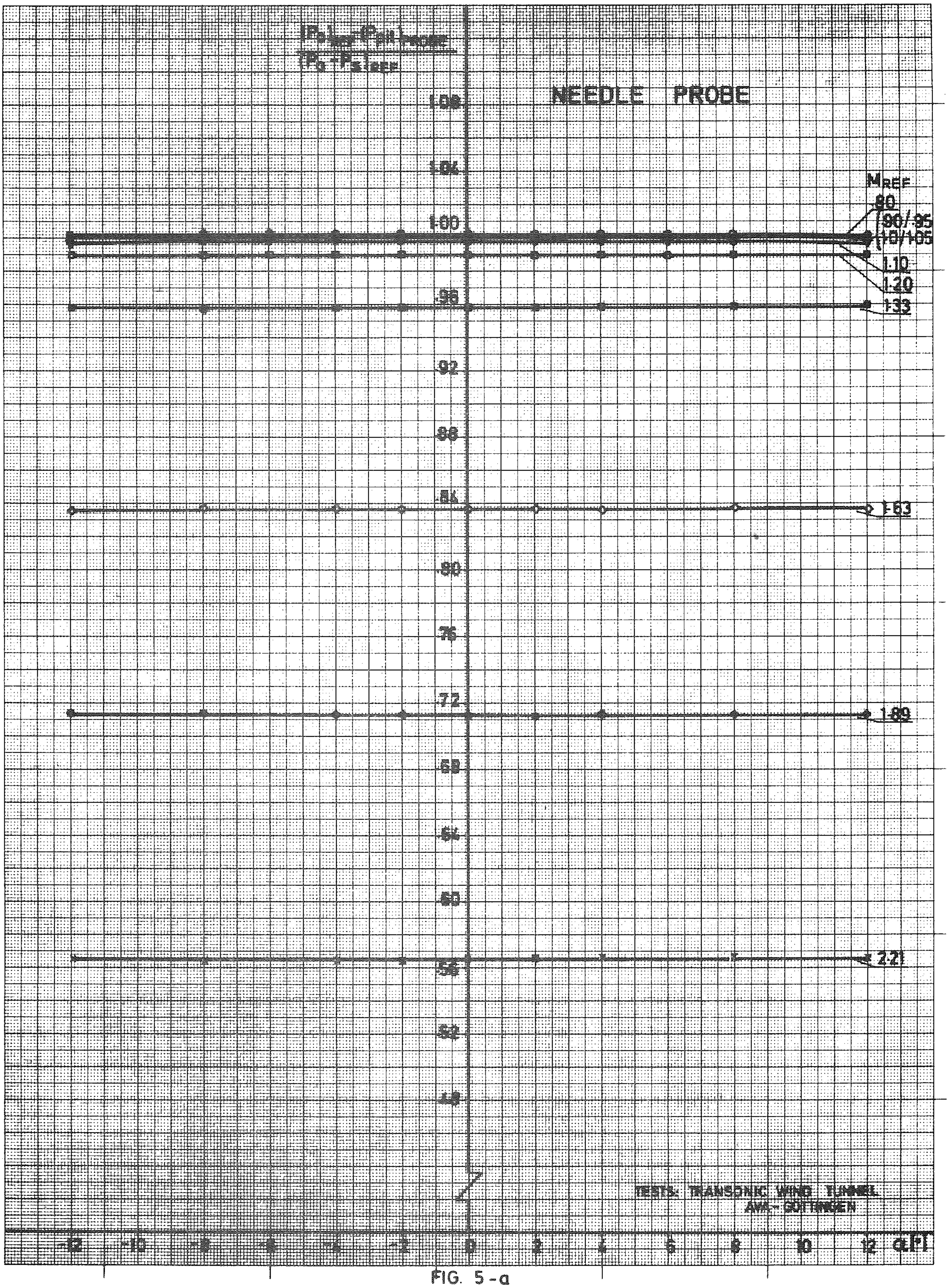
$\frac{(P_S)_{REF}-(P_{SH})_{PROBE}}{(P_0-P_S)_{REF}}$
NEEDLE PROBE
1.08
1.04
1.00
.96
.92
.88
.84
.80
.76
.72
.68
.64
.60
.56
.52
.48
M_{REF}
.80
.90/.95
1.0/1.05
1.10
1.20
1.33
1.63
1.89
2.21
TESTS: TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α[°]

FIG. 5 - a

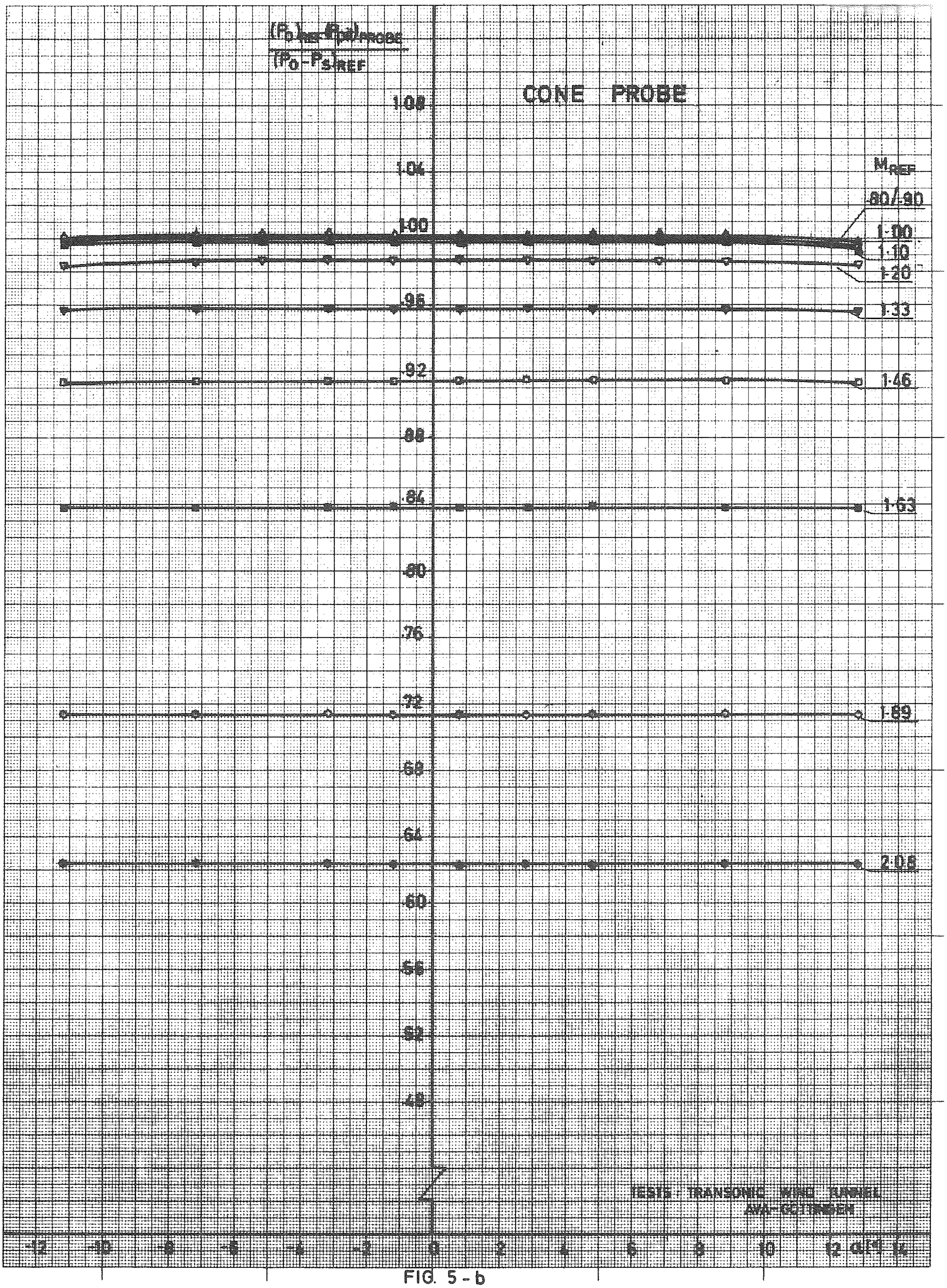

(P0)REF-(Ppit)PROBE
(P0-Ps)REF
CONE PROBE
MREF
.80/.90
1·00
1·10
1·20
1·33
1·46
1·63
1·89
2·08
1·08
1·04
1·00
·96
·92
·88
·84
·80
·76
·72
·68
·64
·60
·56
·52
·48
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α[°]
14
TESTS TRANSONIC WIND TUNNEL
AVA-GOTTINGEN

FIG. 5 - b

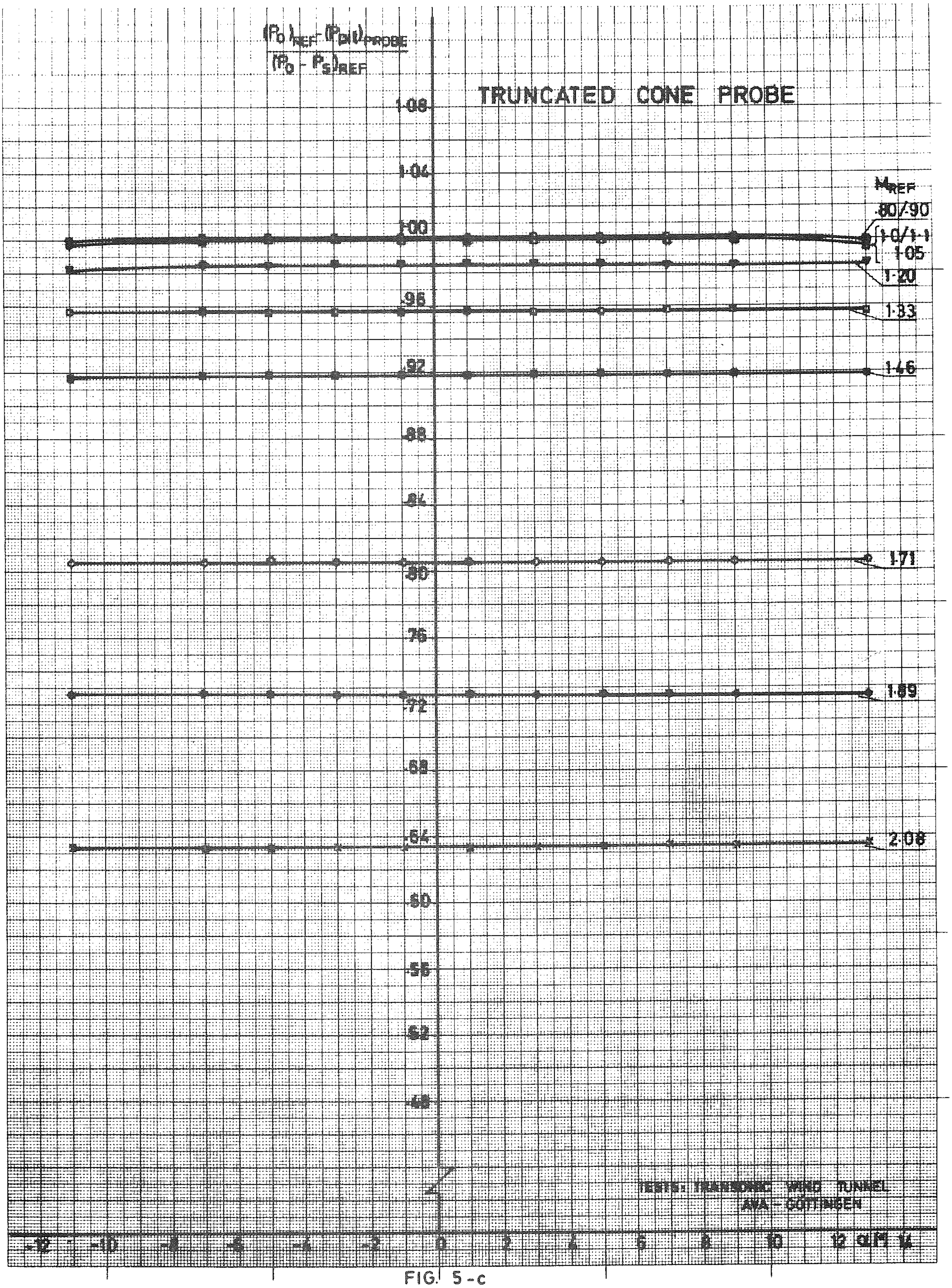

$\frac{(P_0)_{REF} - (P_{0II})_{PROBE}}{(P_0 - P_S)_{REF}}$
TRUNCATED CONE PROBE
1·08
1·04
1·00
·96
·92
·88
·84
·80
·76
·72
·68
·64
·60
·56
·52
·48
M_{REF}
·80/·90
1·0/1·1
1·05
1·20
1·33
1·46
1·71
1·89
2·08
TESTS: TRANSONIC WIND TUNNEL
AVA – GÖTTINGEN
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α(°)
14

FIG. 5-c

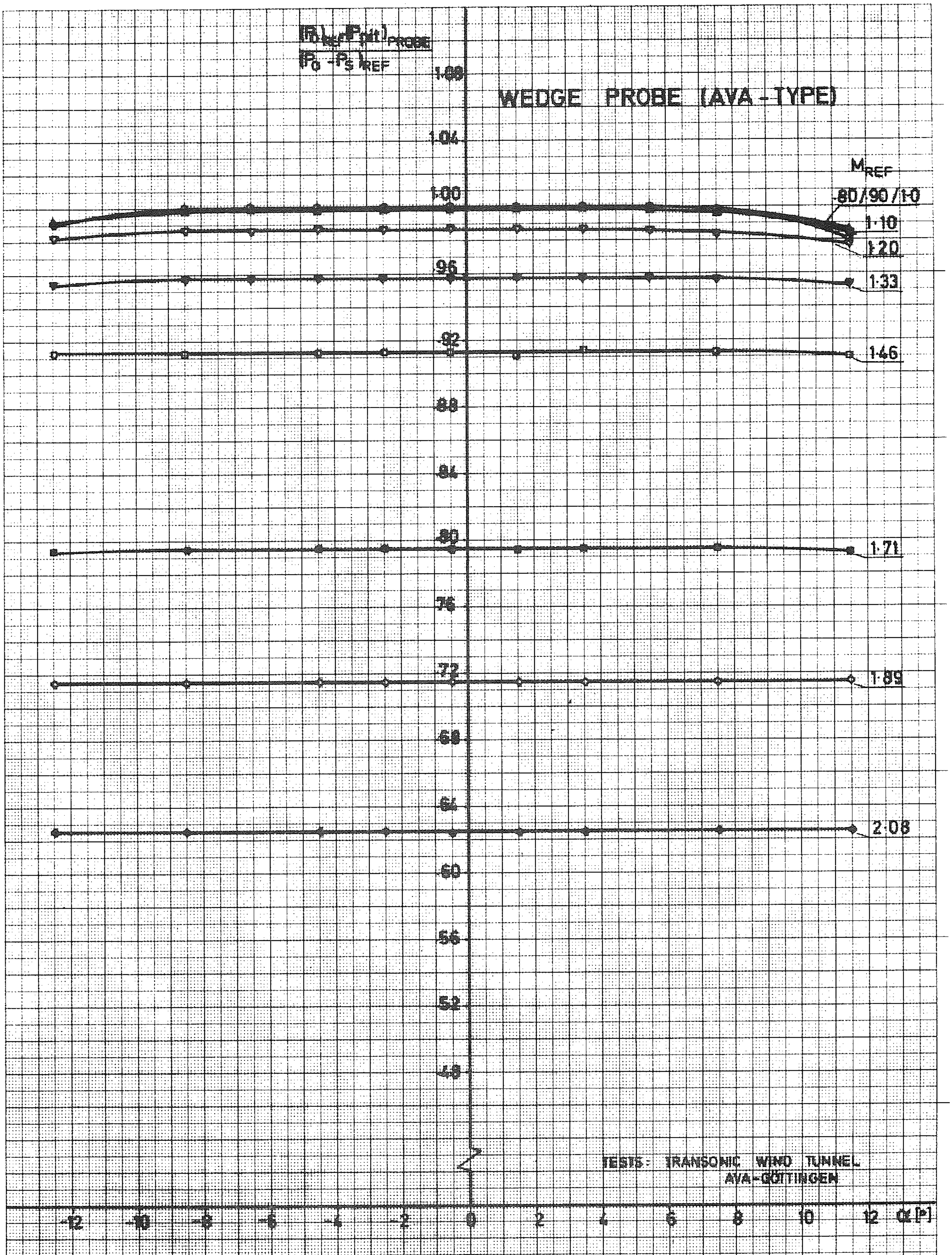
WEDGE PROBE (AVA-TYPE)
(P0)REF - (Ppit)PROBE / (P0 - PS)REF
1.08
1.04
1.00
.96
.92
.88
.84
.80
.76
.72
.68
.64
.60
.56
.52
.48
MREF
.80/.90/1.0
1.10
1.20
1.33
1.46
1.71
1.89
2.08
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α [°]

FIG. 5 - d

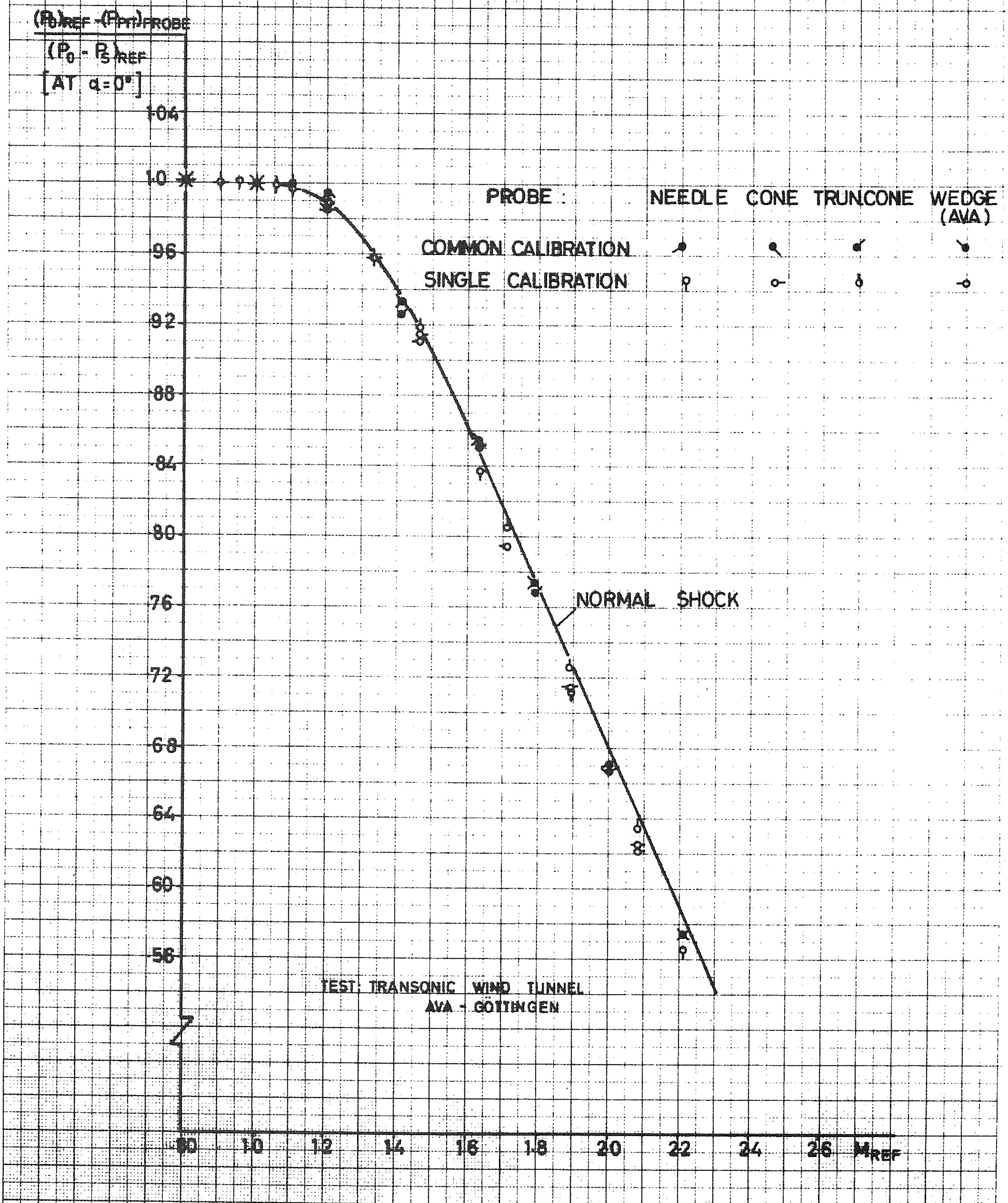

(P0)REF - (PPIT)PROBE
(P0 - PS)REF
[AT α = 0°]
1·04
1·0
·96
·92
·88
·84
·80
·76
·72
·68
·64
·60
·56
·80
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2·4
2·6
MREF
PROBE :
NEEDLE
CONE
TRUNCONE
WEDGE (AVA)
COMMON CALIBRATION
SINGLE CALIBRATION
NORMAL SHOCK
TEST: TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN

FIG. 6

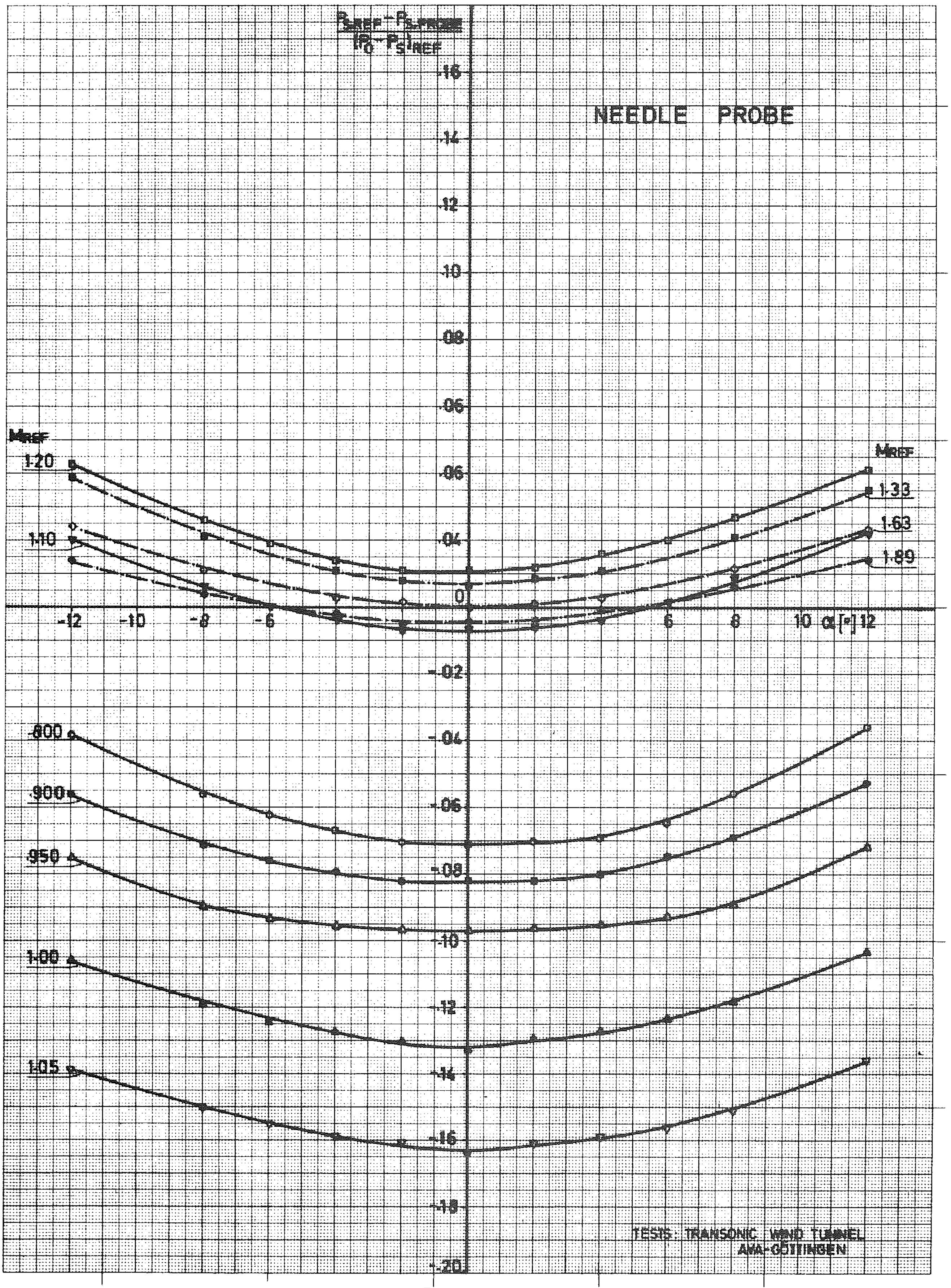

$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$
NEEDLE PROBE
.16
.14
.12
.10
.08
.06
.06
.04
0
-.02
-.04
-.06
-.08
-.10
-.12
-.14
-.16
-.18
-.20
M_REF
1.20
1.10
M_REF
1.33
1.63
1.89
.800
.900
.950
1.00
1.05
-12
-10
-8
-6
6
8
10
α [°] 12
TESIS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 7 - a

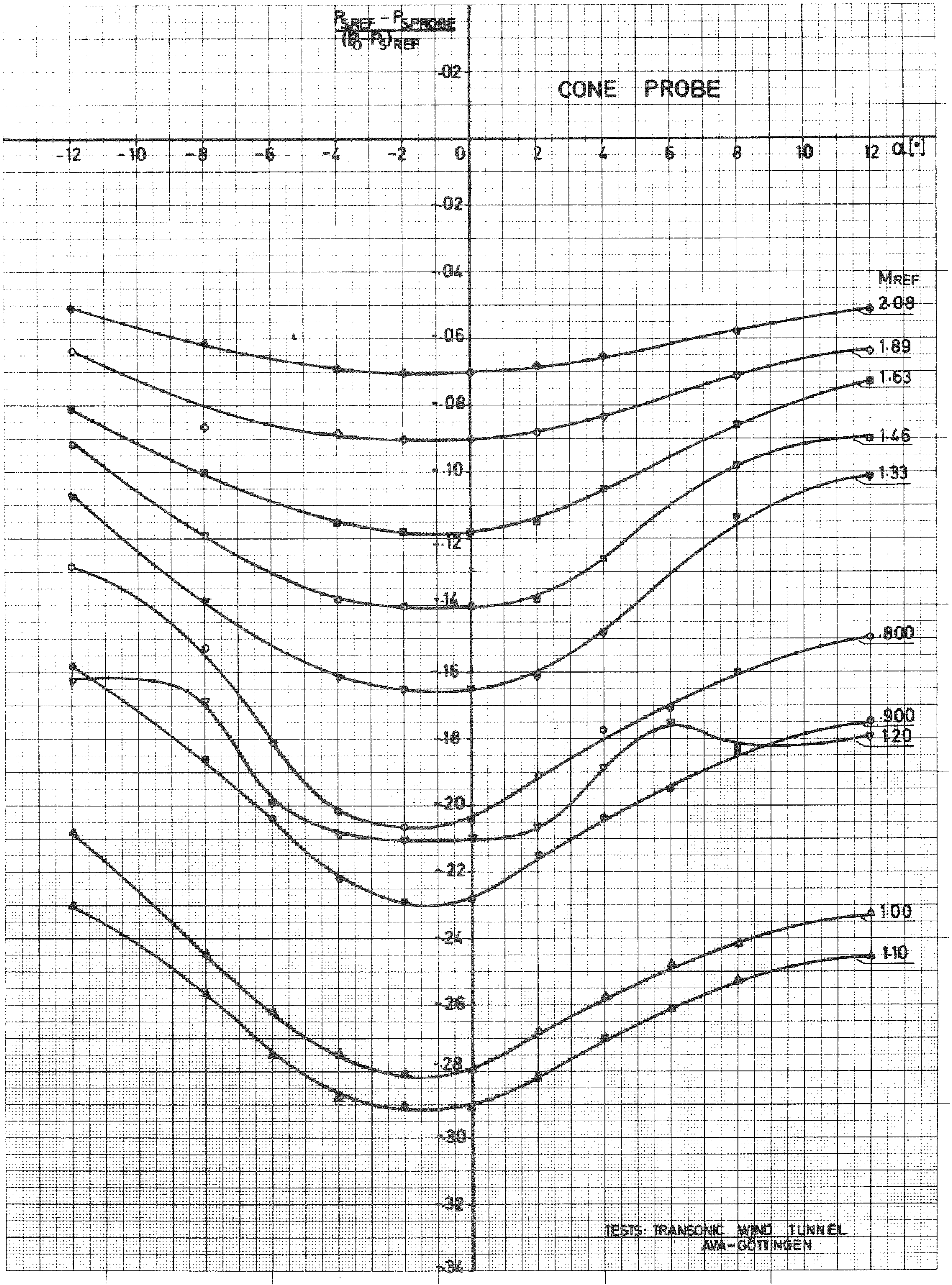

$\frac{P_{S\,REF} - P_{S\,PROBE}}{(P_0 - P_S)_{REF}}$
CONE PROBE
α [°]
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
.02
-.02
-.04
-.06
-.08
-.10
-.12
-.14
-.16
-.18
-.20
-.22
-.24
-.26
-.28
-.30
-.32
-.34
MREF
2.08
1.89
1.63
1.46
1.33
.800
.900
1.20
1.00
1.10
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 7 - b

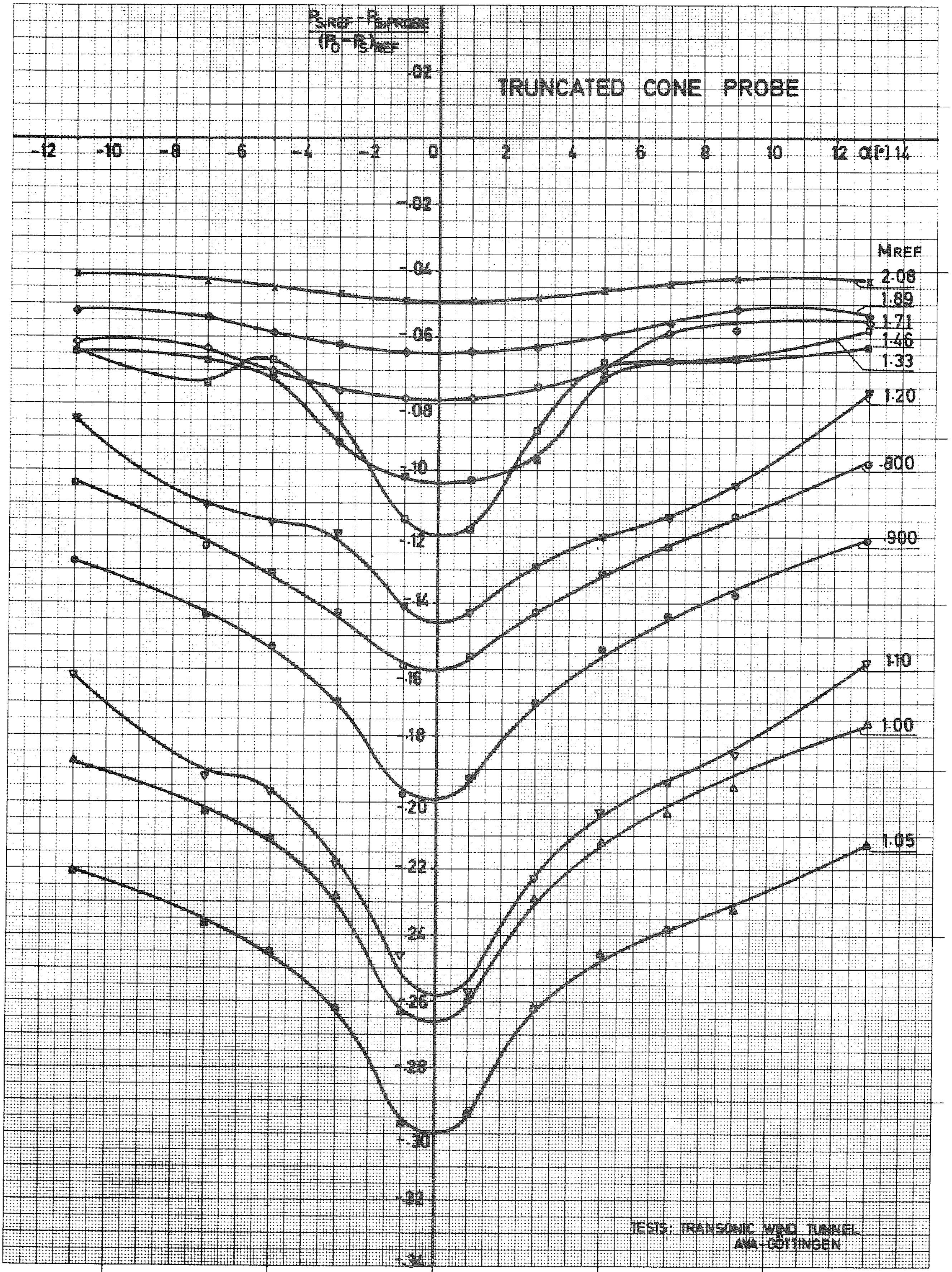

TRUNCATED CONE PROBE
$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$
.02
-.02
-.04
-.06
-.08
-.10
-.12
-.14
-.16
-.18
-.20
-.22
-.24
-.26
-.28
-.30
-.32
-.34
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α[°] 14
M_{REF}
2.08
1.89
1.71
1.46
1.33
1.20
.800
.900
1.10
1.00
1.05
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 7-c

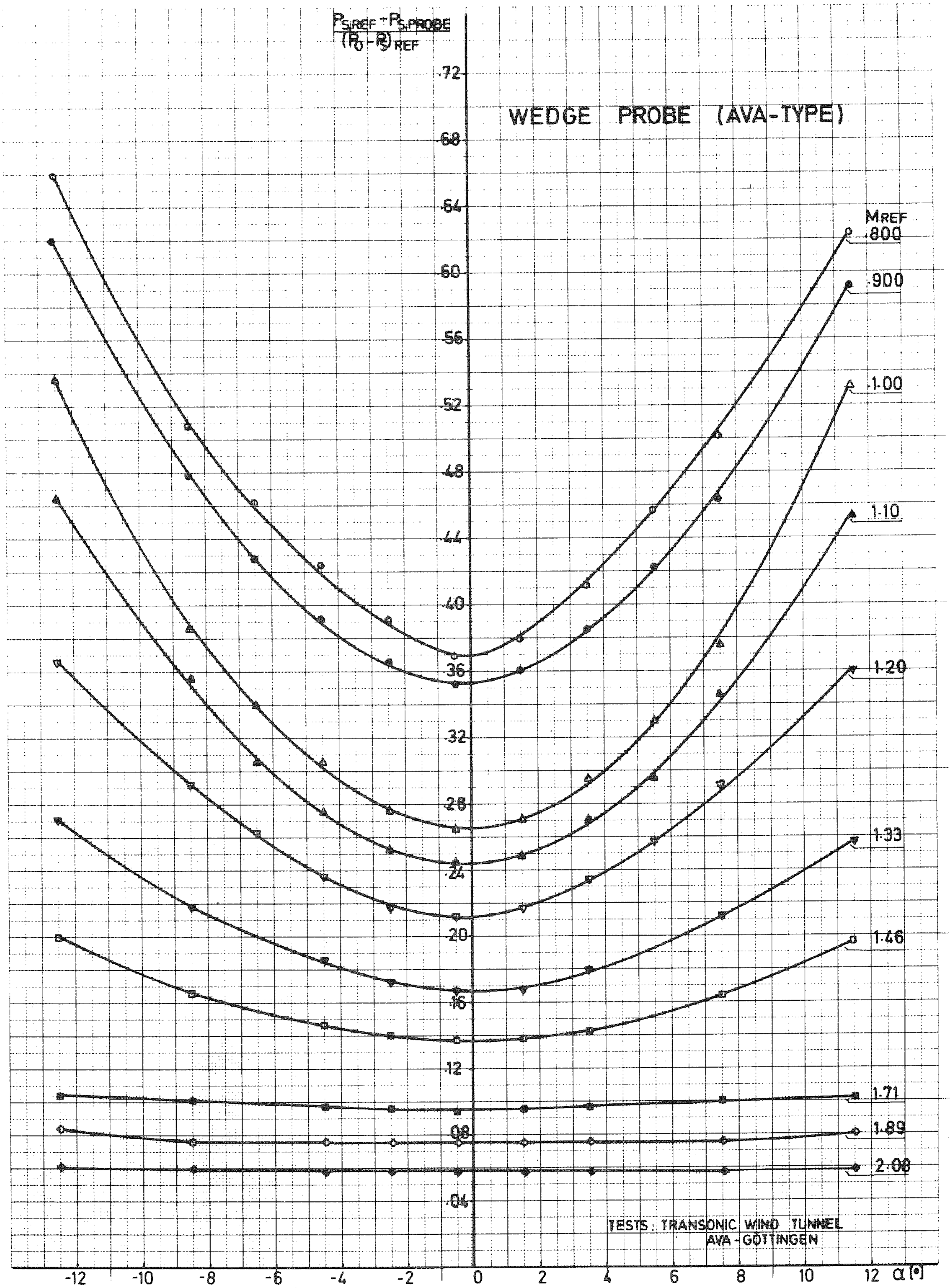

WEDGE PROBE (AVA-TYPE)
$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$
·72
·68
·64
·60
·56
·52
·48
·44
·40
·36
·32
·28
·24
·20
·16
·12
·08
·04
M_REF
·800
·900
1·00
1·10
1·20
1·33
1·46
1·71
1·89
2·08
TESTS : TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
α [°]

FIG. 7 - d

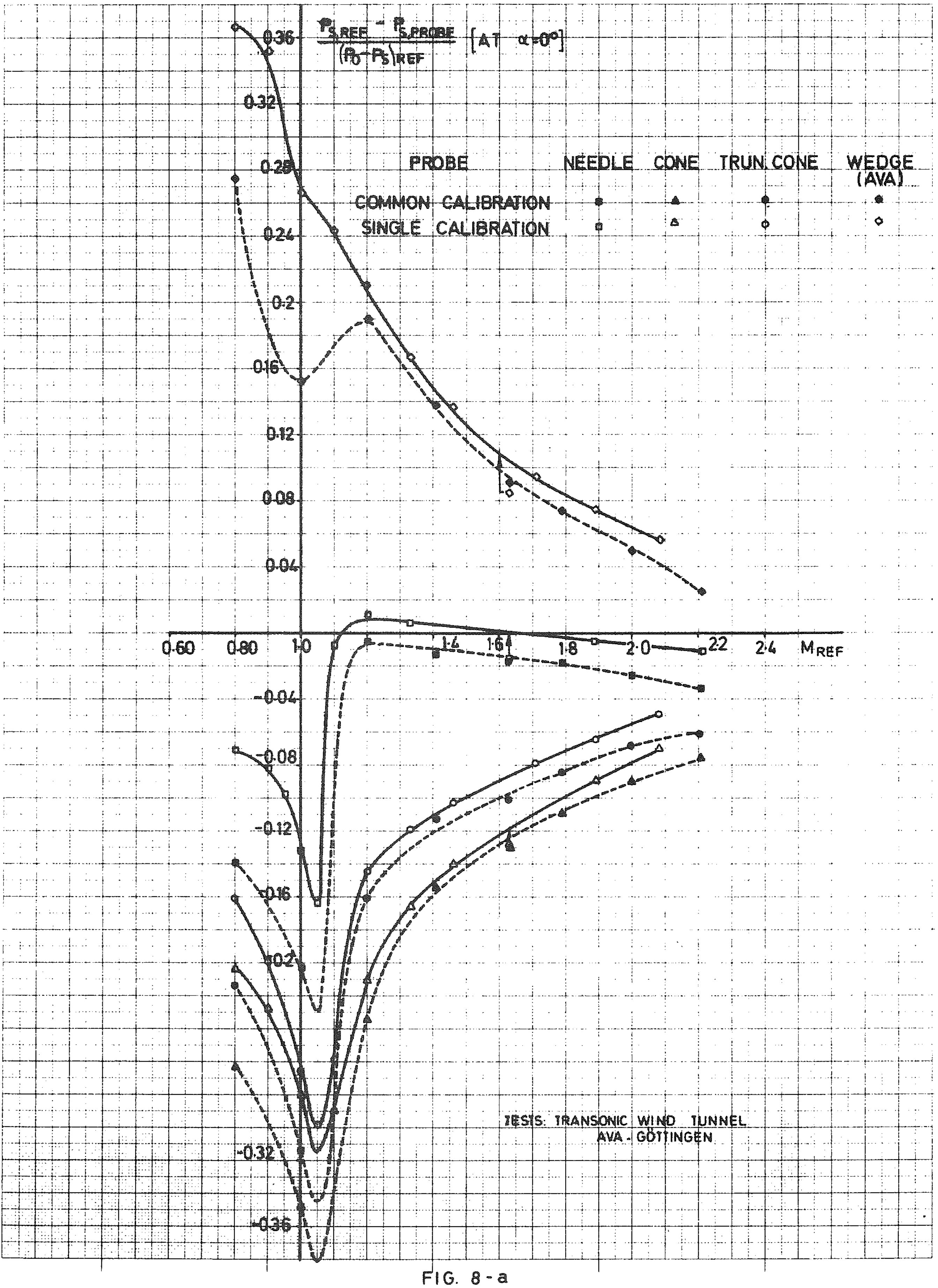

$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$ [AT α=0°]
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
-0.04
-0.08
-0.12
-0.16
-0.2
-0.32
-0.36
0.60
0.80
1.0
1.4
1.6
1.8
2.0
2.2
2.4
M_{REF}
PROBE
NEEDLE
CONE
TRUN. CONE
WEDGE (AVA)
COMMON CALIBRATION
SINGLE CALIBRATION
TESTS: TRANSONIC WIND TUNNEL AVA - GÖTTINGEN

FIG. 8 - a

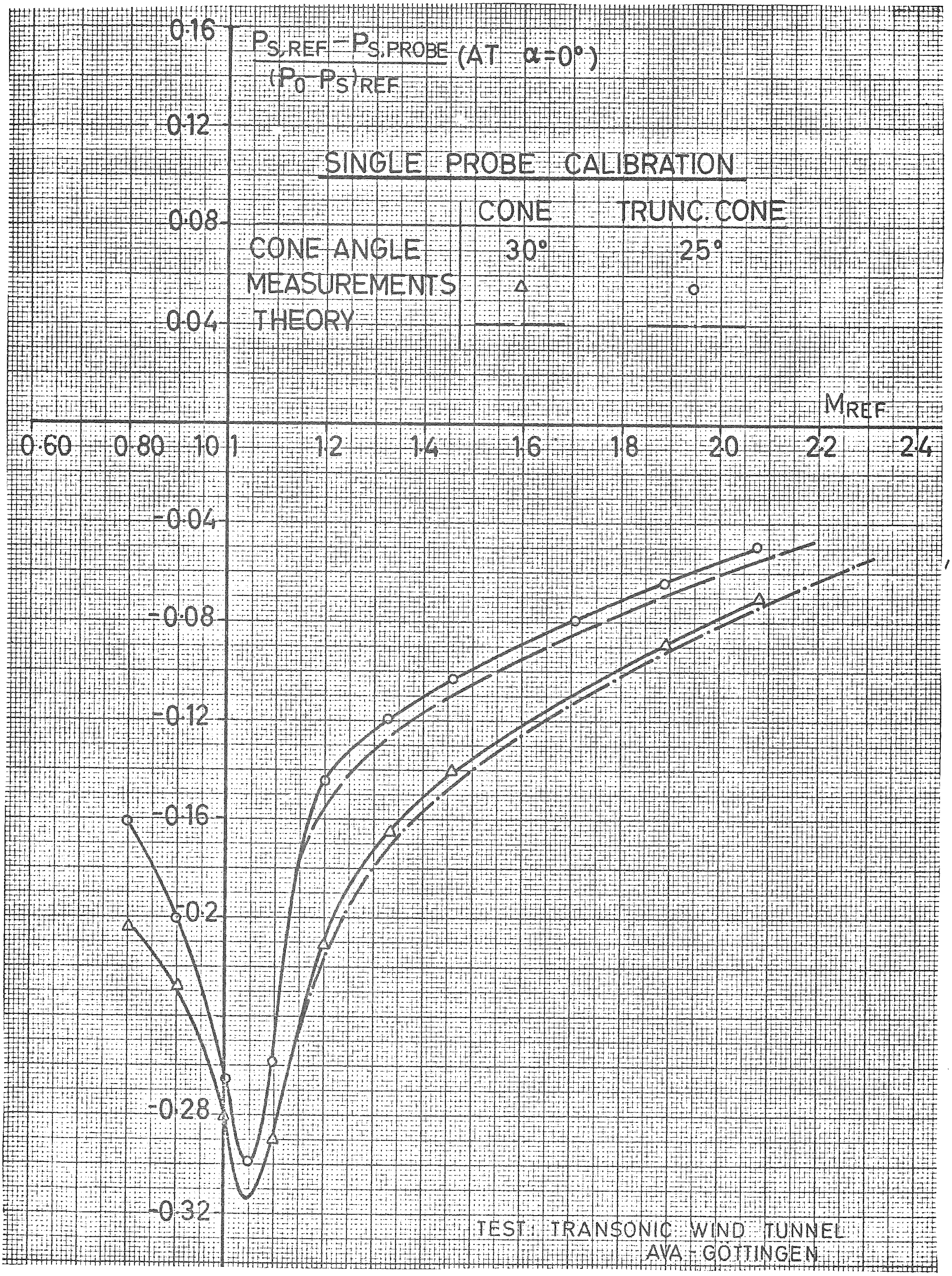
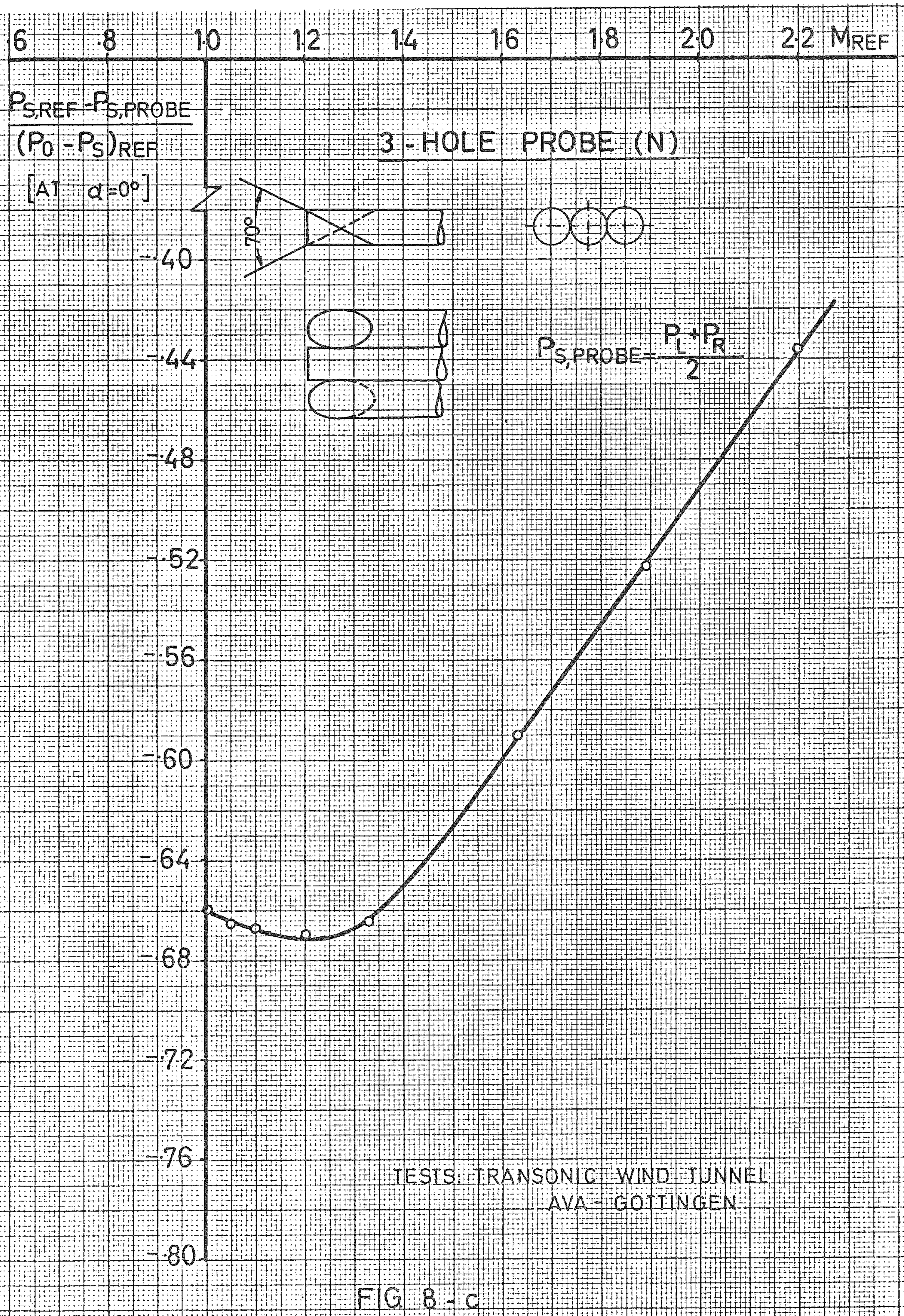
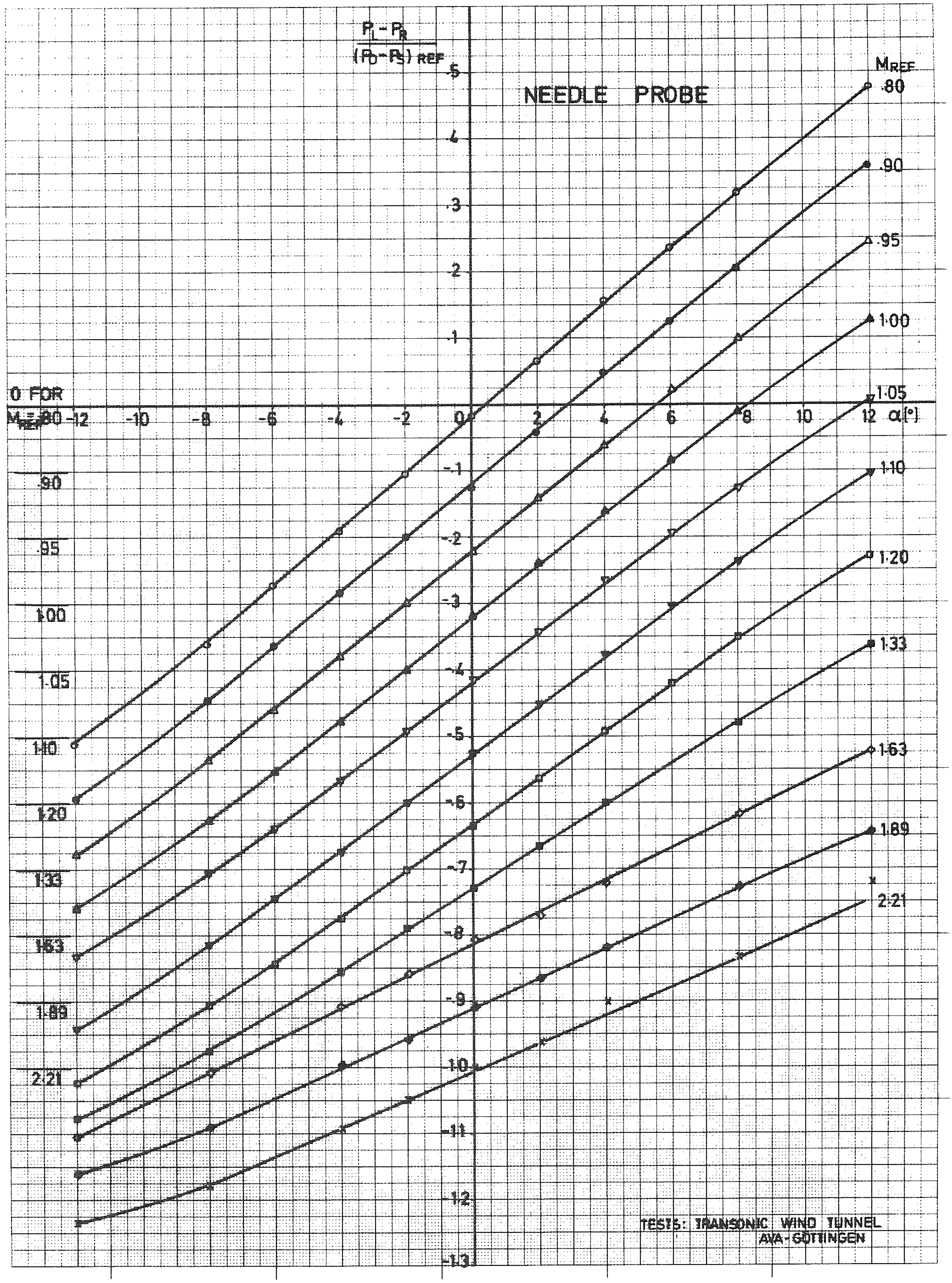

$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$ (AT α = 0°)
SINGLE PROBE CALIBRATION
CONE
TRUNC. CONE
CONE ANGLE
30°
25°
MEASUREMENTS
△
○
THEORY
M_REF
0·16
0·12
0·08
0·04
-0·04
-0·08
-0·12
-0·16
-0·2
-0·28
-0·32
0·60
0·80
1·0
1
1·2
1·4
1·6
1·8
2·0
2·2
2·4
TEST: TRANSONIC WIND TUNNEL
AVA - GÖTTINGEN

FIG. 8- b



·6
·8
1·0
1·2
1·4
1·6
1·8
2·0
2·2
M_REF
(P_S,REF - P_S,PROBE) / (P_0 - P_S)_REF
[AT α = 0°]
3 - HOLE PROBE (N)
70°
P_S,PROBE = (P_L + P_R) / 2
-·40
-·44
-·48
-·52
-·56
-·60
-·64
-·68
-·72
-·76
-·80
TESTS: TRANSONIC WIND TUNNEL
AVA - GOTTINGEN

FIG. 8 - c



P_L - P_R / (P_O - P_S) REF
NEEDLE PROBE
M REF
.80
.90
.95
1·00
1·05
1·10
1·20
1·33
1·63
1·89
2·21
α [°]
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12
·5 ·4 ·3 ·2 ·1 -·1 -·2 -·3 -·4 -·5 -·6 -·7 -·8 -·9 -1·0 -1·1 -1·2 -1·3
0 FOR M REF = ·80
·90
·95
1·00
1·05
1·10
1·20
1·33
1·63
1·89
2·21
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 9 - a

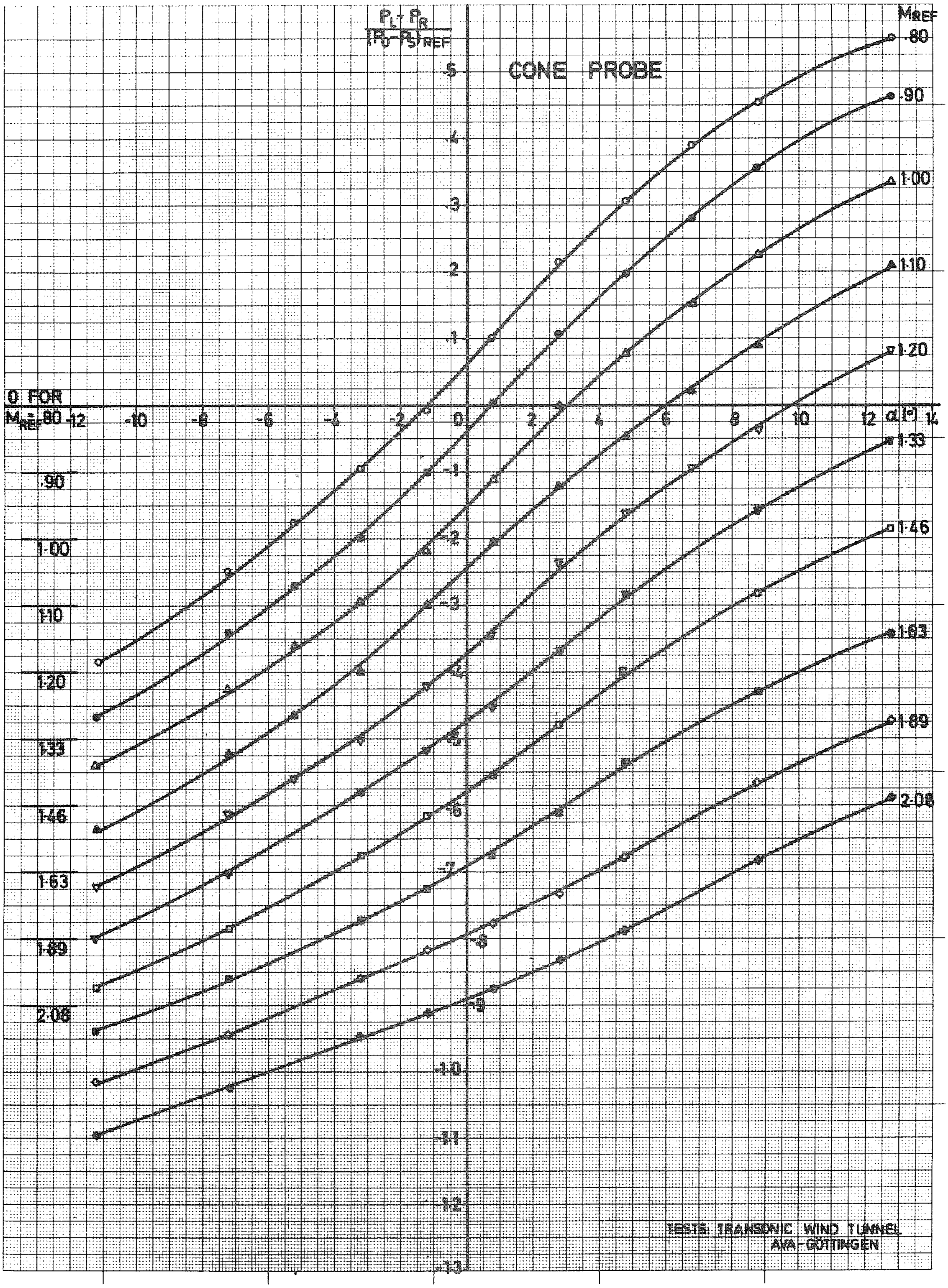

$\frac{P_L - P_R}{(P_0 - P_S)_{REF}}$
CONE PROBE
M_{REF}
.80
.90
1.00
1.10
1.20
1.33
1.46
1.63
1.89
2.08
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
-1.1
-1.2
-1.3
0 FOR
M_{REF} = .80
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
α [°]
.90
1.00
1.10
1.20
1.33
1.46
1.63
1.89
2.08
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 9 - b

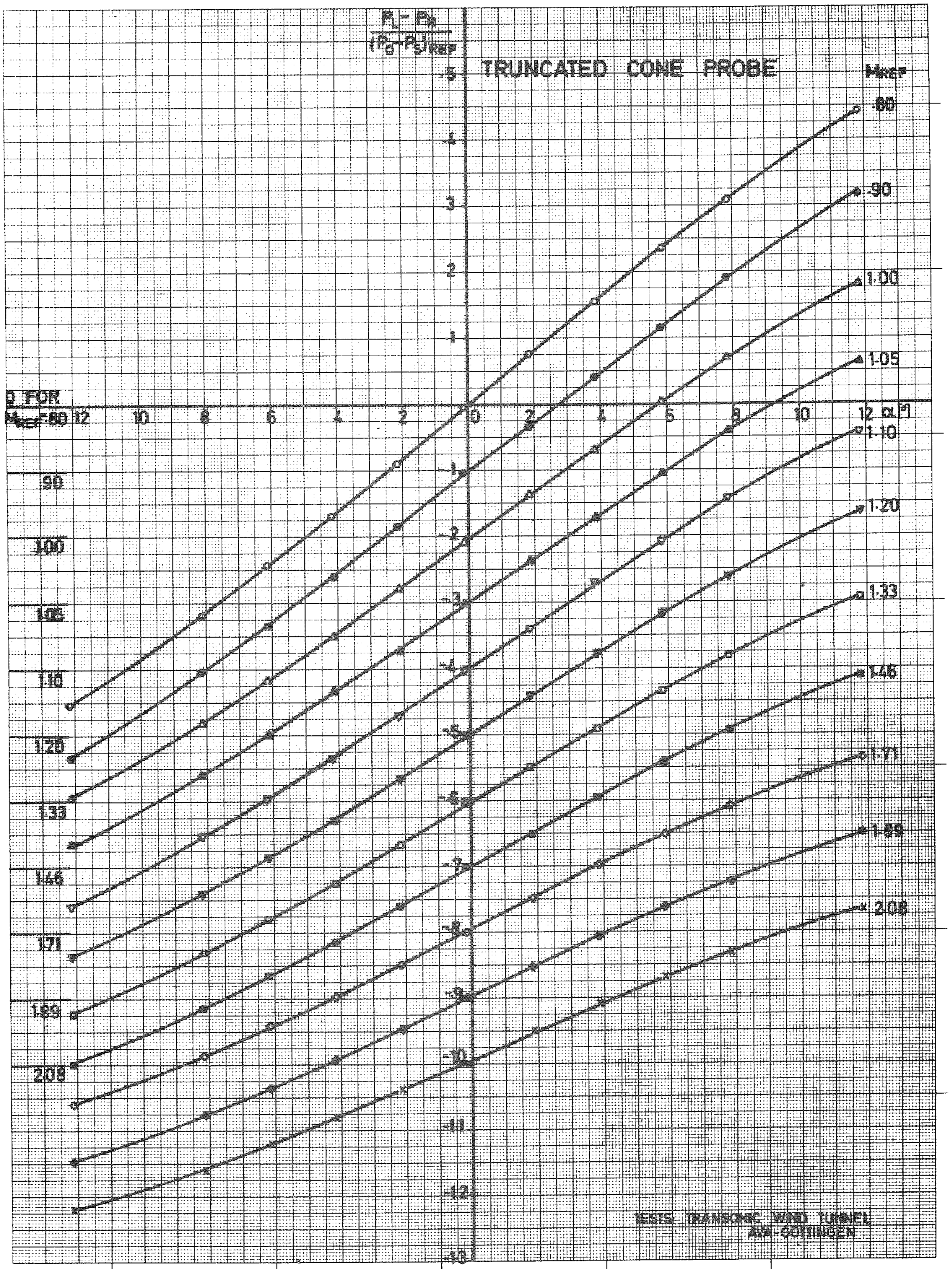

$\frac{P_L - P_R}{(P_O - P_S)_{REF}}$
TRUNCATED CONE PROBE
M_{REF}
.80
.90
1.00
1.05
1.10
1.20
1.33
1.46
1.71
1.89
2.08
0 FOR M_{REF} .80
.90
1.00
1.05
1.10
1.20
1.33
1.46
1.71
1.89
2.08
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
12
10
8
6
4
2
0
2
4
6
8
10
12
α [°]
TESTS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 9 - c

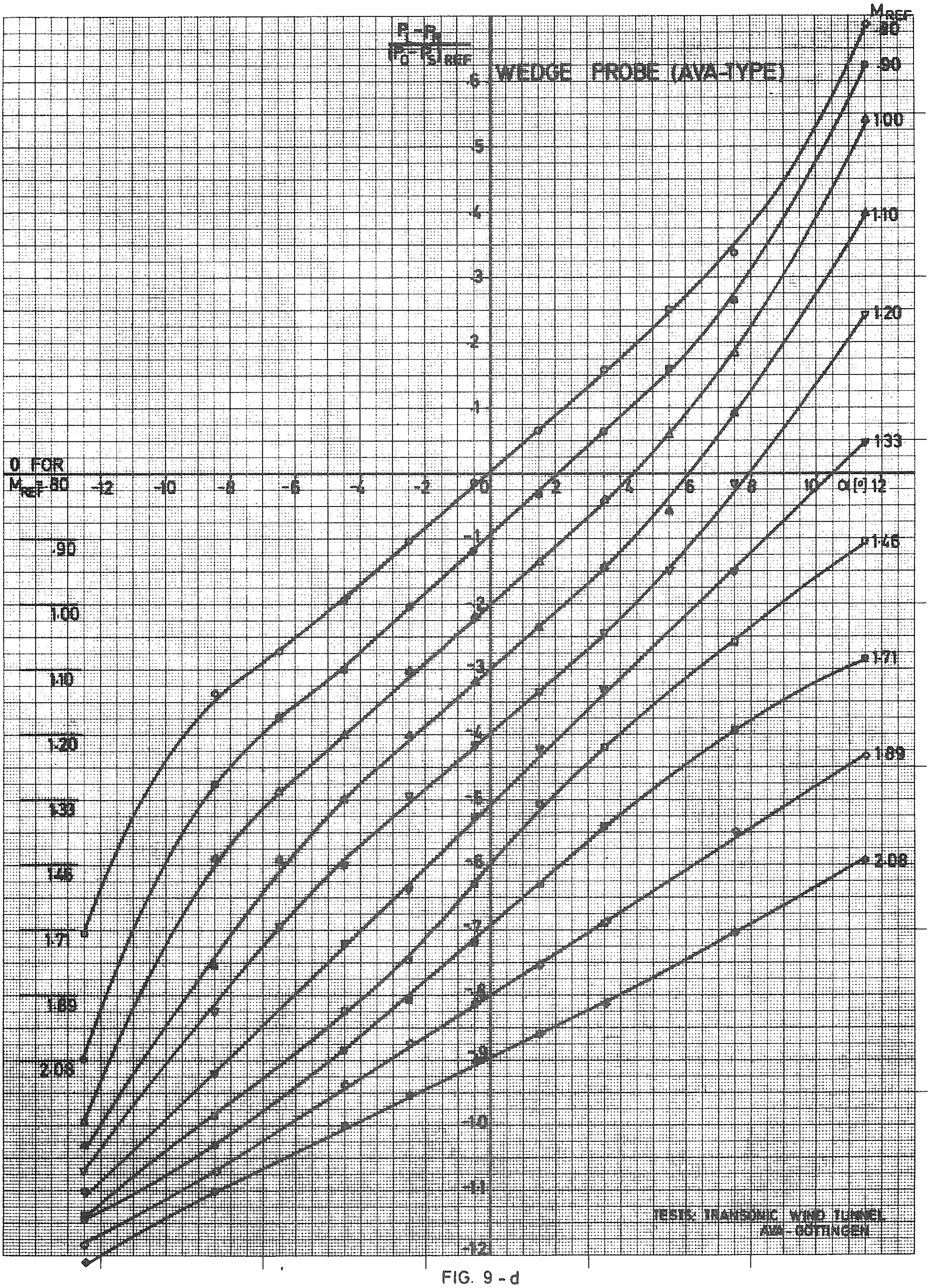

$\frac{P_1 - P_2}{(P_0 - P_S)_{REF}}$
WEDGE PROBE (AVA-TYPE)
M_{REF}
.80
.90
1.00
1.10
1.20
1.33
1.46
1.71
1.89
2.08
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
-.4
-.5
-.6
-.7
-.8
-.9
-1.0
-1.1
-1.2
-12
-10
-8
-6
-4
-2
2
4
6
8
10
α [°] 12
0 FOR
M_{REF} = .80
.90
1.00
1.10
1.20
1.33
1.46
1.71
1.89
2.08
TESIS: TRANSONIC WIND TUNNEL
AVA-GÖTTINGEN

FIG. 9 - d

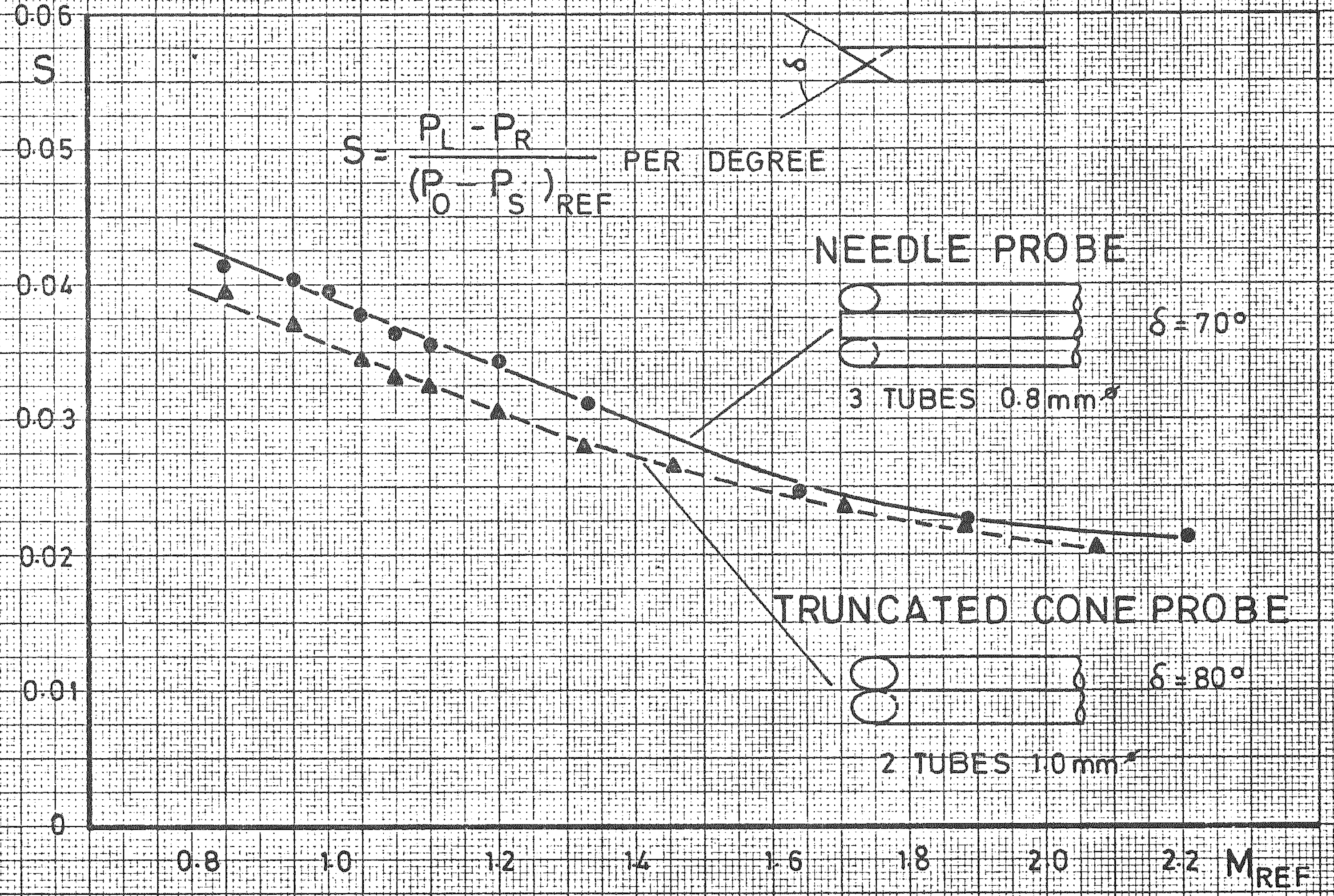

0.06
0.05
0.04
0.03
0.02
0.01
0
S
$S = \frac{P_L - P_R}{(P_0 - P_S)_{REF}}$ PER DEGREE
δ
NEEDLE PROBE
δ = 70°
3 TUBES 0.8 mm ø
TRUNCATED CONE PROBE
δ = 80°
2 TUBES 1.0 mm ø
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
M_{REF}

FIG 9-e

MODIFIED TEST SECTION OF THE VKI
HIGH SPEED CASCADE TUNNEL C-2

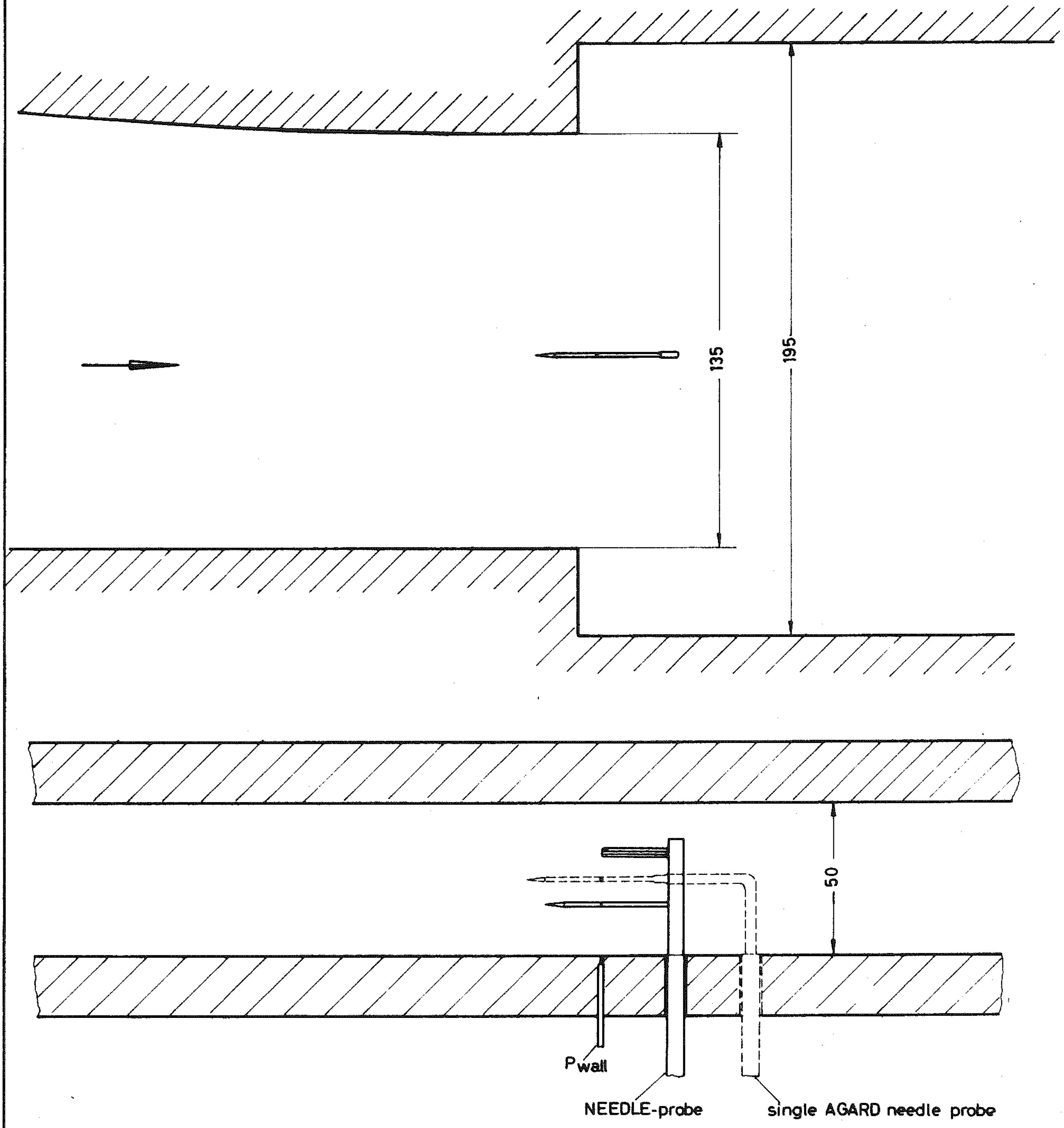


FIG. 10

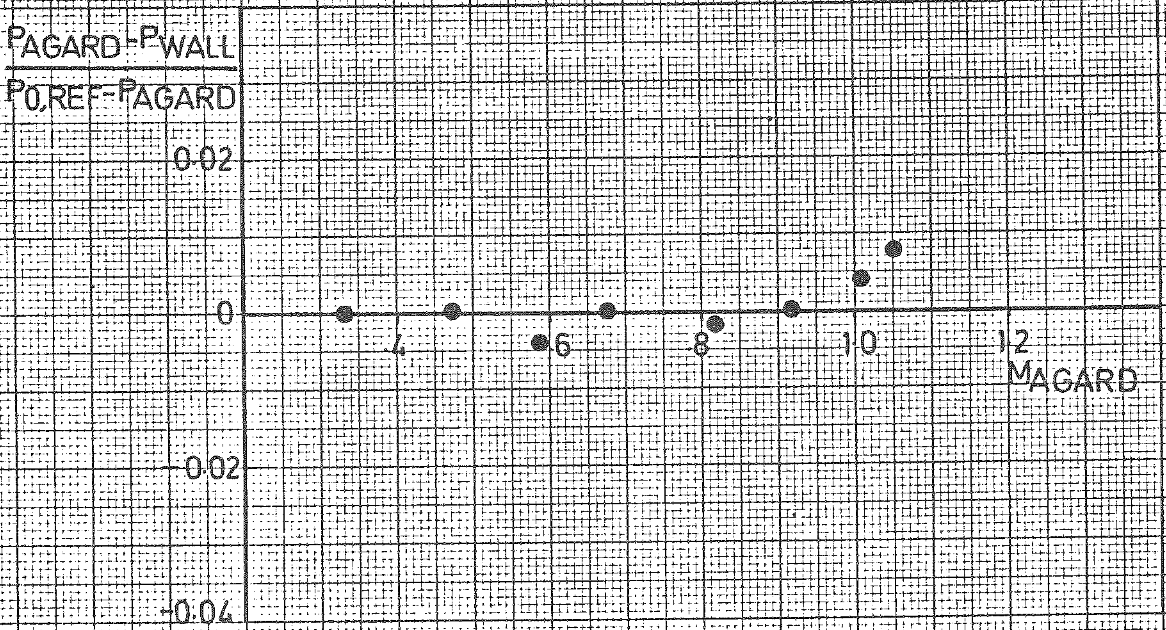


FIG. 11

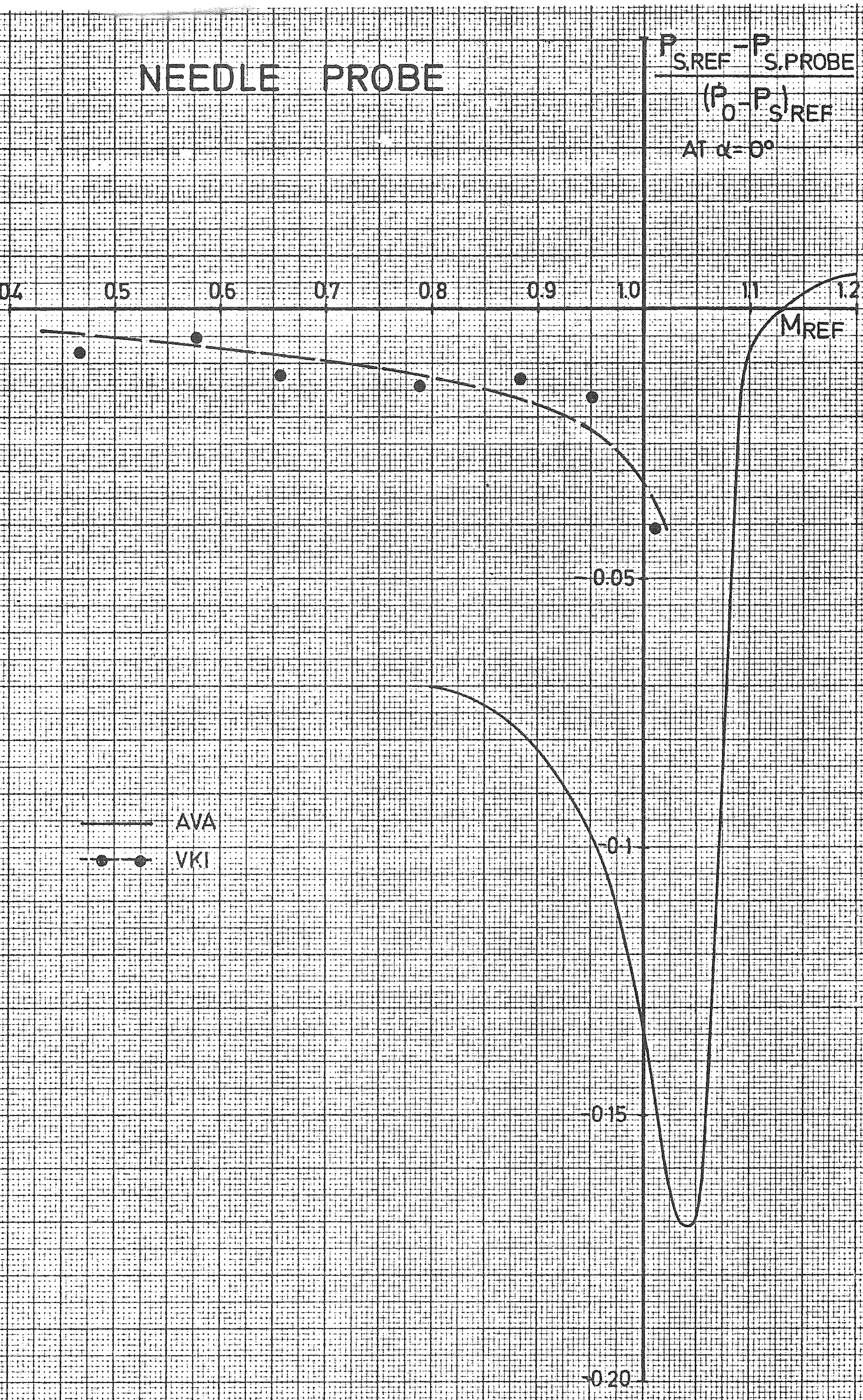
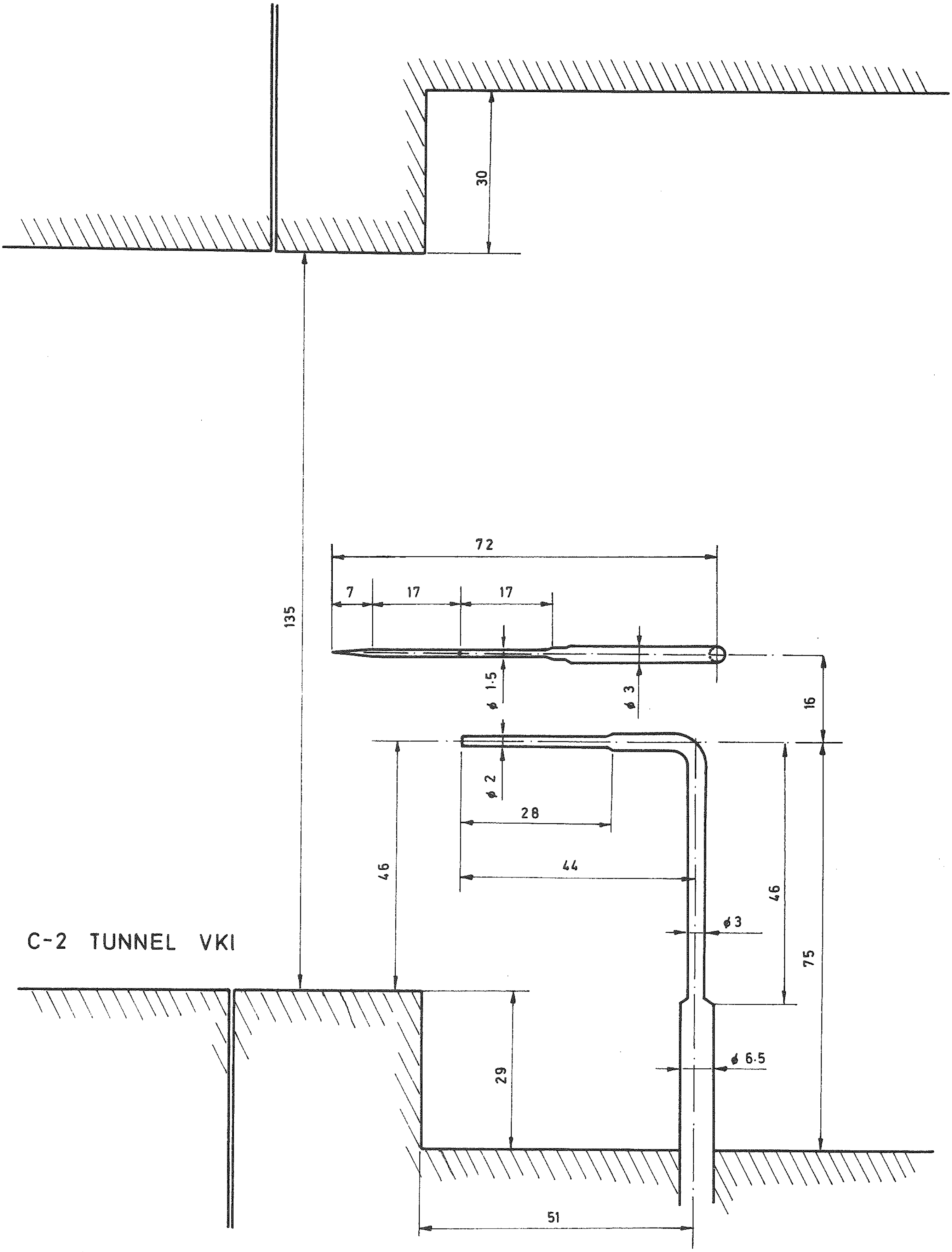
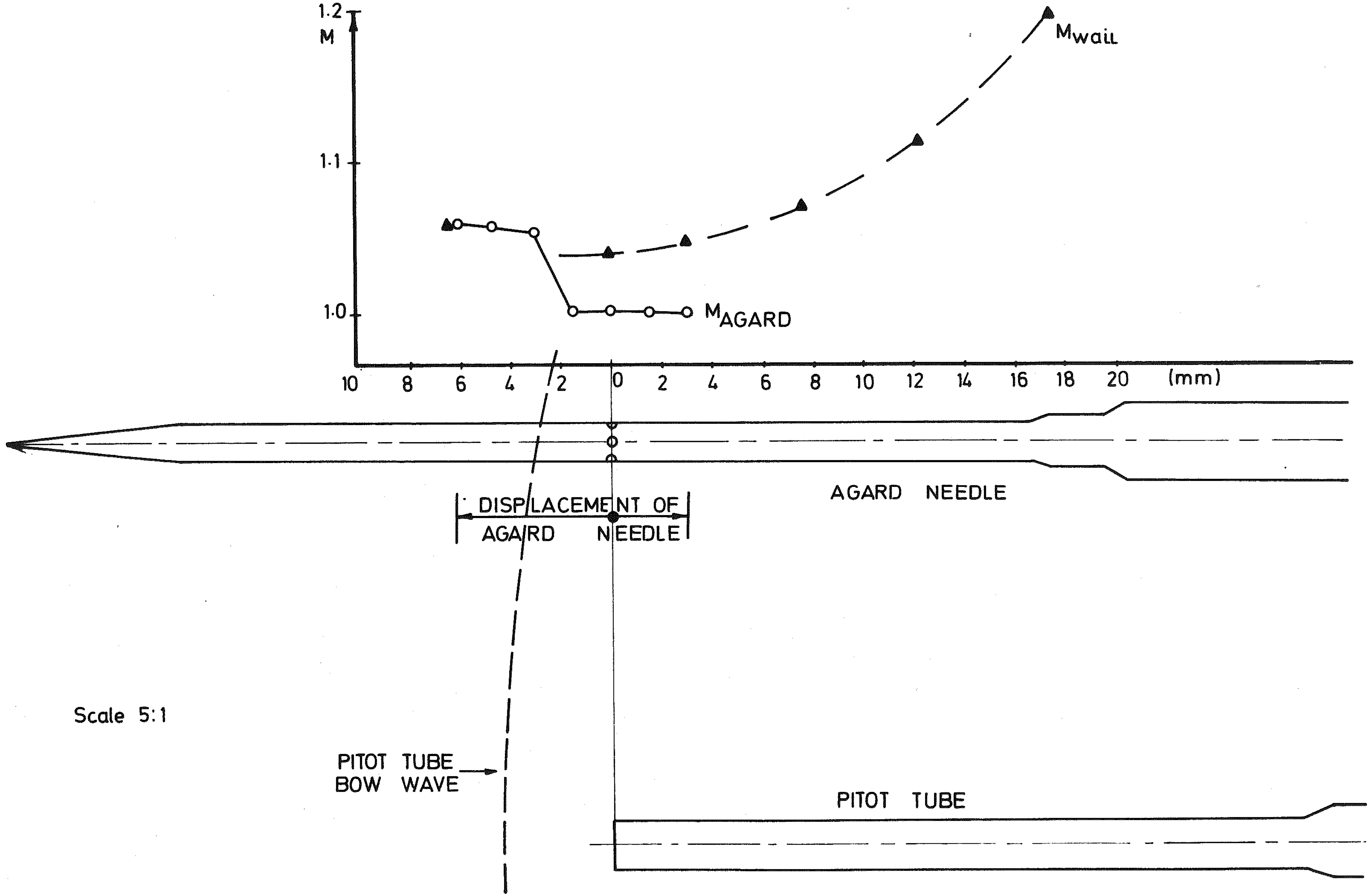

NEEDLE PROBE
$\frac{P_{S,REF} - P_{S,PROBE}}{(P_0 - P_S)_{REF}}$
AT α = 0°
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
M REF
0.05
0.1
0.15
0.20
AVA
VKI

FIG. 12



30
135
72
7
17
17
ϕ 1.5
ϕ 3
16
ϕ 2
28
44
46
46
ϕ 3
75
C-2 TUNNEL VKI
29
ϕ 6.5
51

FIG. 13



Scale 5:1

FIG. 14

VKI SUPERSONIC WIND TUNNEL S-3

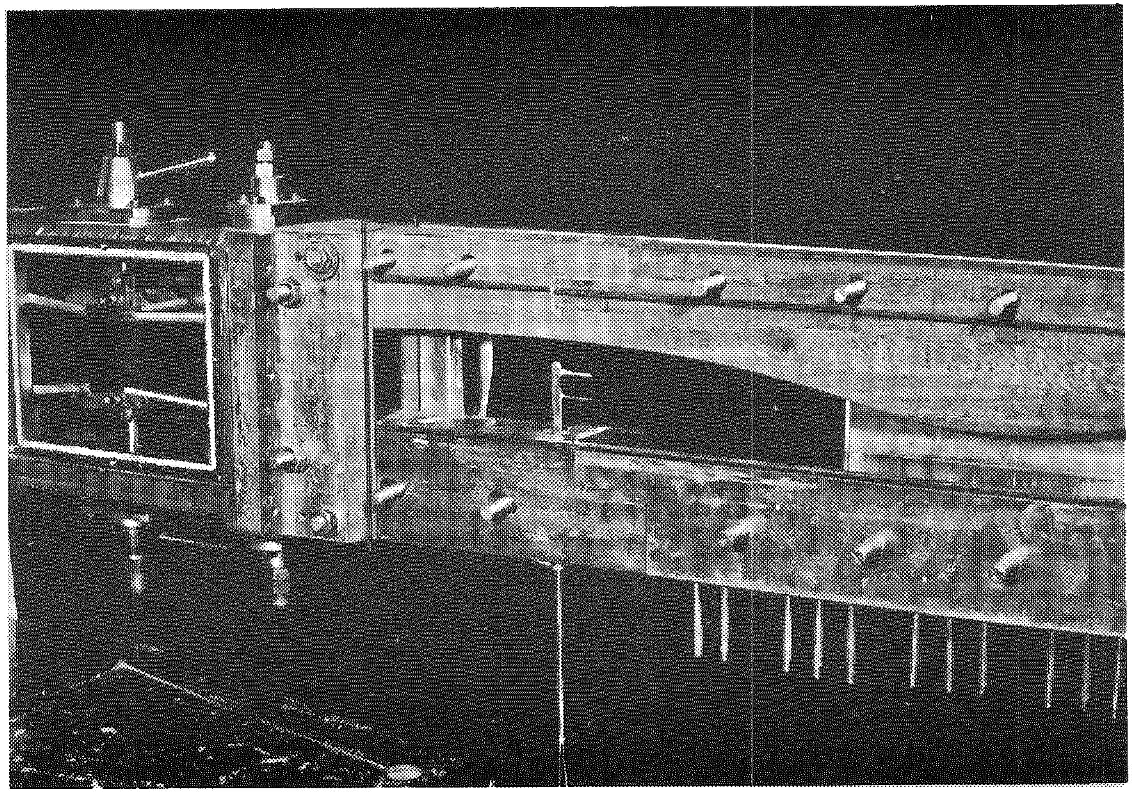


FIG 15

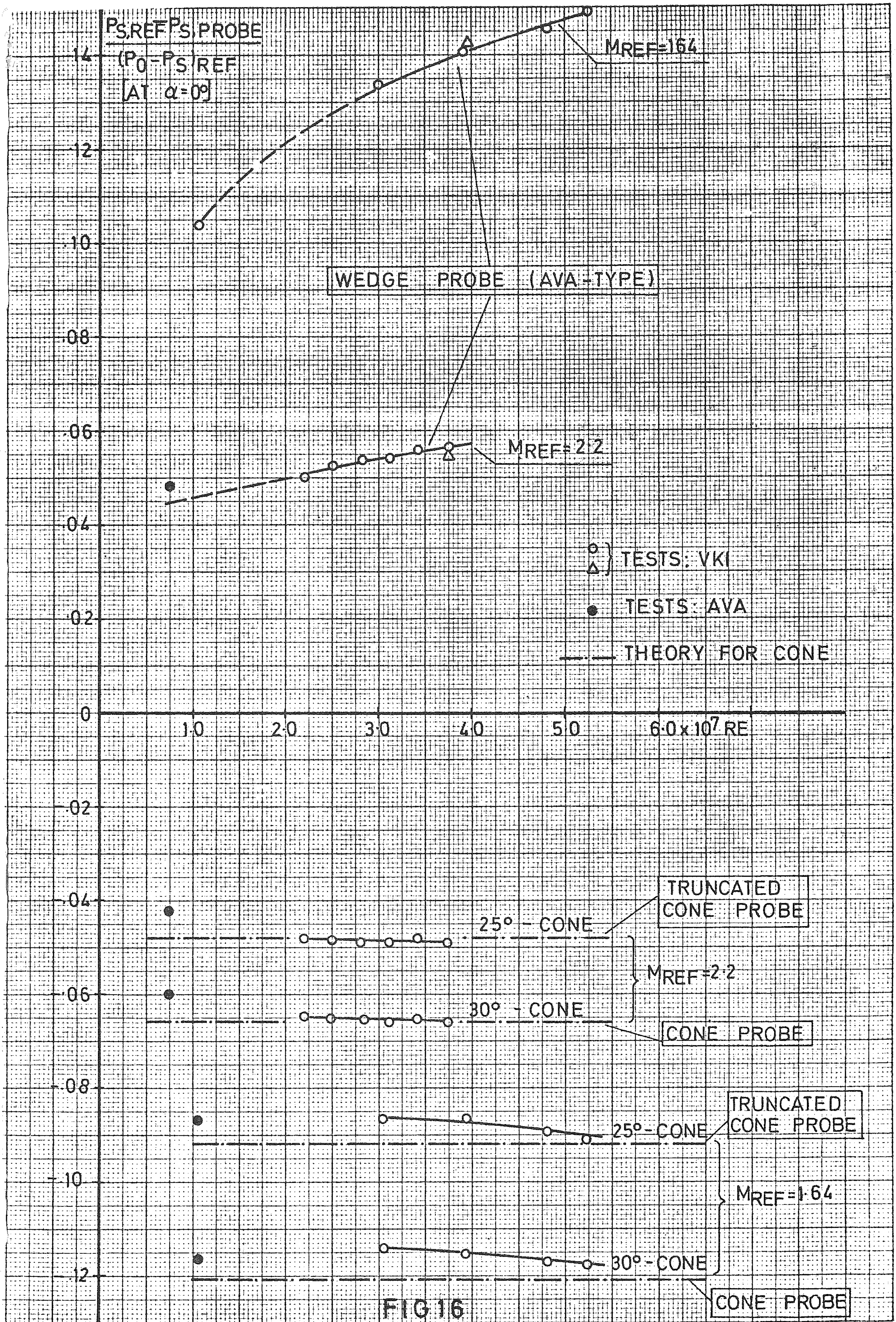

P S,REF – P S,PROBE / (P0 – PS)REF
[AT α = 0°]
·14
·12
·10
·08
·06
·04
·02
0
–·02
–·04
–·06
–·08
–·10
–·12
1·0
2·0
3·0
4·0
5·0
6·0 x 10^7 RE
MREF = 1·64
WEDGE PROBE (AVA-TYPE)
MREF = 2·2
○ △ } TESTS: VKI
● TESTS: AVA
— · — THEORY FOR CONE
TRUNCATED CONE PROBE
25° – CONE
MREF = 2·2
30° – CONE
CONE PROBE
TRUNCATED CONE PROBE
25° – CONE
MREF = 1·64
30° – CONE
CONE PROBE

FIG 16

COMPARISON OF TWO STATIC PRESSURE PROBES.

BY

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SNECMA

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