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The Noise Field from Designed Nozzles at Different Mach Numbers

by

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of Canterbury University College,
Christchurch, New Zealand

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THE NOISE FIELD FROM DESIGNED NOZZLES AT DIFFERENT MACH NUMBERS

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S U M M A R Y

Measurement of the noise radiated by unheated air jets issuing from a series of designed $\frac{1}{2}$" exit diameter nozzles have been made for velocities covering the range 800-1800 ft per sec.

The acoustic efficiency was found to increase with the velocity in a manner that could be explained on the theory of convected quadrupoles as propounded by Lighthill. Comparison with the results of other investigators who used heated air jets to obtain their exit velocities lends support to the theory that the temperature has little effect on the acoustic output of such jets.

Convergent-divergent nozzles at subsonic pressure ratios radiated sound in a similar manner to a simple convergent nozzle. When operating at their design pressure ratios the convergent-divergent nozzles possessed advantages over other undesigned nozzles which exhibited "screeching".

Experiments were also carried out in modifying the velocity profile at the exit of the nozzle by providing a sheath of air moving at a velocity slower than the core jet from a concentric annular exit. The results which support the work of Powell indicate that the velocity profile modification is unlikely to produce worthwhile and economic results in the quietening of jet engines. General reduction in the exit velocities still appears to be the best approach to the problem.

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LIST OF SYMBOLS

A	Area at Nozzle Exit
c	Speed of Sound
d	Diameter of Nozzle Exit
db	Decibels
M_c	Convection Mach number
M_a	Reference Mach number $= \frac{U}{c_a}$
n	Frequency in cycles per second (c.p.s.)
S.P.L.	Sound Pressure Level (quoted in db re 0.0002 mb)
T.P.L.	Total Power Level (quoted in db re 10^{-13} watts)
U	Velocity
η	Acoustic Efficiency
ρ	Fluid Density

Subscripts:

a	Atmosphere
1	Jet Stream
Stag	Stagnation Value

1. INTRODUCTION

While much work has been carried out overseas on the noise radiated by nozzles, only recently has the field of noise from convergent-divergent jets been investigated. It is in this field that most of the present tests were carried out. In addition to these tests, a silencer working on the principle of modifying the velocity profile and lowering the shear gradient in the mixing region by the provision of a slower moving annular sheath of air about the faster moving internal jet has been tested. The arrangement is similar to a by-pass jet engine with a small by-pass mass ratio.

The difference between this method and one tested by both Powell (Ref.1) and Lassiter and Hubbard (Ref.2) is that, while they altered the whole of the velocity profile of the jet, the present method was to try to retain the square velocity profile over most of the jet, but to reduce the shear gradient of the external mixing region.

2. SCOPE OF THE TESTS

All measurements were carried out at a radial distance of 100 diameters between the angles of 15° and 165°. Within this range there was virtually no interference from reflection or background noise.

Four nozzles for M = 1.0, 1.4, 1.8 and 2.2 designed by Rainbird and Norrie (Ref.3) were used. The nozzles were 0.5 in. exit diameter but the largest compressor available was not quite able to reach the design pressure of the M = 2.2 nozzle.

3. DESCRIPTION OF THE APPARATUS

3.1 Test Rig.- A diagrammatic outline of the rig is shown in Fig.1, and a photograph of the tower and nozzle is shown in Fig.2. The nozzles were at a height of 23 feet in a flat open field, and at least five hundred feet from any reflecting surface other than the ground. A boom swinging in a horizontal plane with its centre vertically below the nozzle exit (see Fig.2) carried the microphone, or alternatively the total head traversing gear. Fig.3 is an assembly drawing of the annular silencer, while Figs.4 and 5 are close-up views of the nozzle and the nozzle with the silencer in position. The turbulence screens were 30 meshes to the inch with 30 gauge brass wire.

3.2 Nozzles.- The nozzles were designed and manufactured by Rainbird and Norrie (Ref.3) using the method of Kuro Foelsch (Ref.4). Their manufacture was aarried out with considerable precision and the external contours are within 0.001 in. of the designed contours.* A contraction of ratio 64:1 was also designed and manufactured.

3.3 Sound measuring equipment.- The sound pressure level was measured with a Type 1551-A Sound Level Meter manufactured by the General Radio Company and was used in conjunction with a Type G.R. 1551 P1 Condenser Microphone system (see Fig.6 for a typical response curve of the system). The sound measuring equipment was acoustically checked by means of a G.R. 1552-A Sound Level Calibrator. The Sound Level Meter was also checked against another Sound Level Meter that had been flown to Sydney and calibrated at the Commonwealth Acoustic Laboratories.

The only Wave Analyser available had a range of 20-7500 c.p.s. and as the broad peak frequency was expected in the neighbourhood of 12,000 c.p.s. (Ref.5), it was thought that not much would be gained by its use. Measurements subsequently showed that nearly all the noise was above 7500 c.p.s. Instead a band pass filter was constructed of the range of 7500-15,000 c.p.s. to divide the measurable spectrum into approximately "high" frequency and "low" frequency bands. Fig.6 shows the response of the filter.

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*See Ref.3 for method of manufacture.

3.4 Other measurements.- Pressure measurements were taken on a standard 1-150 p.s.i. Budenburg Gauge which was stated by the manufacturers to be within ± 0.02 p.s.i.; the stagnation pressure in the silencer was measured on a small 0-50 p.s.i. Bourdon type gauge.

A pitot tube of 0.020 in. diameter hypodermic tubing was traversed across the jet by means of a micrometer screw. The stagnation temperature was measured upstream of the turbulence screens and a small portable barometer calibrated at the Christchurch Seismological Laboratory was used to determine the pressure ratio employed for each run. A wet and dry bulb thermometer determined the ambient temperature and humidity.

3.5 Local conditions.- Testing was carried out in early morning till about 8 a.m. and in the evening at dusk. The wind velocity was always less than 5 m.p.h. for any of the runs and was usually calm. The background noise levels from the compressor were an overall 81 db re 0.0002 m.b., and a Sound Pressure Level of 30 db for the high frequency band. Corrections were necessary for the overall S.P.L. in the case of the lower Mach number runs. (The method by which this was done is indicated in Ref.6, page 49.)

4. DETAILS OF TESTS AND RESULTS

4.1 Nozzles operating at design Mach number

4.1.1 Angular distribution of noise level.- Figs.7-13 show the angular distribution of the noise field. For overall sound pressure levels the peak of the lobe moves from an azimuth angle of 15° or less to 30°-35° as the Mach number increases from 0.70 to 2.16 (U_e 704 ft per sec to 1790 ft per sec). This change is shown in Fig.16.

There is also a general change in the shape of the polar diagram; as the Mach number increases the S.P.L. at 90° drops relative to the peak S.P.L. There is also a general lessening of the upstream values of the S.P.L. This does not ignore the fact that small upstream peaks appear in Figs.11 and 12. Figs.17 and 18 show the effect of exit velocity on the Total Power Level and on the Sound Pressure Level. More will be said about these figures in Section 5.1.2.

4.1.2 Changes in frequency spectrum.- While it is not possible to give an absolute value of the S.P.L. measured when the high pass filter was inserted in the S.P.L. meter (since the spectrum of this type of noise is known to be very broad), the filter values can be used qualitatively. The first noticeable fact in Figs.7-13 is that the content of the noise in the filter band compared to the overall noise is increasing. In other words the frequency peak of the noise appears to increase with the velocity. Without extensive spectrum analysis it is not possible to say more than this.

4.1.3 Acoustic efficiency (η).- Fig.19 illustrates the increase of acoustic efficiency (η) with increase in Mach number of the jet. Most investigators in this field have not had to correct for density changes at the exit from those in the reservoir when calculating their jet stream energy. The "uncorrected" acoustic efficiency varies to the 6.85th power of reference Mach number, while the "density corrected" efficiency appears to vary as Mach number to the 5.8th power. Fig.20 illustrates how the acoustic power output seems to bear a very definite relation to the jet stream power. More will be said about this in Section 5.1.3.

4.1.4 Acoustic power coefficient (K).- This is one of Lighthill's coefficients (see Ref.7) and for subsonic flows it is expected to remain fairly constant. Lighthill has also suggested a modified coefficient K' for flows of different density to the surrounding atmosphere. These coefficients are given in Table 1.

4.2 Nozzles operating at "off design" pressure ratios

4.2.1 Angular distribution of noise level.- For subsonic pressure ratios the angular distribution was unchanged for the various nozzles. Table 2 gives the Total Power Level for the different nozzles.

At M = 1.0 the error in T.P.L. is greater as the nozzles tend to "spit", that is, the noise level fluctuates to quite some degree. This was especially noticeable with the M = 1.8 nozzle. This factor is indicated in the decreased accuracy ascribed to the comparative results in Table 2. At M = 1.0 the distribution of the overall S.P.L. was similar to Fig.10. The convergent-divergent nozzles did however radiate 3 - 5 db more sound upstream than the M = 1.0 nozzle. For the M = 2.2 nozzle the S.P.L. at 90° was 6 db higher than that of the M = 1.0 nozzle.

For a pressure ratio of 3.18 (M = 1.4) severe "screeching" was experienced with the M = 1.8 nozzle (see Fig.15), and to a lesser extent with the M = 1.0 nozzle. The upstream lobe for the M = 1.0 nozzle was 6 db higher and for the M = 1.8 nozzle 18 db higher.* The M = 2.2 nozzle gave a distribution similar to the M = 1.4 nozzle (Fig.11).

Angular distribution of the noise levels for pressure ratio of 5.8 are similar to Fig.12 for all nozzles. The only notable fact is that the M = 2.2 nozzle gives the lowest acoustic output - this was probably due to the fact that the highest pressure possible gave only M = 2.16 and so the exit velocity would be considerably reduced. Except when a nozzle was "screeching" it appears that a nozzle designed for a specific purpose has relatively little advantage over another at that pressure ratio.

4.2.2 "Screeching".- Table 3 gives the pressure ratios at which screeching was audible, but results are incomplete. A severe case was the M = 1.8 nozzle running at a pressure ratio of 3.16 as illustrated in Fig.15, whereas a mild case was the M = 2.2 nozzle running at a pressure ratio of 5.8 as in Fig.14. The upstream lobe is apparent in both cases.**

4.2.3 Annular silencer.- The method used in any particular run was to keep the nozzle at a fixed pressure ratio and then vary the pressure for the silencer. The angular distribution of noise was found to be not much affected by the silencer and most of the tests were carried out by measuring the sound levels at the 30° station only and at a distance of 100 diameters.

Generally speaking, when the silencer stagnation pressure was of the order of 10 p.s.i. a reduction in S.P.L. of about 1 or 2 db was obtained. Table 4 gives some representative results obtained with the silencer in position, and Fig.21 shows the effect of the silencer on the velocity profile. Fig.22 compares the noise levels with and without silencer for the usual criteria of equal thrust and equal area.

4.2.3.1 Mixing region for annular air sheath.- It was possible to provide a mixing region between the central core and annular sheath of the jet by setting the silencer cone downstream. Table 5 shows that there is no advantage in providing a mixing region, and in many cases edge tones were introduced which increased the noise level as much as 6 db.

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* Even though the upstream level changed by 18 db the total acoustic power was increased by only $5\frac{1}{2}$ db. (Ref.10, Chap.8).

** The difference in peak levels for the two runs for the M = 1.8 nozzle is hard to explain. These two runs were made some months apart (runs 11 and 12 Table 1 - the stagnation temperature for run 12 was higher and oil and condensation water were evident in the jet).

5. DISCUSSION OF RESULTS

5.1 Noise field results

5.1.1 Variation of acoustic power output with velocity.- Only a few investigators in the field recorded results of total acoustic output. Fitzpatrick and Lee (Ref.8), who obtained their results from measurements in a reverberation chamber, which had been calibrated in some frequency bands, obtained a result close to an eighth-power law variation with jet exit velocity. This result is confined to subsonic velocities and was for convergent nozzles of 1.53 in., and 0.765 in. diameter respectively. The accuracy to which their reverberation tank was calibrated is not clear in their report, but sources of uncertainty are indicated on pages 7 and 8. Gerrard (page 21, Ref.5) finds acoustic power varying 7.2th and 7.7th power of the mean velocity for circular pipes, 1 in. diameter, and 36 in. and 54 in. long, respectively. Gerrard's velocity profiles would be fairly fully developed pipe flow, so a somewhat lower rate of increase of acoustic output might be expected with respect to velocity increases. An N.A.C.A. investigation (Ref.6) for a small model airjet found the acoustic output varying to the eighth power of the exit velocity up to a Mach number of about 1.2. There was only one value for the supersonic range, as apparently only one convergent-divergent nozzle had been made (with a design pressure ratio of about 3.0). The only report available containing the acoustic efficiency of air jets in the velocity range that the present tests covered, is the investigation by Greatrex (Ref.9). His report concerns full size jet engines, but interestingly he records that in this range of exit velocity (1000 - 2000 fps) the acoustic power output varies as something like velocity to the 9th power. This corresponds almost exactly with our investigation, which as recorded earlier in the report, gives an index of 9.0 for density corrected acoustic outputs for the velocity range 700-1800 fps). (Note: Other investigations have noted increase in sound pressure level at a certain station - while this gives a good idea of how directional efficiency changes with velocity, it does not, in the authors' opinion, give an accurate picture of how the total radiated acoustic power varies. Ref.10, chapter 8 describes this aspect fully.)

Temperature effects are almost certainly not the cause of the rise in the velocity index from the basic eighth power to the ninth in the local tests. The increase is probably due to increased "eddy convection velocity" and to increased "shear effects". (See Refs.5 and 7).

5.1.2 Directional changes in the propagated sound.- As stated before (Section 4.1.1), the peak lobe moves from 15° to about 33° as the exit velocity changes from 766 fps to 1790 fps. This result is consistent with Lassiter and Hubbard's findings (Ref.2), although they obtained their high exit velocities by increasing the temperature and keeping the local Mach number in the jet subsonic (see Fig.16(b)). The "high frequency" lobe in the present series of tests remained fairly steadily at the 30° station. This band corresponds to Strouhal numbers, nd/U, from about 0.3 to about 0.5, and thus this lobe position agrees with other investigations (Ref.5, page 23). The sound equipment used in the local testing was not able to measure Strouhal number higher than about 0.7. This is unfortunate, because the "high" frequencies, as Lighthill uses the term, are those above 0.7 (i.e. in our case above 15 Kcs).

The increase in intensity of sound radiated in the downstream direction at the 30° station (see Fig.18) over and above the U^8 rule (in our case about $U^{10.5}$) is what would be expected from the effects of quadrupole convection, taking an eddy convection velocity of about 0.6 the exit velocity (Ref.5, page 5). A similar increase occurs in the investigations of Lassiter and Hubbard (when their results in Ref.2 are corrected for density) who were working with similar exit velocities. Most investigators in the "subsonic" field have recorded sound intensity at the 30° station varying about the 8th power of the exit velocity.

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At the 90° station, where convection effects must be absent, investigators in all fields have reported values for the velocity index from about 5 to 7 (in our case about 7). The fact that this is always below the theoretical value of 8 has led Lighthill to suggest that increase in noise production due to increased velocity is somewhat modified by a general reduction in either the turbulence level, or in those aspects of turbulence that generate sound. As Lighthill points out, this is evidenced by the slow rate of spread of supersonic mixing regions. He also indicates that there may be less turbulence than expected, because in the mixing region, where turbulence builds up, energy is being lost in not inconsiderable amounts by sound radiation.

An interesting section of Lighthill's paper (Ref.5, page 26) refers to the possibility of supersonic convection of quadrupoles. This could conceivably have occurred in Run 14 (Fig.12). Here is shown a strongly directional lobe with a peak at about 33°. Lighthill's theory shows that an eddy Mach number M_c would produce infinite sound at an angle equal to $\sec^{-1}(M_c)$. Now sec 33° gives M_c equal to about 1.2; that is, about 0.76 M, where M is the reference Mach number of the jet flow at exit. Such a value is in excess of what might be expected, but the trend of increase of the angle of maximum radiation at high exit velocities (as shown in Fig.16(b)) is probably associated with this "supersonic" eddy, convection theory.

5.1.3 Acoustic efficiency and acoustic power coefficient.- As might be expected, from the result that the acoustic power output increased over and above the 8th power of the exit velocity, both the acoustic efficiency and the acoustic power coefficient increase faster than has been noted by investigators in the subsonic field. When the results of Lassiter and Hubbard (Ref.2, page 435) are corrected for density differences in the jet relative to atmosphere density, it would appear that the changes in acoustic efficiency and acoustic power coefficient in their experiments, that they have only broadly defined, would be very similar to the present results. This then indicates that the increase in acoustic efficiencies in the range of velocities of 1000-2000 fps, which they ascribe to increase in temperature, are due to other causes, i.e. quadrupole convection effects. This appears to be good confirmation of one of Lighthill's suspicions (see Ref.5), that temperature inhomogenities cause little increase in acoustic efficiency.

It should be noted that the local results have been calculated using jet density ρ_1 in the term for jet energy $\frac{1}{2}\rho_1 U^3 A$ when estimating the acoustic efficiency. The acoustic power coefficients, as shown in Table 1, have used atmospheric density in the denominator to provide easy comparison with other investigators, and to remain strictly consistent with Lighthill's basic postulates.

Fig.20 illustrates the increase in acoustic output with increase of the jet stream power. The acoustic power here has not been corrected for density changes in the jet.

5.1.4 "Screeching".- The screeching noted in Results of Tests (Section 4.2.2) can be explained by a mechanism propounded by Dr. A. Powell of University of Southampton (Ref.11). This mechanism gives a powerful lobe at the disturbance frequency upstream (as shown in Fig.15), and a narrow beam at twice the disturbance frequency is expected to arise about normally to the jet. The normal beam, with a frequency possibly beyond the range of our instruments, was not apparent in our tests.

5.2 Discussion of annular silencer results

5.2.1 Methods used in modifying the exit velocity profile.- In the available literature it appears that only two other methods have been utilised in investigating the change in acoustic output with velocity profile changes. The first is where the main flow is surrounded by a slower moving annular sheath of air by induced flow. This method has been tried both in England and the United States (Refs.6 and 12). In both cases no appreciable reduction was found, and indeed in some instances a severe resonance was encountered, which greatly increased the noise level. As Powell (Ref.1) points out, an efficient induced flow depends on a high rate of early turbulent mixing; and this is the very origin of the sound which it is wished to reduce.

The other method of modifying the exit velocity profile described, is to make measurements on the flow issuing from a long pipe, since the onset of "pipe flow" will at least partly achieve the desired changes of velocity profile. This method has been tried by Lassiter and Hubbard (Ref.2) and by Powell (Ref.1). Both found, for a fixed centreline velocity, considerable reductions in the noise levels with the rounded velocity profile, mainly in the higher frequency components of the radiated noise. Because of the reduction of mean velocity, however, the calculated thrust of the jet with the modified velocity profile was considerably less. When comparing noise levels on a basis of equal thrusts (equal maximum velocities and diameters adjusted) a slight reduction was afforded by velocity profile changes (Ref.1 and 2). When compared on the basis of equal exit diameters, and centreline velocities adjusted to give equal thrusts, Powell shows a constant velocity across the exit is preferable to the modified profile. Lassiter and Hubbard also showed, as Lighthill had forecast, the jet is relatively insensitive to turbulence changes in the core, but is apparently much affected by changes in the mixing region.

5.2.2 <u>Use of annular sheath of air employing forced flow</u>.- The local method of providing auxiliary forced flow, in the form of an annular sheath, corresponds to a "by-pass" engine of the Conway type. One of the advantages the local method was expected to afford was that it would not automatically reduce the comparative thrust of the jet by lowering velocities in the core of the jet - a process unavoidable in Powell's, and Lassiter and Hubbard's methods. Fig.21 illustrates how effectively this was achieved, although it must be admitted the shear gradient has not been reduced as much as was desired. It is unfortunate that time was not available to measure the profiles further downstream, for it is some diameters downstream of the exit that the majority of the radiated noise is thought to emanate. Without turbulence measurements, these additional velocity measurements would not have afforded much additional information.

The results of the local tests only serve to reinforce Powell's conclusions, in that velocity profile modification does not appear to offer an avenue for economical reduction of noise from jet engines. It is interesting to note that the noise reductions afforded by the Conway jet engine are due, not to lowering of the shear gradient, but in the words of Greatrex (Ref.9), "to lower temperature (hence lower velocity), higher mass flow and larger diameter exit". For these reasons, by-pass jet engines can offer up to a reduction of 20 decibels for a by-pass primary mass flow ratio of 2.3 for a fully mixed jet (Ref.6). The same reference indicates, however, that at extremely high by-pass ratios, the question of compressor whine may become important with this type of engine.

As many previous investigators have noted, for worthwhile reductions in acoustic output (over 10 decibels), general velocity reduction at exit appears by far the most effective and economical method of silencing jet engines. The high frequency noise, that velocity profile modification reduces slightly, only occurs in the case of a static or slow moving aircraft. At speed, the aircraft's own passage through the air reduces the shear gradient automatically.

6. <u>CONCLUSIONS</u>

1. For density-corrected acoustic outputs, a straight line can be drawn through subsonic and supersonic points on a logarithmic graph of acoustic output against velocity, giving an increase in intensity against jet velocity to the power of approximately nine.

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2. From a comparison with other investigators' figures for similar velocity jets, it appears that the temperature of the jet has little effect on the acoustic output.

3. The increase in acoustic efficiency and the change in directional properties of the radiated noise agree with Lighthill's predictions for effects of "eddy convection".

4. At the highest velocities tested, the effects of "supersonic eddy convection" appeared to be coming into play.

5. Convergent-divergent nozzles exhibit the resonant "Powell" type of noise production, associated with the shock formations, both above and below the design pressure ratio in the supersonic range of pressure ratios. At design pressure ratio, the convergent-divergent nozzle has a reduction of up to 6 decibels in the acoustic output, below the output of a nozzle which is exhibiting the "Powell" type of noise production. At subsonic pressure ratios there is negligible difference in the noise radiated by a convergent-divergent nozzle and a convergent nozzle.

6. There appears to be little hope of achieving worthwhile and economic reductions in acoustic output of jets, on the basis of modifying the velocity profile and reducing the shear gradient, by auxiliary flow methods. The reduction in the noise level of a by-pass engine is mainly due to a lowering of the mean velocity, rather than differences in the velocity profile.

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Table 1

General Results

Run No.	1	2	3	4	5	6	8	9	10	11	12	13	14
Nozzle design Mach number	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.4	1.4	1.8	1.8	2.2	2.2
Flow Mach number U/c_{local}	0.65	0.70	0.79	0.90	0.95	1.0	1.0	1.4	1.4	1.8	1.8	2.10	2.16
Velocity feet/sec	704	766	854	961	1005	1025	1035	1348	1382	1610	1673	1760	1790
Reference Mach number U/c_{air}	0.63	0.68	0.76	0.85	0.89	0.92	0.92	1.21	1.215	1.45	1.465	1.58	1.56
Stagnation temperature °F abs	526	548	547	550	549	526	535	535	566	550	593	551	560
Total power level db re 10^{-13} watts	103	107.5	112	116.5	118	119	119.5	131	133.5	140.5	144	144	146
T.P.L./ρ_1^2/ρ_a^2 db re 10^{-13} watts	102	106	110.5	114.5	116	117.3	117.7	128.2	129.8	136	139	138.3	139.6
Total power level watts	0.002	0.0056	0.0158	0.0447	0.0631	0.0793	0.0891	1.259	2.239	11.22	25.12	25.12	39.81
Ambient sound speed f.p.s. c_{air}	1112	1127	1121	1123	1130	1112	1118	1112	1138	1112	1144	1112	1147
Stagnation density slugs/ft^3 ρ_0	0.00312	0.00349	0.00378	0.00428	0.00449	0.00441	0.00462	0.00727	0.00826	0.0136	0.0156	0.0214	0.0259
Nozzle exit density slugs/ft^3 ρ_1	0.00255	0.00276	0.00282	0.00294	0.00297	0.00279	0.00293	0.00316	0.00362	0.00387	0.00423	0.0044	0.0050
Density ratio ρ_1/ρ_{air}	1.12	1.16	1.185	1.235	1.248	1.22	1.232	1.38	1.522	1.69	1.78	1.93	2.10
Flow energy $\frac{1}{2}\rho_1 U^3 A$ watts $\times 10^{-3}$	0.826	1.15	1.61	2.42	2.79	2.83	3.02	7.15	8.86	14.95	18.5	22.25	26.5
Acoustic efficiency T.P.L./$\frac{1}{2}\rho_1 U^3 A \times 10^6$	2.42	4.86	9.82	18.50	22.6	28.0	29.5	176	253	752	1360	1130	1500
Acoustic efficiency $\dfrac{\text{T.P.L.}/\rho_1^2/\rho_a^2}{\frac{1}{2}\rho_1 U^3 A} \times 10^6$	1.93	3.61	7.0	12.15	14.5	18.8	19.4	92.3	109	263	429	303	340
Acoustic power coefficient $K \times 10^4 = \dfrac{\text{T.P.L.}}{\rho_a U^8 c_a^{-5} d^2}$	0.105	0.153	0.181	0.202	0.199	0.204	0.216	0.536	0.570	0.777	1.58	0.860	1.342
Acoustic power coefficient $K' \times 10^4 = \dfrac{\text{T.P.L.}}{\rho_1^2 \rho_a^{-1} U^8 c_a^{-5} d^2}$	0.084	0.114	0.129	0.133	0.128	0.137	0.142	0.281	0.246	0.272	0.501	0.231	0.305
Run No.	1	2	3	4	5	6	8	9	10	11	12	13	14

Table 2

Total Power Level of Different Nozzles at Different Pressure Ratios

Press. Ratio	Nozzle	Eq Mach No.(local)	TPL (db re 10^{-13}w)
1.5	'1.0'	0.8	112 ± 1
1.5	'1.4'	0.8	112 ± 1
1.5	'1.8'	0.8	112 ± 1
1.5	'2.2'	0.8	112 ± 1
1.89	'1.0'	1.0	119.5 ± 1
1.89	'1.4'	1.0	120 ± 2
1.89	'1.8'	1.0	123.5 ± 3
1.89	'2.2'	1.0	121 ± 2
3.18	'1.0'	1.4	136 ± 2
3.18	'1.4'	1.4	133.5 ± 1
3.18	'1.8'	1.4	139 ± 1
3.18	'2.2'	1.4	131 ± 1
5.4	'1.0'	1.76	142 ± 1
5.8	'1.4'	1.8	143 ± 1
5.8	'1.8'	1.8	142.5 ± 1
5.8	'2.2'	1.8	140 ± 1

$$\text{Pressure ratio} = \frac{P_{stag}}{P_{atmos}}$$

Table 3

"Screeching" Pressure Ratios

Nozzle	Design P.R.	Audible Screech P.R's	Audible Peak Screech P.R's
1.0	0 - 1.9	2.6 - 3.5	-
1.4	3.18	3.7 - 5.8	4.2, 4.6
1.8	5.8	2.9-3.7 6.8 on	3.3
2.2	10.7	4.45 - 6.1	-

$$\text{P.R.} = \text{Pressure ratio} = \frac{P_{stag}}{P_{atmos}}$$

Table 4/

Table 4

Effect of the Annular Silencer on Sound Pressure Level

Nozzle	P_{stag}	P_{sil}	Overall SPL	High Freq SPL (7.5 Kcs-15 Kcs)	Thrust (lb)
'1.0'	13.2	0	104.5	101.5	4.08
'1.0'	13.2	5	104	100.5	5.14
'1.0'	13.2	10	104.5	100.5	5.92
'1.0'	32.2	0	121	119.5	7.80
'1.0'	32.2	7.5	119	117	9.32
'1.0'	32.2	28	120.5	-	12.12
'1.4'	32.2	0	119	117.5	7.84
'1.4'	32.2	4	118.5	116.5	8.68
'1.4'	32.2	9	118	115.5	9.54
'1.4'	32.2	18	120	117.5	11.86
'1.8'	70.4	0	129	127.5	13.24
'1.8'	70.4	7.5	129	127.5	14.70
'1.8'	70.4	18	128	125.0	16.26
'1.8'	0	13.2	100	94.5	2.36
'1.8'	0	32.2	113	110	4.52
Barometric pressure = 14.78 psia					

P_{stag} is the stagnation pressure for nozzle (psig)

P_{sil} is the stag pressure for the silencer chamber

Note: that Table 4 refers to the case where the silencer exit is set flush with nozzle exit.

Table 5

Effect of Mixing Region with the Annular Silencer

P_{stag} psig	P_{sil}	Thrust lb	Nozzle SPL	Nozz-Sil SPL	Equiv Nozzle SPL
13.2	0	4.08	104.5	104.5	94.0
13.2	5	5.14	110	104	100
13.2	10	5.92	113	104.5	104
32.2	0	7.84	119	119	111
32.2	4	8.68	121	118.5	114
32.2	9	9.54	123.5	118	115.5
32.2	18	11.86	125.5	120	119
70.4	0	13.24	129	129	123
70.4	7.5	14.70	139	129	125
70.4	18	16.26	133	128	127
Barometric pressure = 14.78 psia.					

FIG. 1. SCHEMATIC LAYOUT OF AIR FLOW SYSTEM

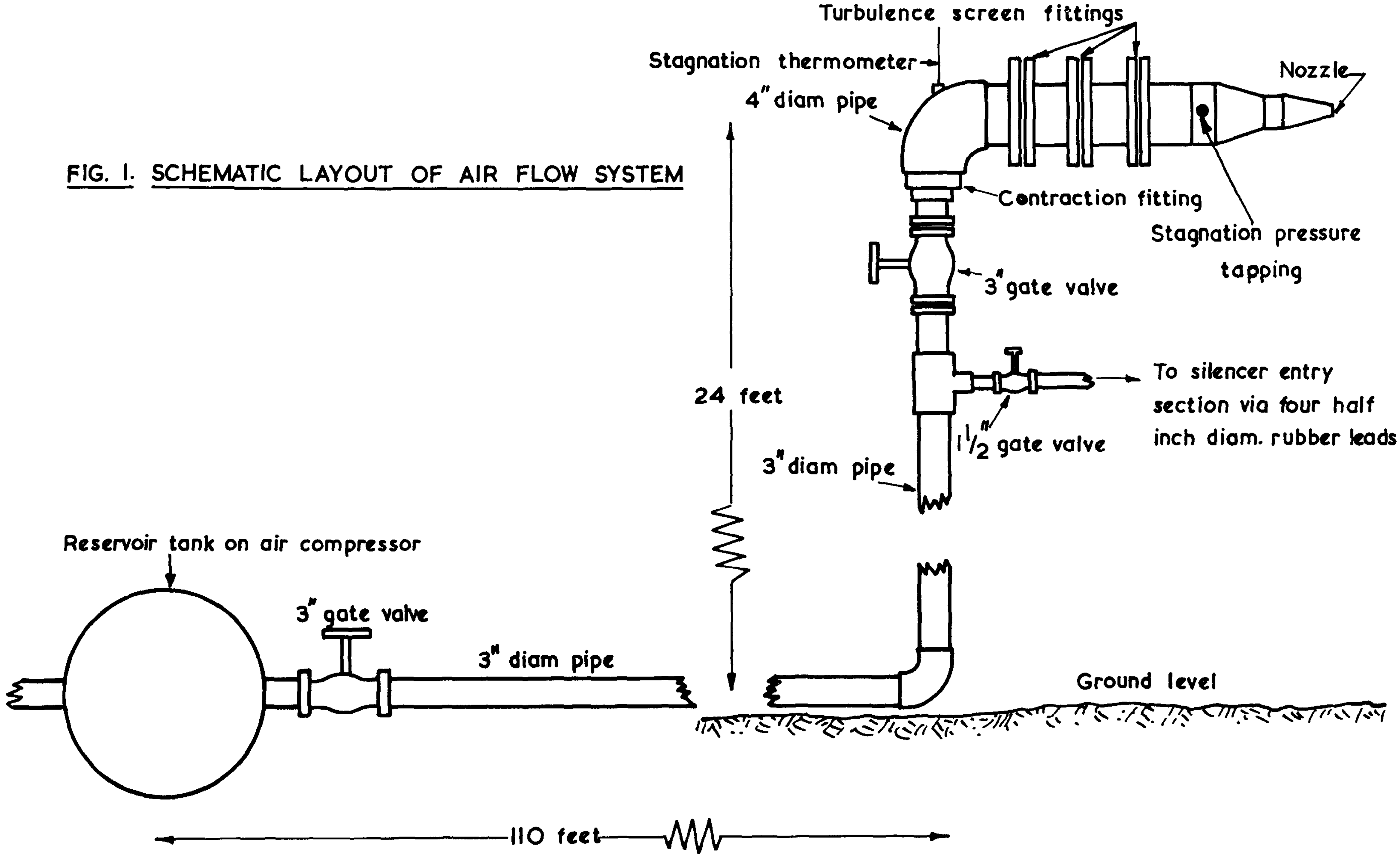
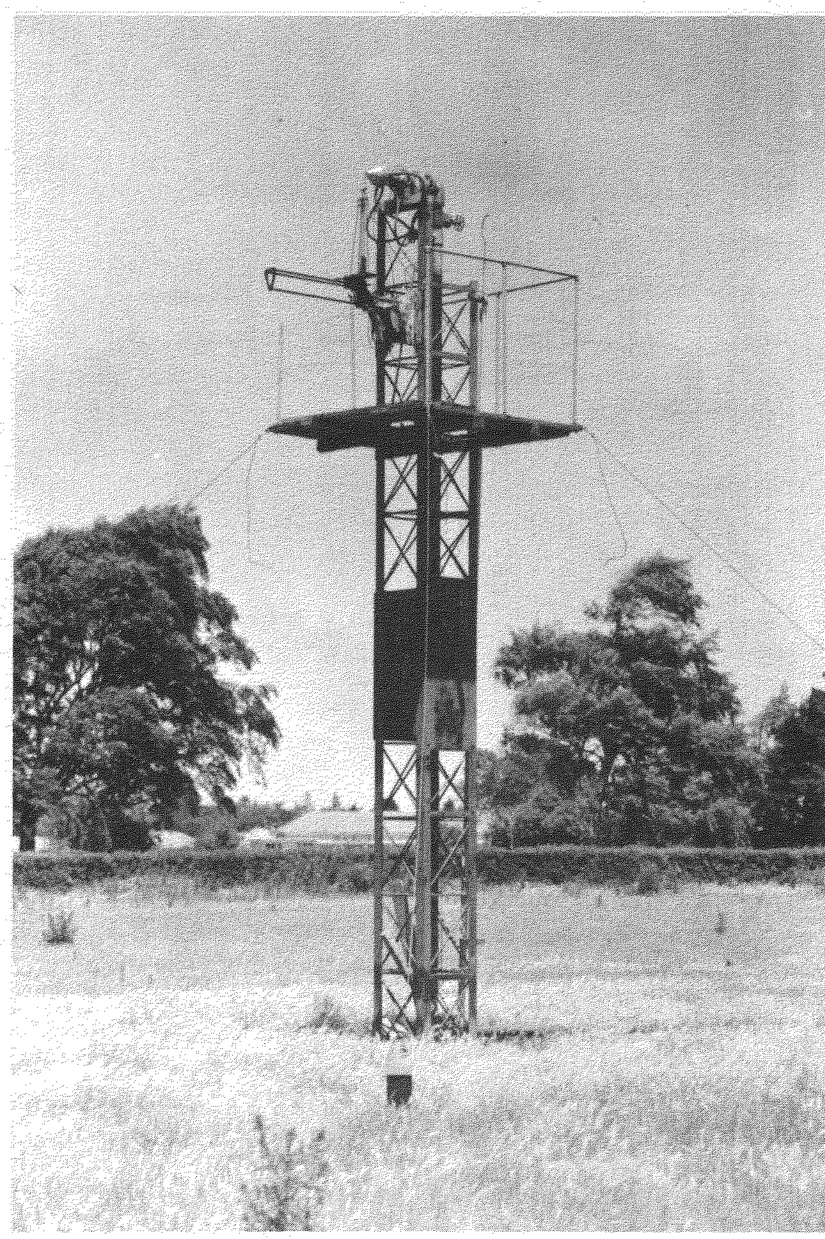


FIGURE 2

A GENERAL VIEW OF TOWER AND WORKING PLATFORM FOR EXPERIMENTS



The pipeline, from the compressor, which is not in the photograph but is positioned 110 feet to the right of the tower, runs at ground level to the base, then right-angles vertically up the centre of the tower, through the gatevalve and turbulence screen fitting to the nozzle. In the above picture, the silencer is fitted over a nozzle, and the pitot traverse gear, not the microphone, is fitted to the swinging boom.

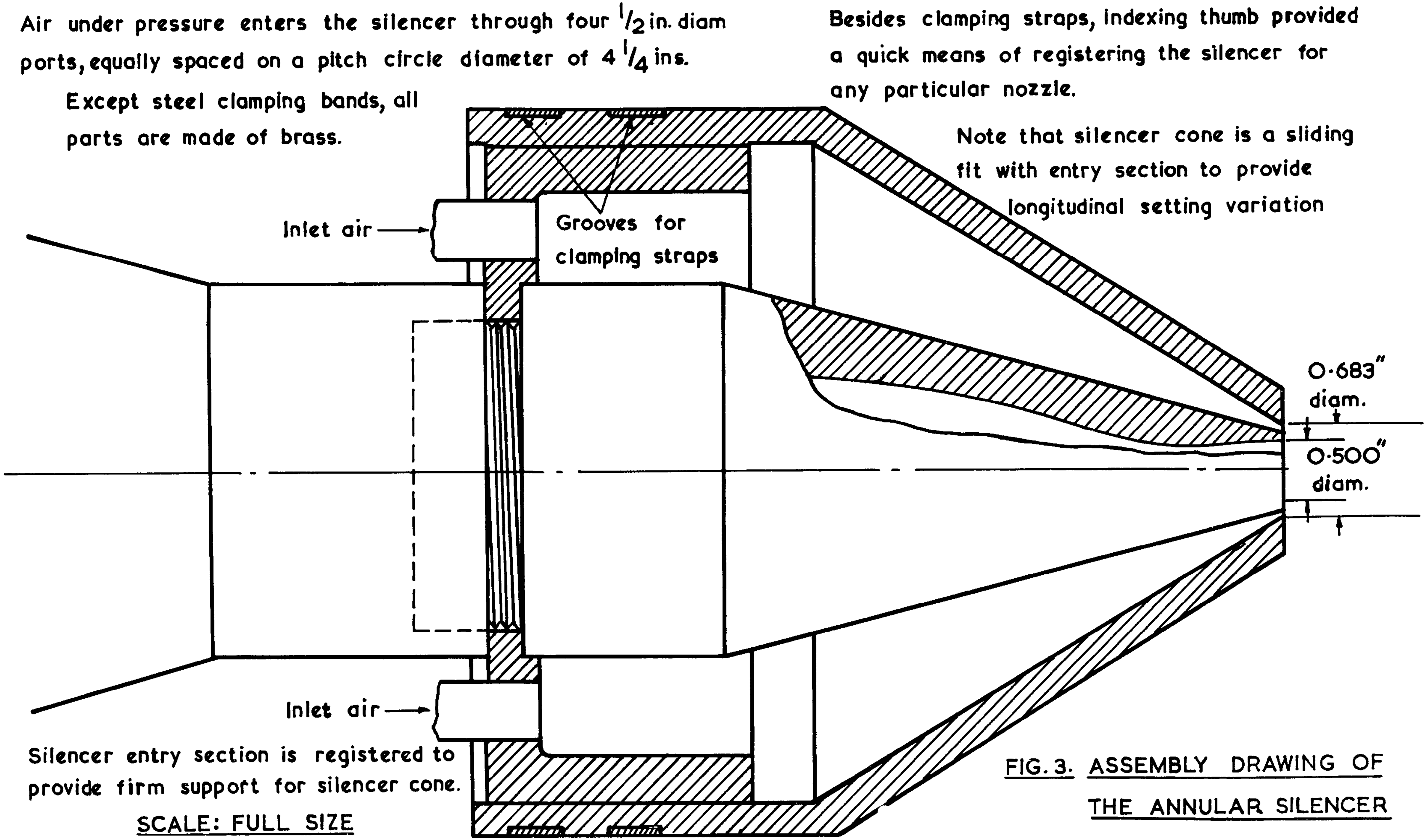
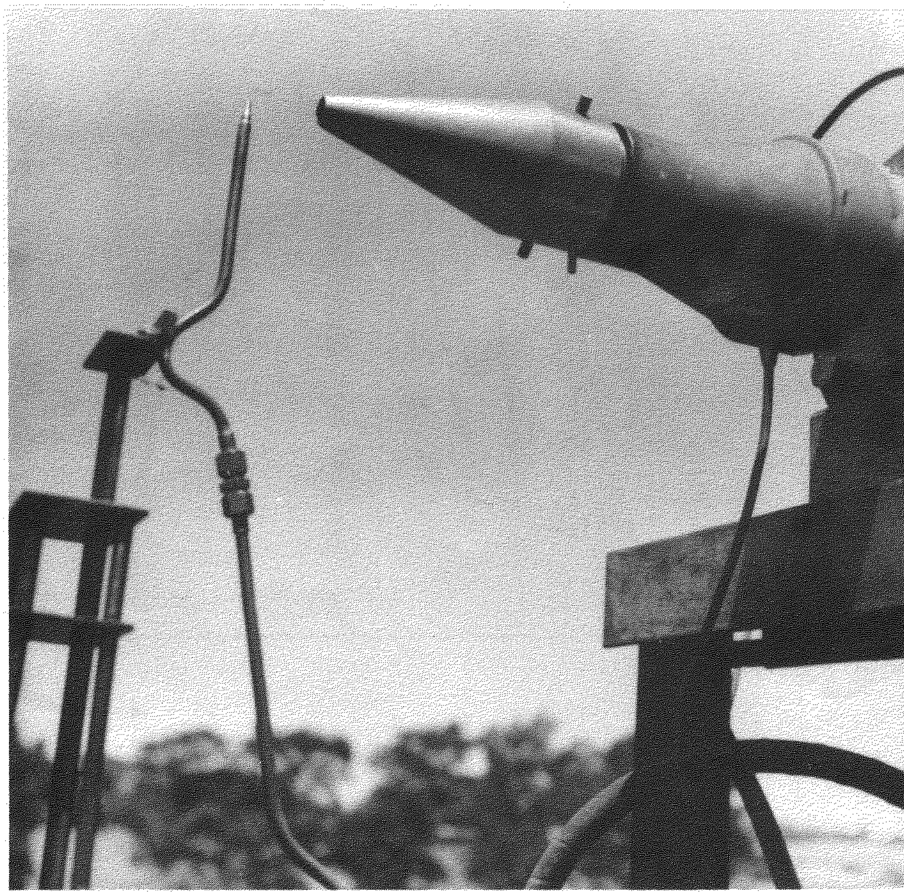


FIG. 3. ASSEMBLY DRAWING OF THE ANNULAR SILENCER

FIGURE 4

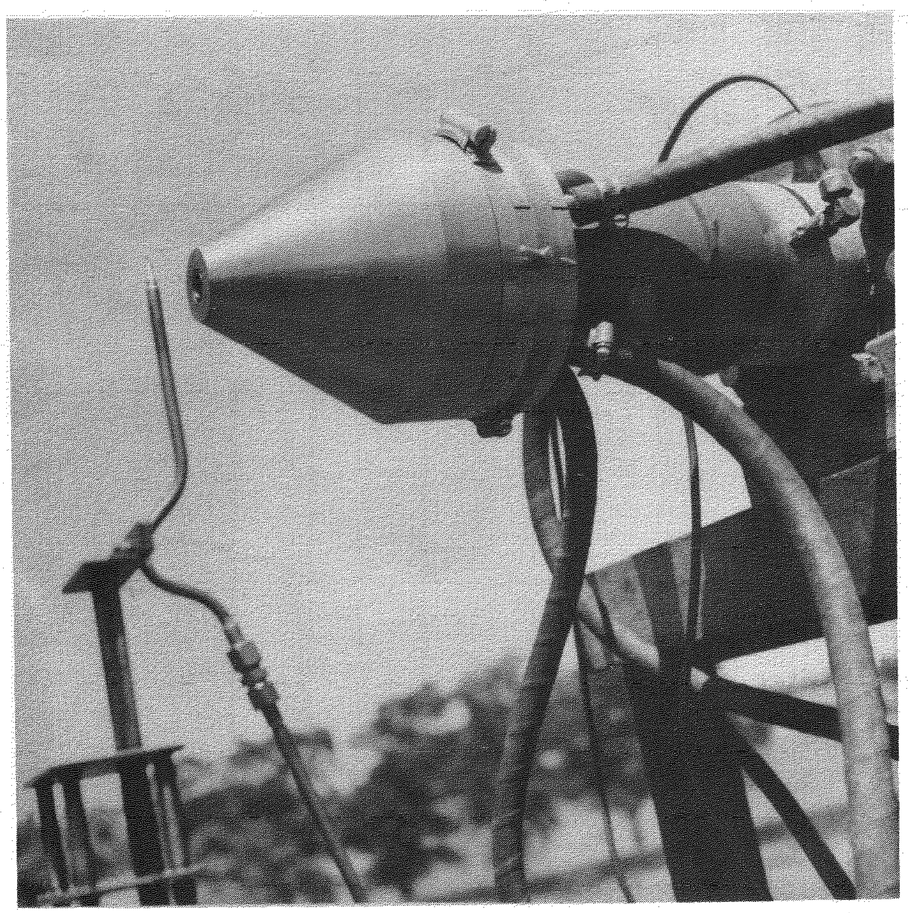
A CLOSE-UP VIEW OF ONE OF THE NOZZLES IN POSITION



The above view shows the pitot traversing gear in position to measure the total head 1.8 diameters downstream of the nozzle exit. The lugs for tightening the nozzle into place are visible, as is also the contraction fitting, joining the nozzle to the pipeline. Just upstream of the nozzle, but not visible here is the fitting containing the turbulence screens.

FIGURE 5

A CLOSE-UP VIEW OF THE SILENCER IN POSITION



The above view affords an idea of the silencer rig. The steel clamping bands, and the positioning thumbscrews are evident, and as the silencer has been fitted flush with the inner nozzle, it is also possible to see the nozzle exit. The four rubber hose leads bringing the air to the silencer inlet ports, the stagnation pressure tapping on the main pipe, and the pitot gear are also visible.

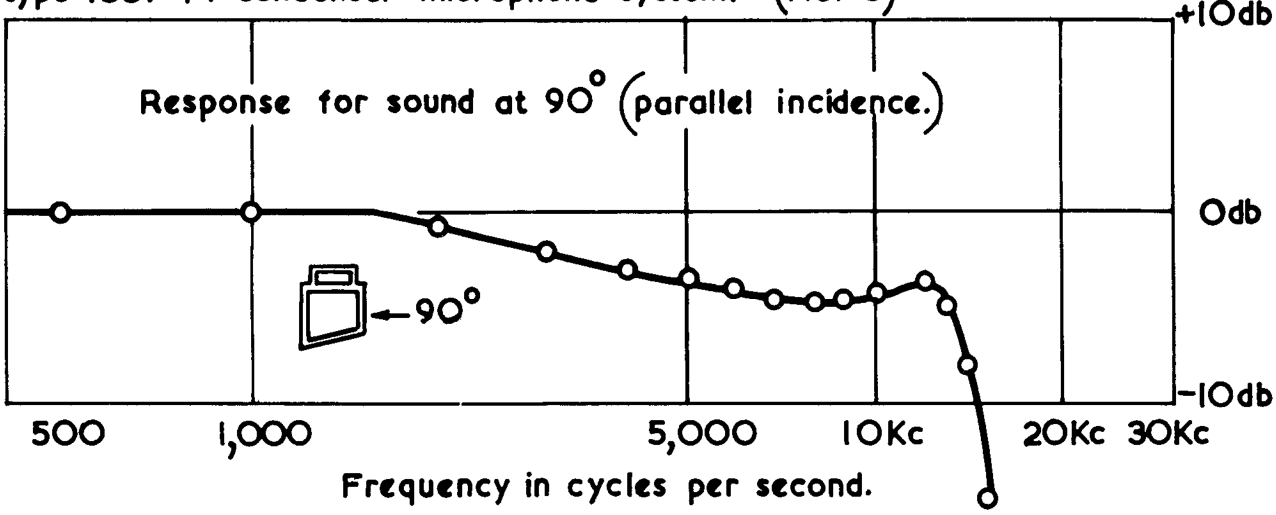
The stagnation pressure tapping to the silencer is not visible in the above picture, but it is situated at the rear face of the inlet section, on the same pitch circle as the inlet ports.

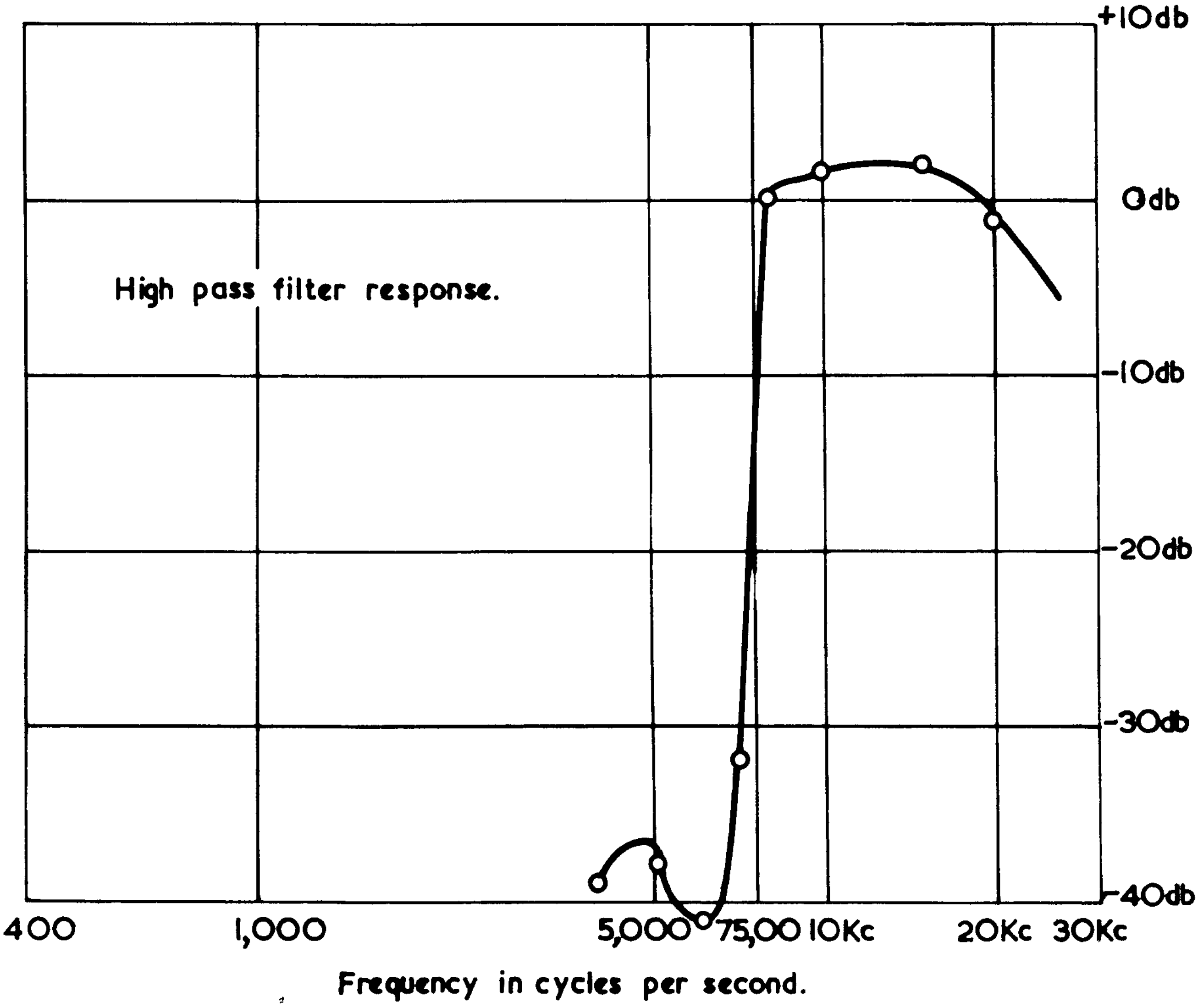
Just visible to the upper right of the photograph is one of the fittings containing a 'turbulence' screen.

<u>FIG. 6.</u>

<u>CALIBRATION OF THE SOUND EQUIPMENT</u>

A typical response curve for the type 1551-A sound level meter and the type 1551-P1 condenser microphone system. (Ref 8)





Response of high pass filter is shown in the diagram immediately above.

Note that decibels here are db re 1 volt per microbar.

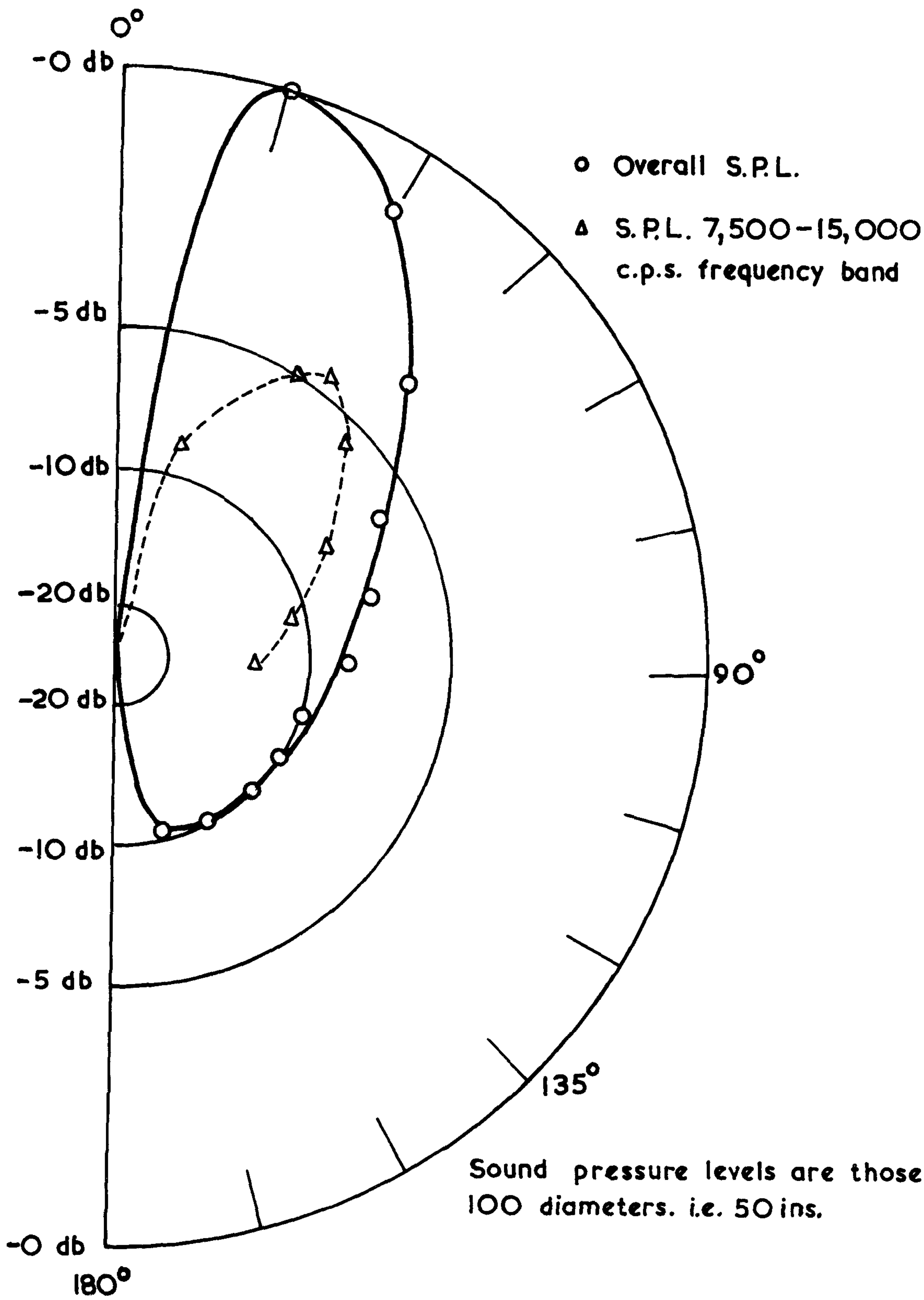
Because the high pass filter gave an average response of 1·5 db above the input signal, all filter readings were reduced by this amount. This obviates the anomaly of having a band level higher than the overall level as would occur in the very high speed jet flow readings.

FIG. 7.

Angular distribution of sound pressure levels for Run No. 2. See Fig. 1. for details of flow parameters.

Nozzle "1·0" running at a design pressure ratio to given flow Mach No 0·70, Ref Mach No 0·68, U_e of 766 fps. S.P.L. is given in db re 0·0002 microbar; T.P.L. is db re 10^{-13} watts.

For the diagram below, the reference S.P.L. value is 90·5 db
T.P.L. is 107 db re 10^{-13}w.

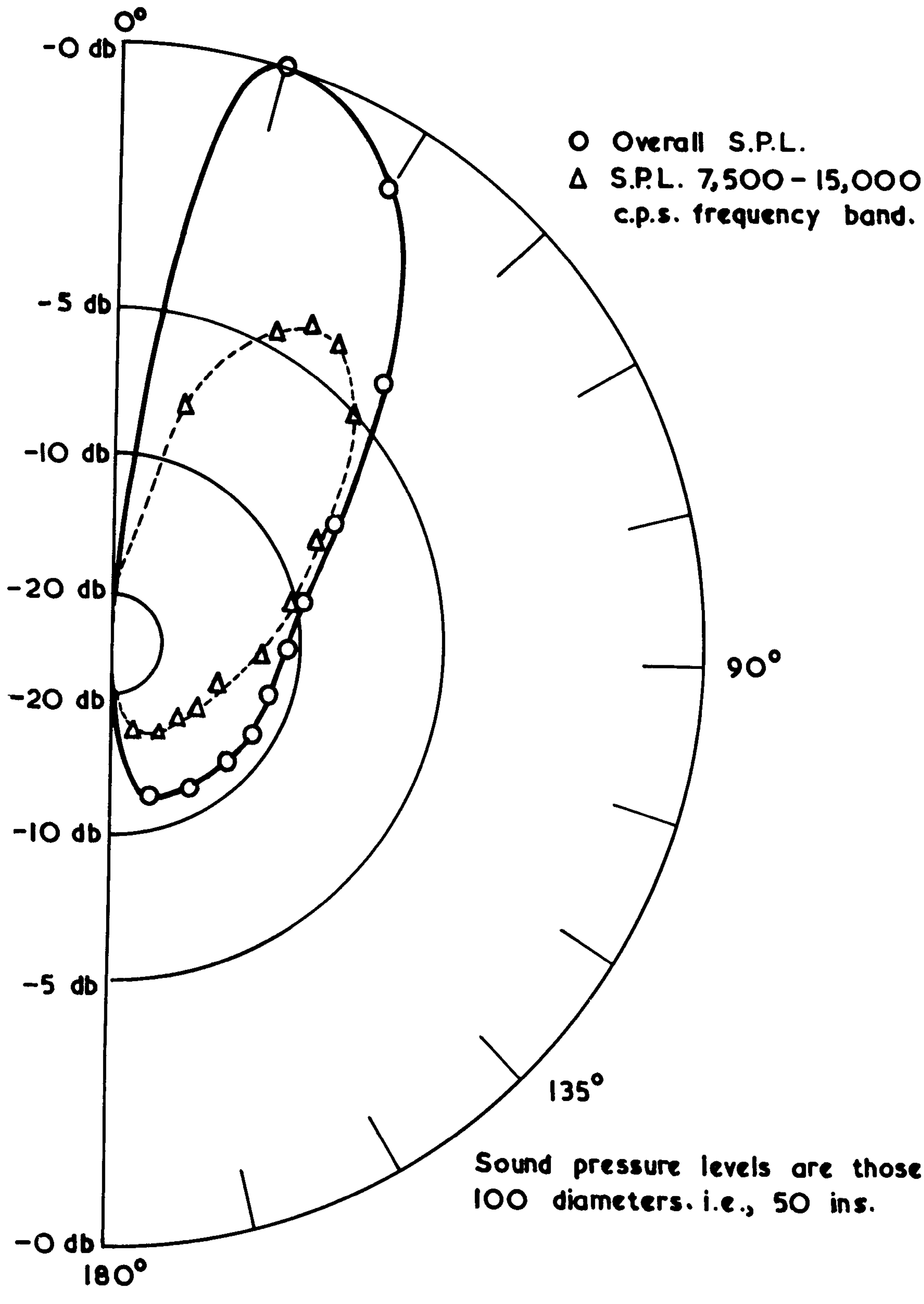


Sound pressure levels are those at 100 diameters. i.e. 50 ins.

FIG. 8.

Angular distribution of sound pressure levels for Run No. 3.
See Figure 1. for details of flow parameters.
Nozzle "1·0" running at a design pressure ratio to give a flow Mach No·0·79. Ref. Mach No. 0·76, U_e of 854 fps. S.P.L. were measured in db re 0·0002 microbar. T.P.L. is db re 10^{-13} watts.

For diagram below, the reference S.P.L. is 96·5 db.
T.P.L. is 112 db re 10^{-13} watts.

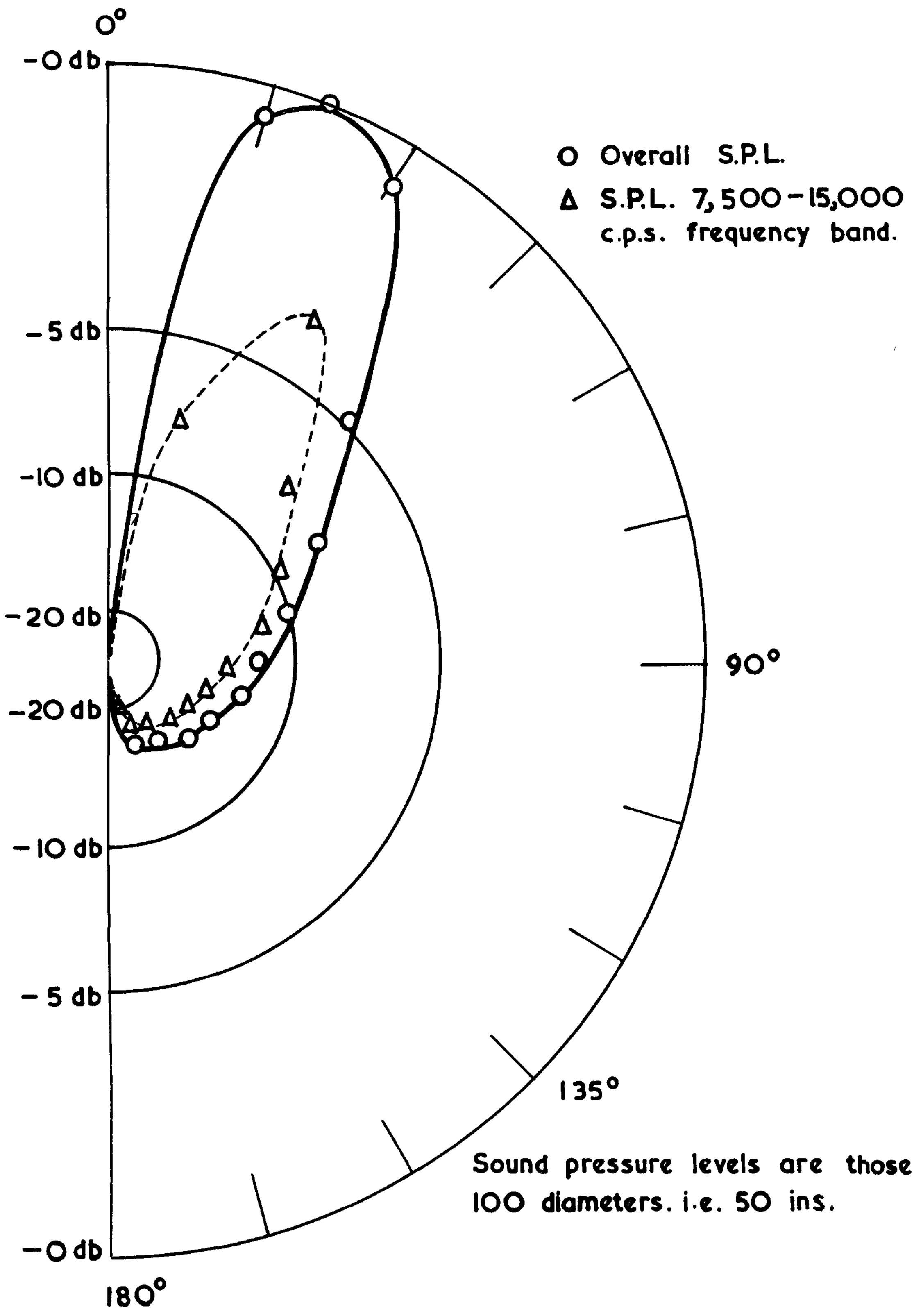


Sound pressure levels are those at 100 diameters. i.e., 50 ins.

FIG.9.

Angular distribution of sound pressure levels for Run No. 4. See Fig. 1. for details of flow parameters. Nozzle "1·0" running at a design pressure ratio to give a flow Mach No. 0·90 Ret Mach No. 0·85 U_e of 961 fps. S.P.L. were measured in db re 0·0002 microbar. T.P.L. is db re 10^{-13} watts.

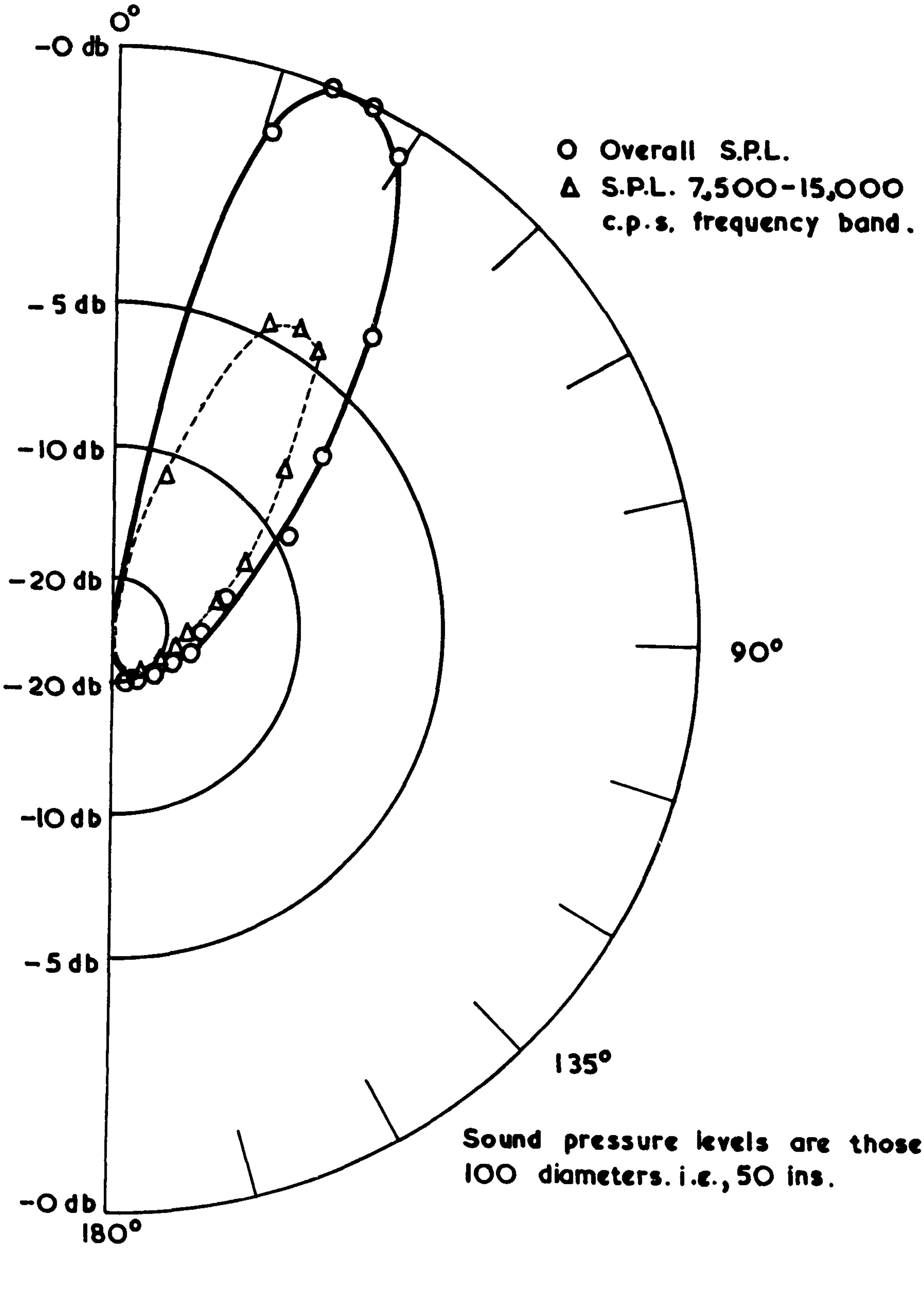
For diagram below, the reference S.P.L. is 101 db re 0·000 mb
T.P.L. is 116·5 db re 10^{-13} watts.



Sound pressure levels are those at 100 diameters. i.e. 50 ins.

FIG. 10.

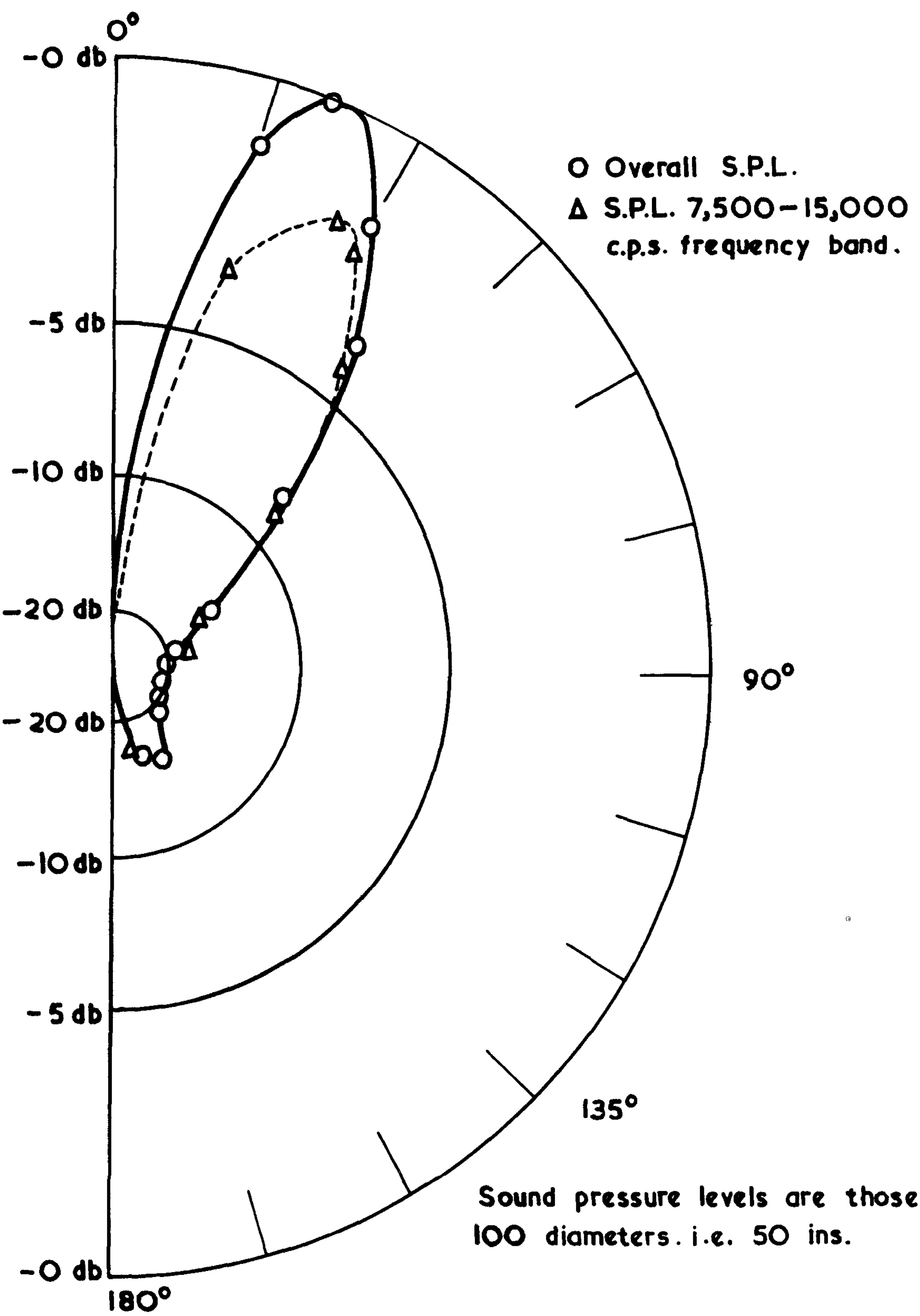
Angular distribution of the sound pressure levels for Run No. 8
See Figure 1 for details of flow parameters.
Nozzle "1·0", running at a design pressure ratio to give a flow Mach No. 1·0, Ref. Mach No. 0·92, U_e of 1035 fps, S.P.L. were measured in db re 0·0002 microbar. T.P.L. is in db re 10^{-13} watts.
For diagram below, the reference S.P.L. is 104·5 db re 0·0002 mb.
T.P.L. is 119·5 db re 10^{-13} watts.



Sound pressure levels are those at 100 diameters. i.e., 50 ins.

FIG.11.

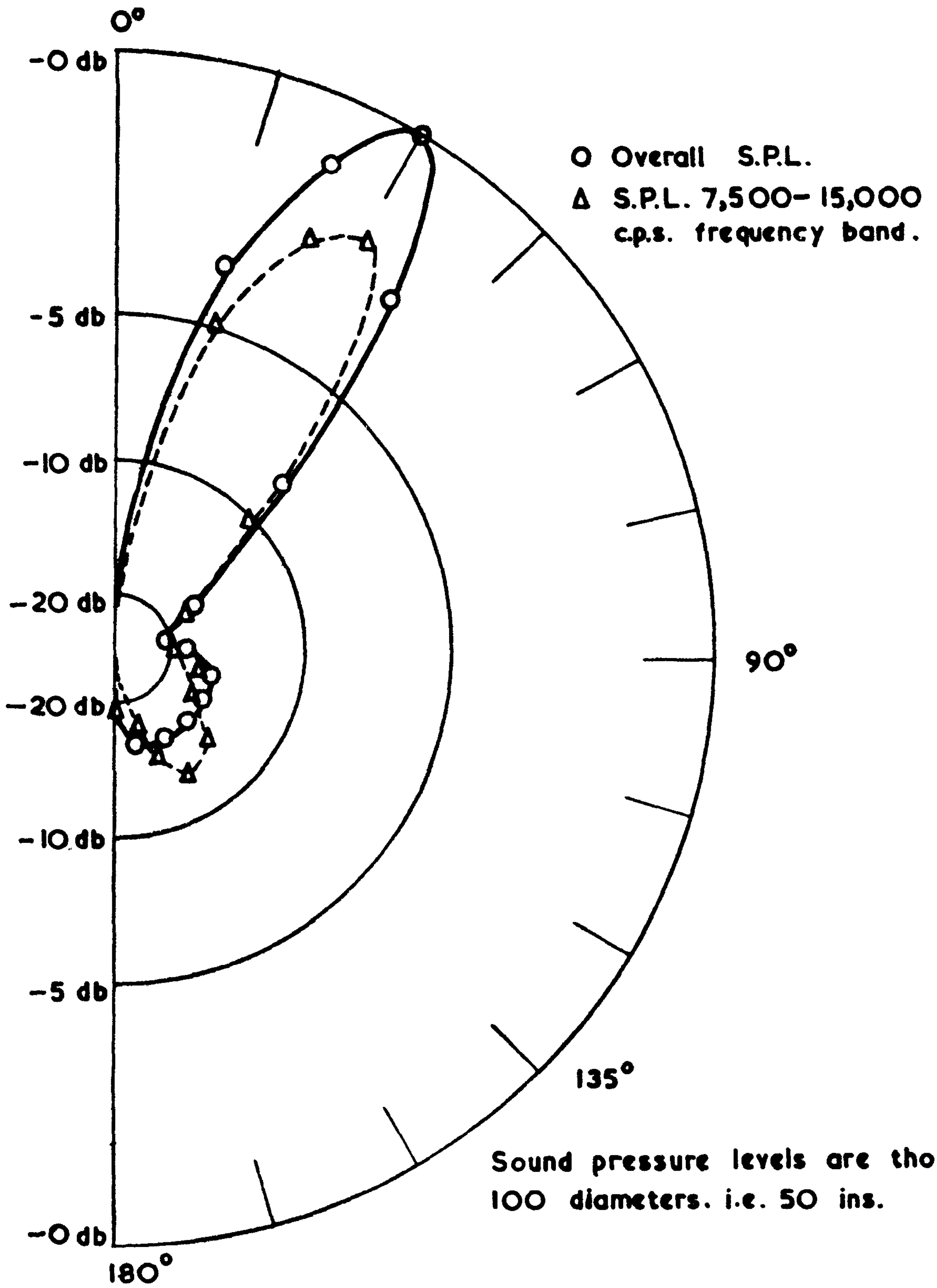
Anguiar distribution of sound pressure levels for Run No.10
See Figure 1 for details of flow parameters.
Nozzle "1·4" running at a design pressure ratio to give a flow Mach No. 1·4, Ref. Mach No. 1·215, U_e of 1382 fps. S.P.L. were measured in db re 0·0002 microbar. T.P.L. is in db re 10^{-13} watts.
For diagram below, the reference S.P.L. is 120 db re 0·0002 mb.
T.P.L. is 133·5 db re 10^{-13} watts.



Sound pressure levels are those at 100 diameters. i.e. 50 ins.

FIG.12.

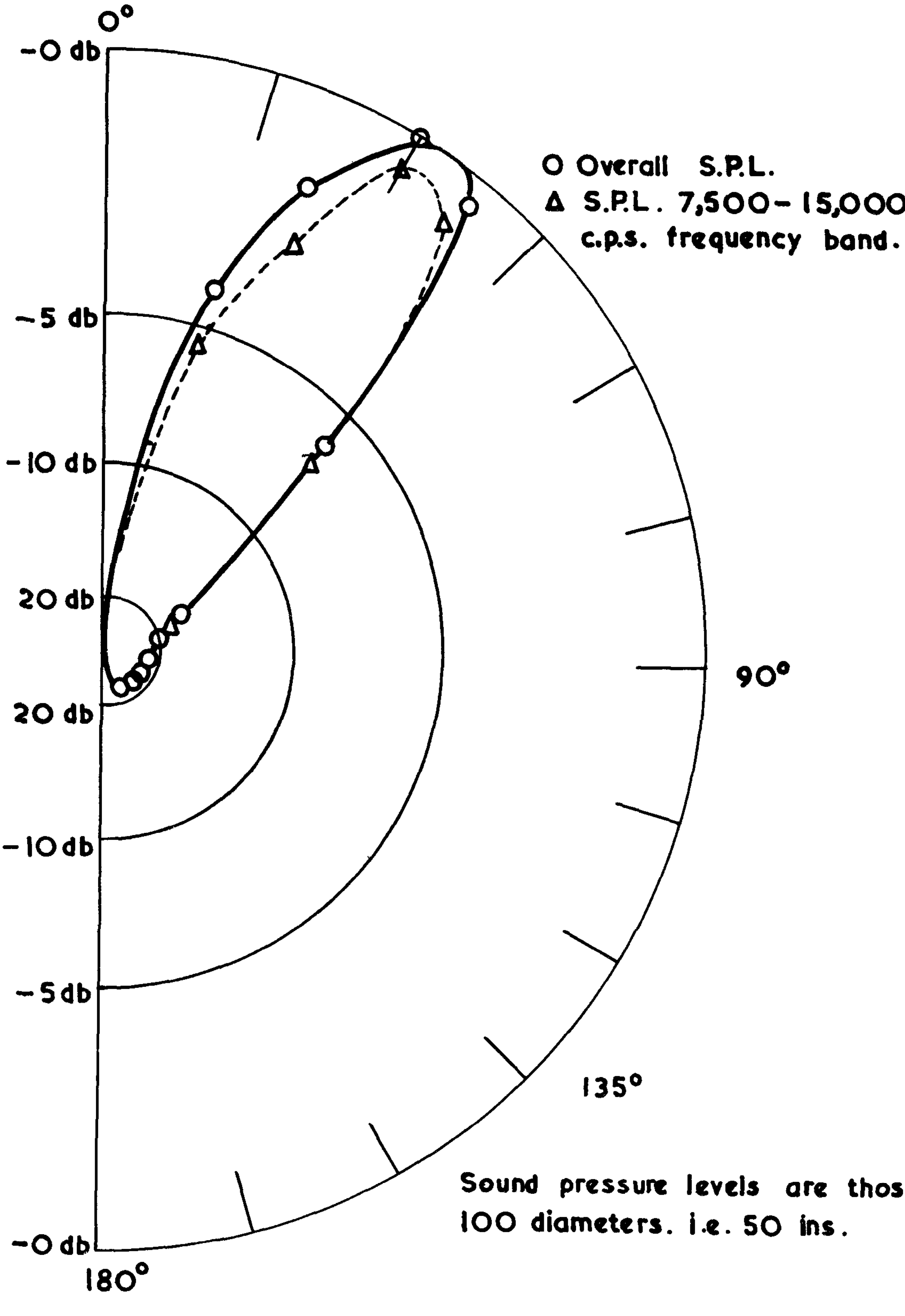
Angular distribution of sound pressure levels for Run No.12 see Figure 1 for details of flow parameters.
Nozzle "1·8" running at design pressure ratio to give a flow Mach No. 1·8, Ref Mach No. 1·465, U_e of 1673 fps. S.P.L. were measured in db re 0·0002 microbar. T.P.L. is in db re 10^{-13} watts.
For diagram below the reference S.P.L. is 130·5 db re 0·0002 mb.
T.P.L. is 144 db re 10^{-13} watts.



Sound pressure levels are those at 100 diameters. i.e. 50 ins.

FIG. 13.

Angular distribution of sound pressure levels for Run No. 14.
See Figure 1 for details of parameters of flow.
Nozzle "2·2" running close to its design pressure ratio to give a flow of Mach No. 2·16, Ref Mach No. 1·56 U_e of 1790 fps. S.P.L measured in db re 0·0002 microbar. T.P.L. in db re 10^{-13} watts.
For diagram below the reference S.P.L. is 132 db re 0·0002 mb.
T.P.L. is 146 db re 10^{-13} watts.

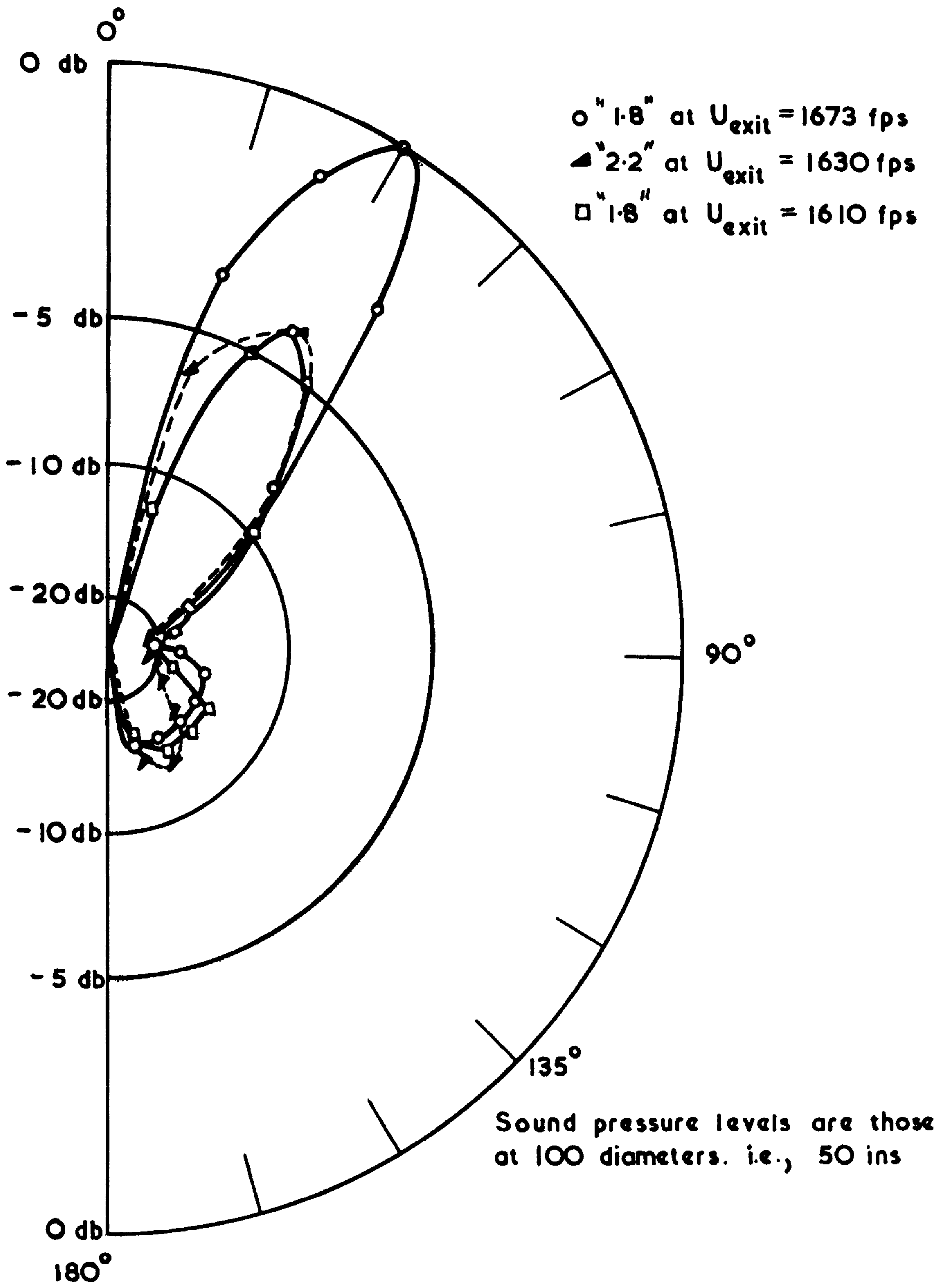


Sound pressure levels are those at 100 diameters. i.e. 50 ins.

FIG. 14

Angular distribution of sound pressure levels for two nozzles running at the same pressure ratio (equivalent to give Mach 1·8) to illustrate the different distribution of noise. Note that both two diagrams for the "1·8" nozzle are similar, though the velocities are different due to the different stagnation temps.
The "2·2" nozzle, however gives a distinct upstream lobe of intensity at about 155°. All nozzles give a low level at 90°.

For diagram below the reference S.P.L. is 130.5 db re 0·0002 mb

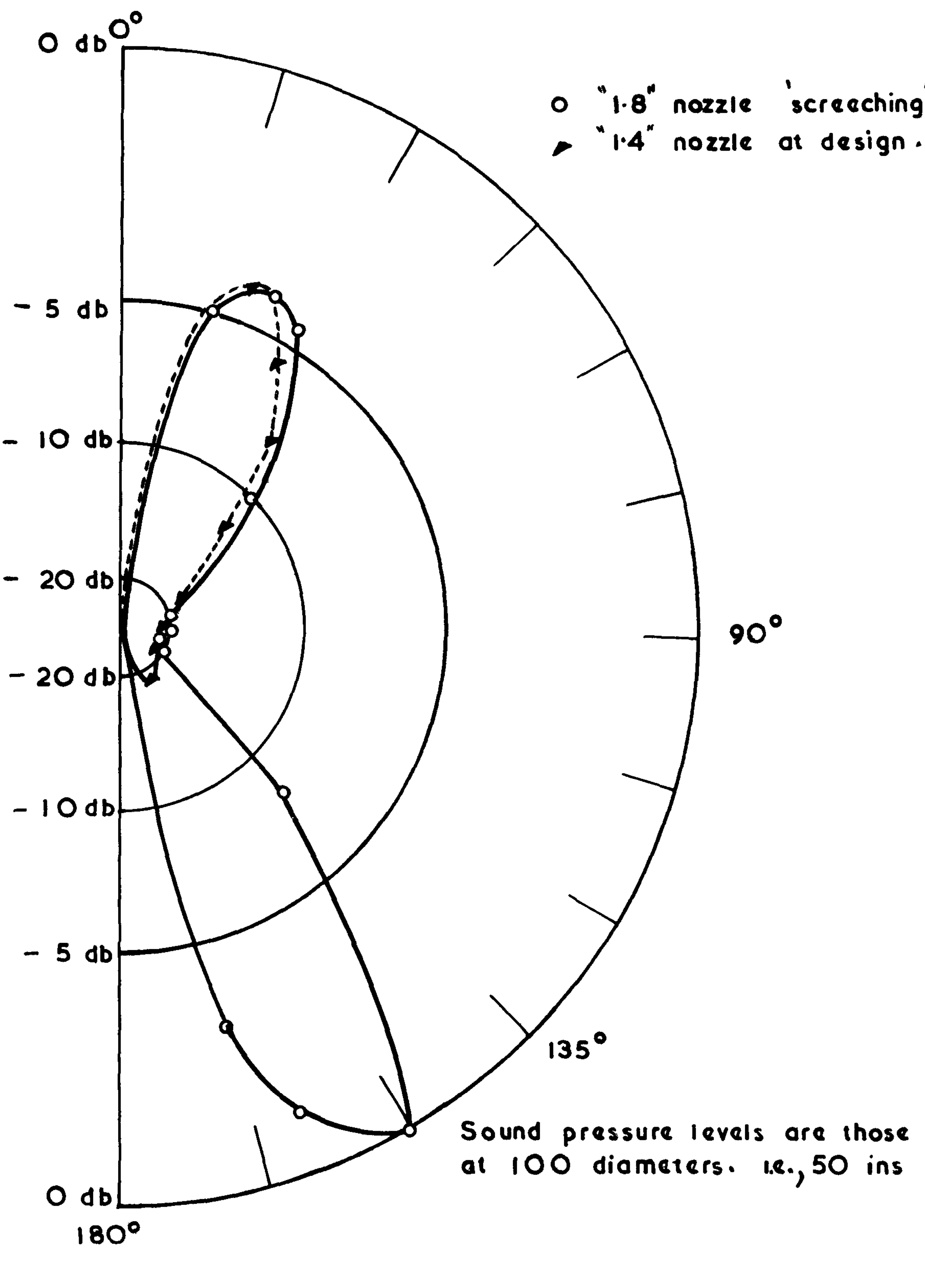


Sound pressure levels are those at 100 diameters. i.e., 50 ins

FIG. 15

Angular distribution of sound pressure levels for two nozzles running at the same pressure ratio (equivalent to that for Mach 1·4) to illustrate an extreme case of the advantage of a nozzle designed for the particular pressure ratio, over another nozzle designed for a different pressure ratio. Note the upstream lobe of high intensity in the case of the "1.8" nozzle. While this portrays perhaps an extreme case, whenever the 'Powell' type of noise generation occurred, a definite upstream lobe of intensity, usually some 3-5 db lower level than the downstream lobe level, appeared.

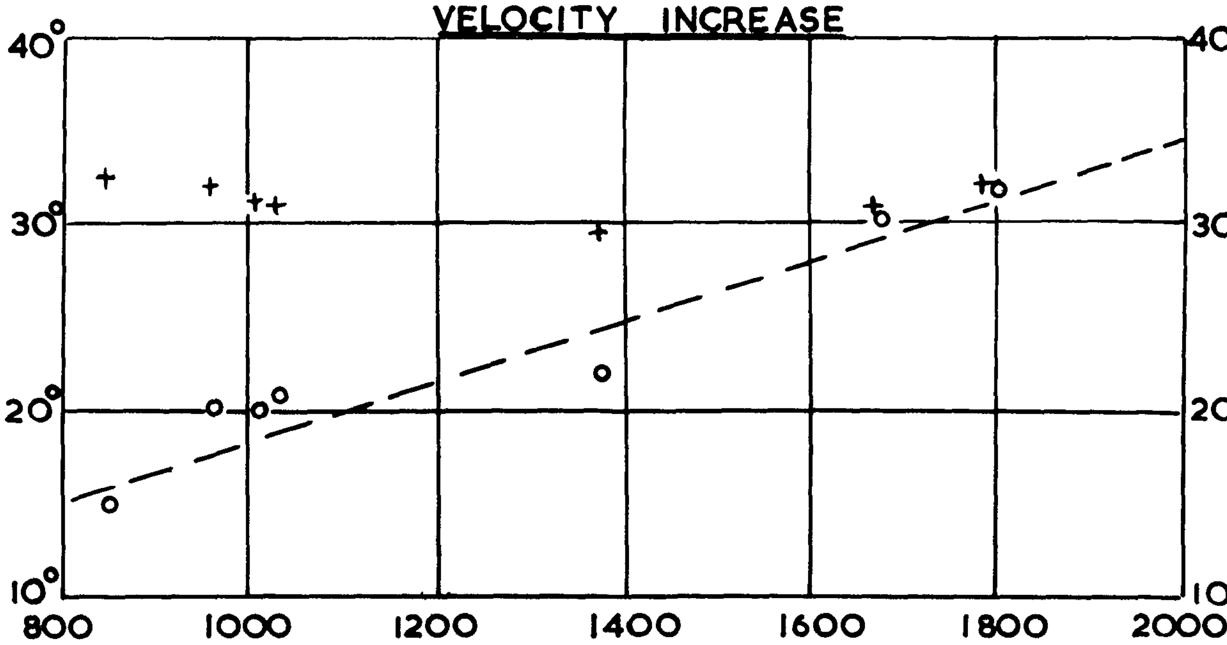
For the diagram below the reference S.P.L. is 124 db re 0·0002 mb.



Sound pressure levels are those at 100 diameters. i.e., 50 ins

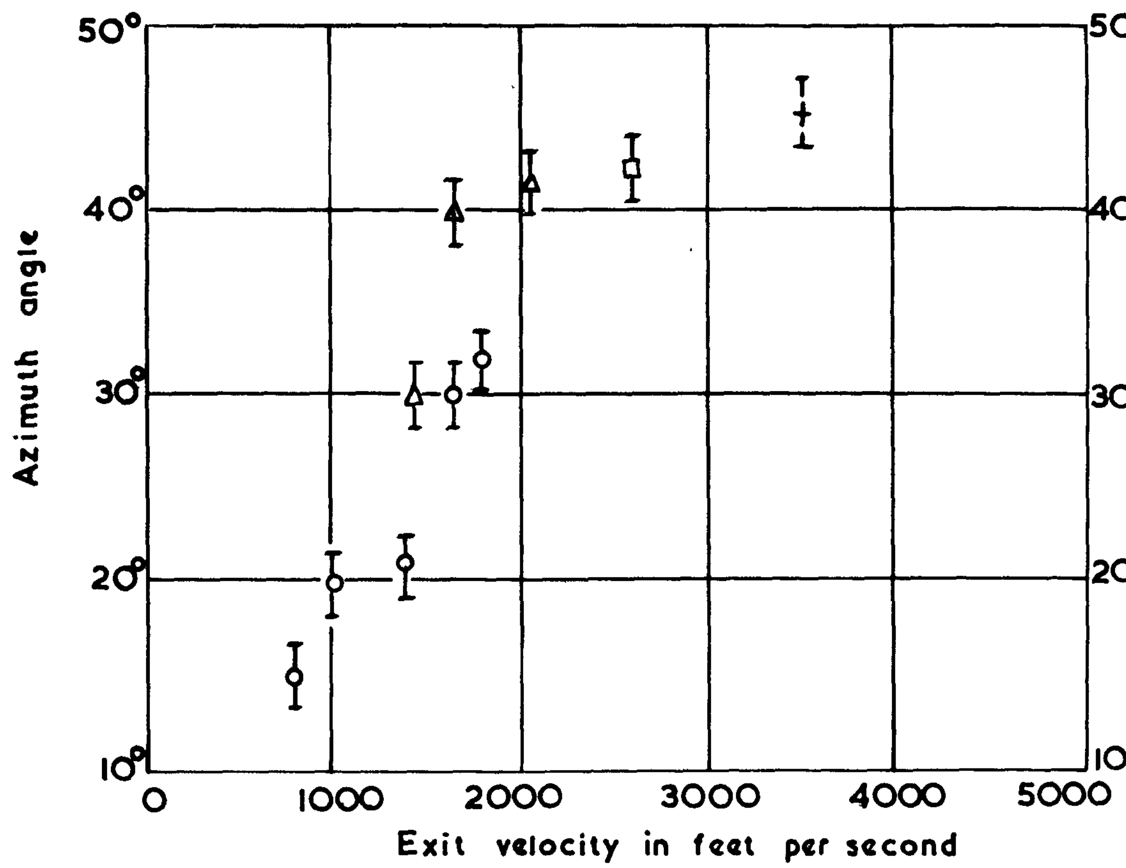
FIG 16

VARIATION OF ANGLE OF MAXIMUM RADIATION WITH VELOCITY INCREASE



o Overall noise

\+ 7,500 – 15,000 cps bandwidth.



□ Helium jet (Lassiter & Hubbard, Ref. 5)

Δ Heated air jet, 1" diam, M=0·995. (L&H, Ref. 6.)

o Cold air, designed nozzles, see Figs 7–13.

\+ Rocket motor, M=3·16, 1·625" diam. (Ref. 6)

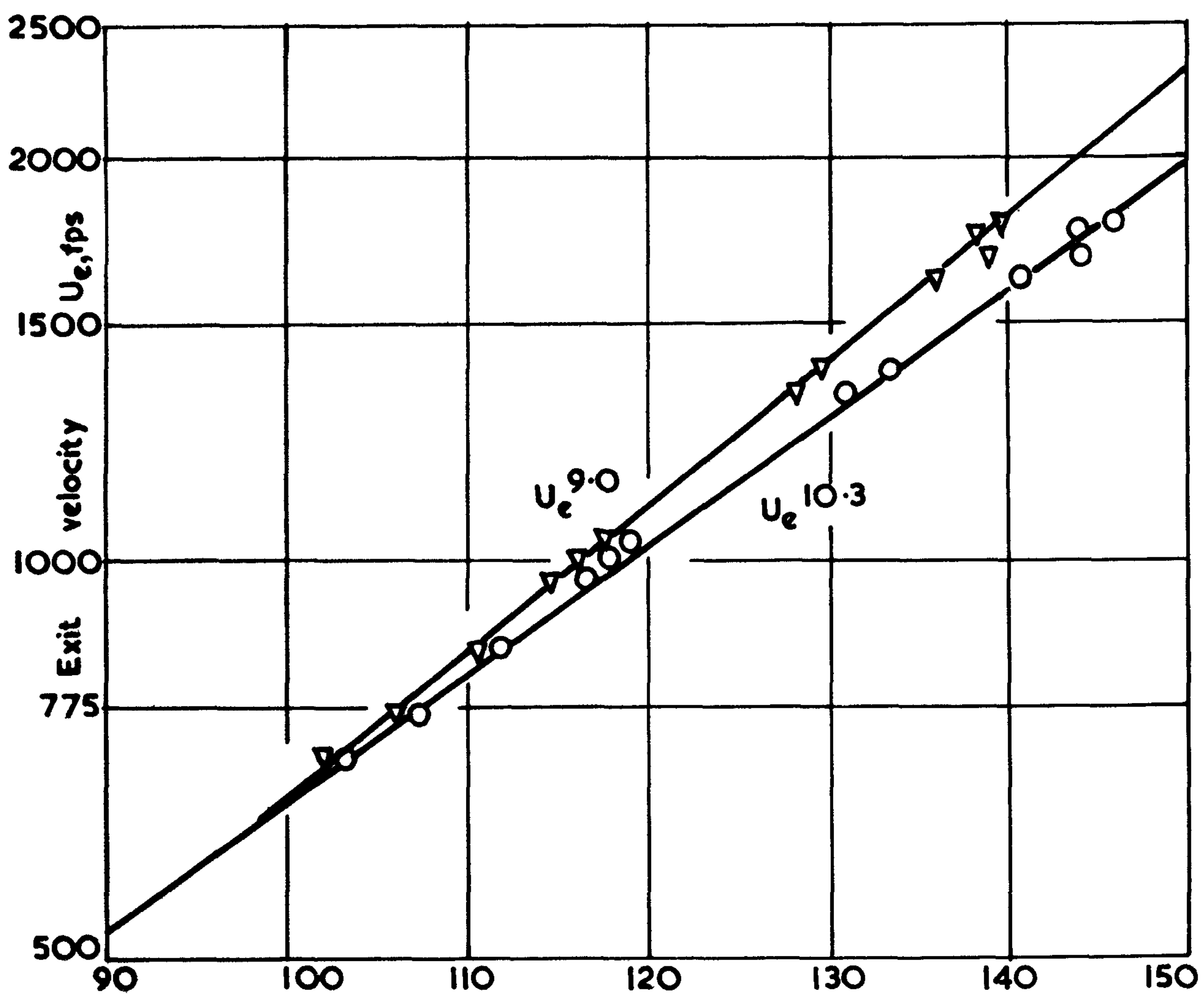
The above figures illustrate the trend for increase in azimuth angle of maximum radiation of overall noise with increase in velocity of jet above the ambient speed of sound

FIG. 17.

Effect of exit velocity, U_e, on total power level (T.P.L.) or acoustic power output. Refer to Figure 1. for actual values.

T.P.L. varies as velocity $^{10 \cdot 3}$

$\frac{\text{T.P.L.}}{\rho_1^2/\rho_a^2}$ varies as velocity $^{9 \cdot 0}$ where ρ_1 is density of jet and ρ_a is atmos. density



T.P.L. in db re 10^{-13} watts

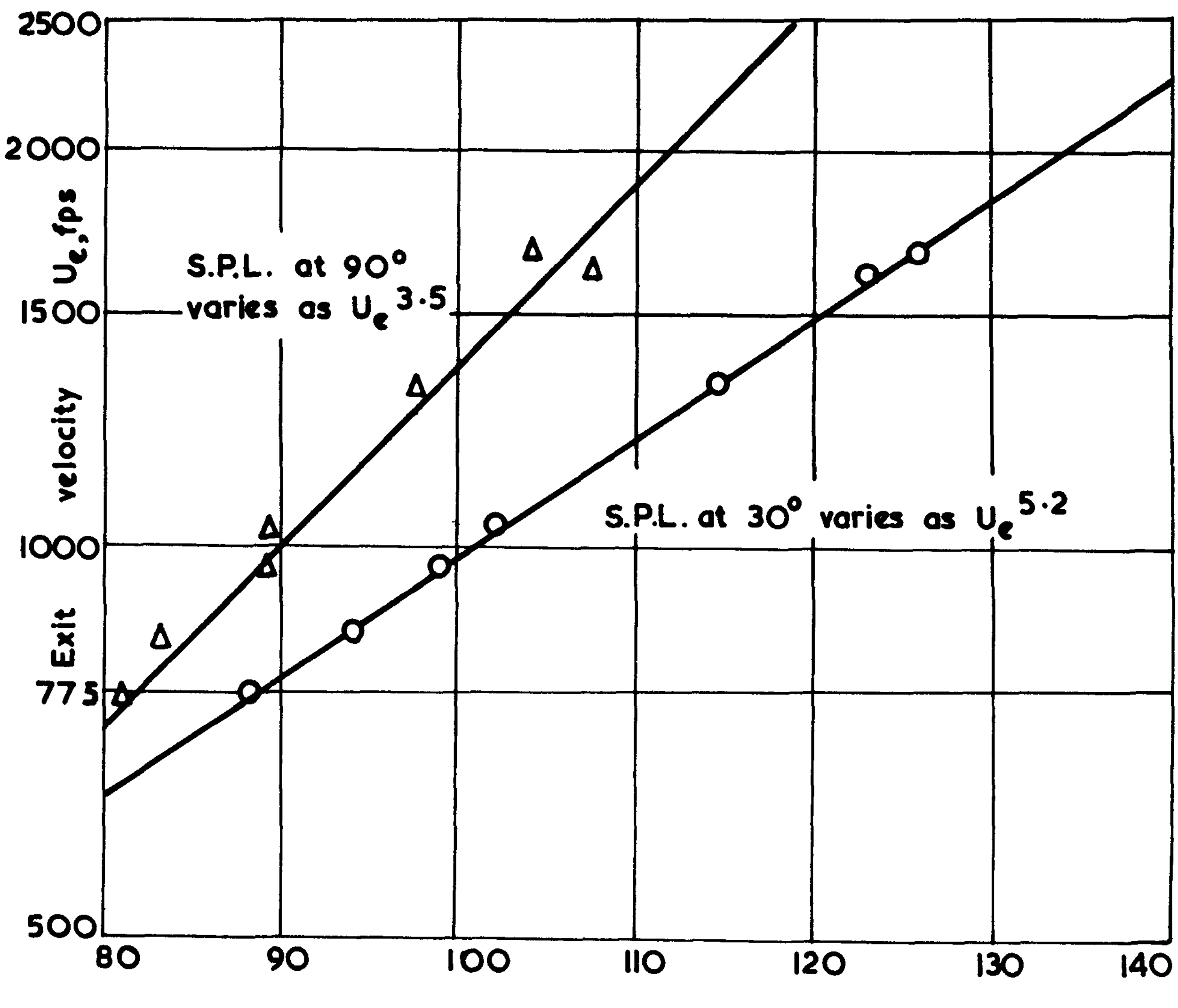
▽ $\frac{\text{T.P.L.}}{\rho_1^2/\rho_a^2}$ i.e. corrected for density difference.

O T.P.L. uncorrected for density difference.

FIG.18.

Effect of exit velocity on the sound pressure level (S.P.L.)
At 30° station, S.P.L. varies as velocity$^{5 \cdot 25}$
At the 90° station, S.P.L. varies as velocity$^{3 \cdot 5}$

The sound pressure levels have been corrected for the density difference between the jet density ρ_1 and the atmospheric density ρ_a.



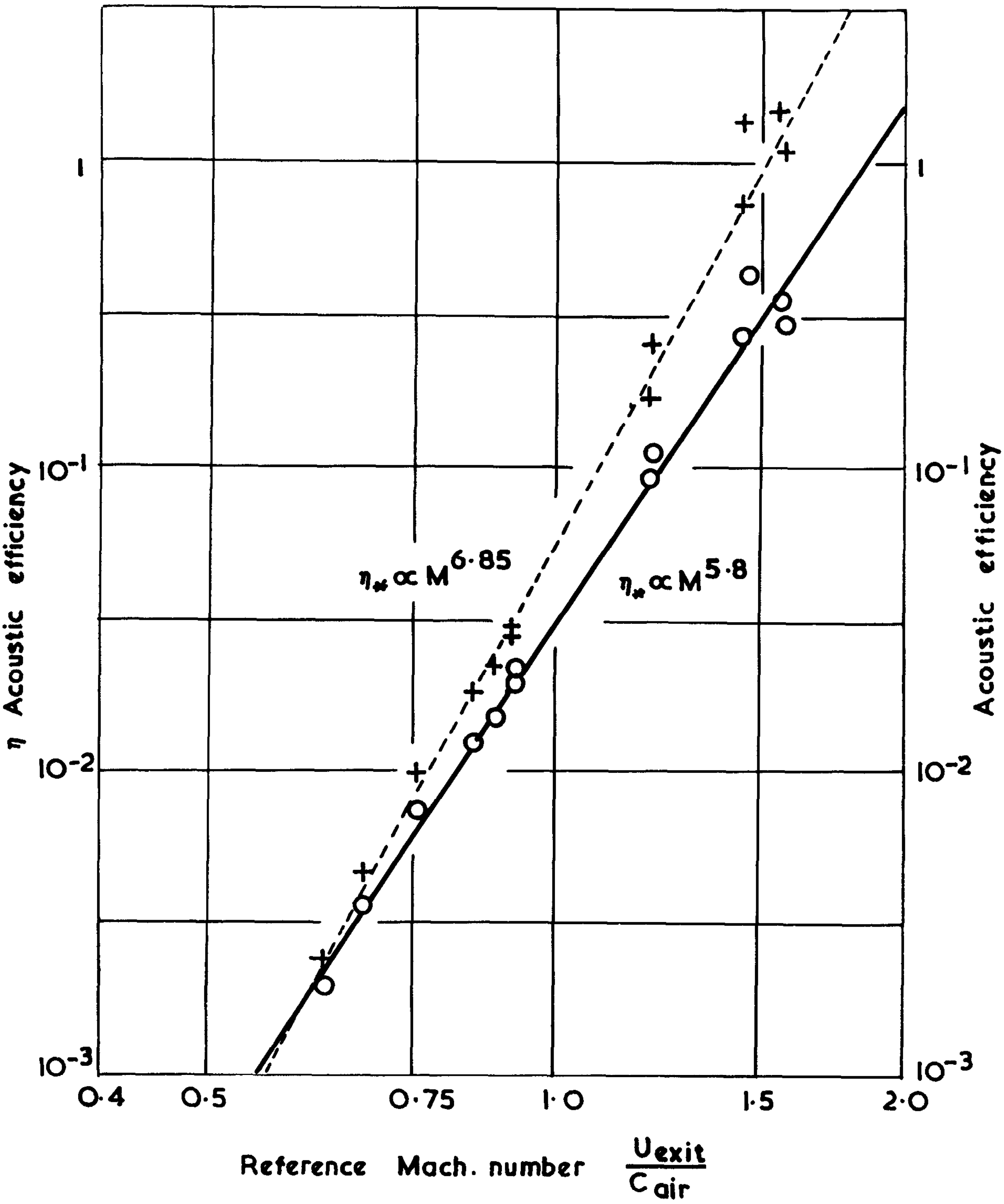
Sound pressure level at 50 inches
db re 0·0002 microbar.

Δ refers to 90° station
O refers to 30° station

FIG. 19.

This figure illustrates the variation of 'acoustic efficiency' with respect to changes in reference Mach. No. of the flow. i.e., the flow velocity, U_{exit}, divided by the ambient speed of sound.

In calculating the energy in the jet stream, the actual exit density, ρ_1, has been used. The actual, and the density-corrected, acoustic power outputs are used in the efficiency calcns.



η_* —o— $\dfrac{T.P.L./\rho_1^2/\rho_{air}^2}{1/2\,\rho_1 U^3 \times \text{Area exit}}$ $M^{5.8}$ for actual values of graph points, consult

--+-- $\dfrac{T.P.L.\ (actual)}{1/2\,\rho_1 U^3 \times \text{Area exit}}$ $M^{6.85}$ figure 1.

FIG. 20.

Acoustic power output versus jet stream power output rates

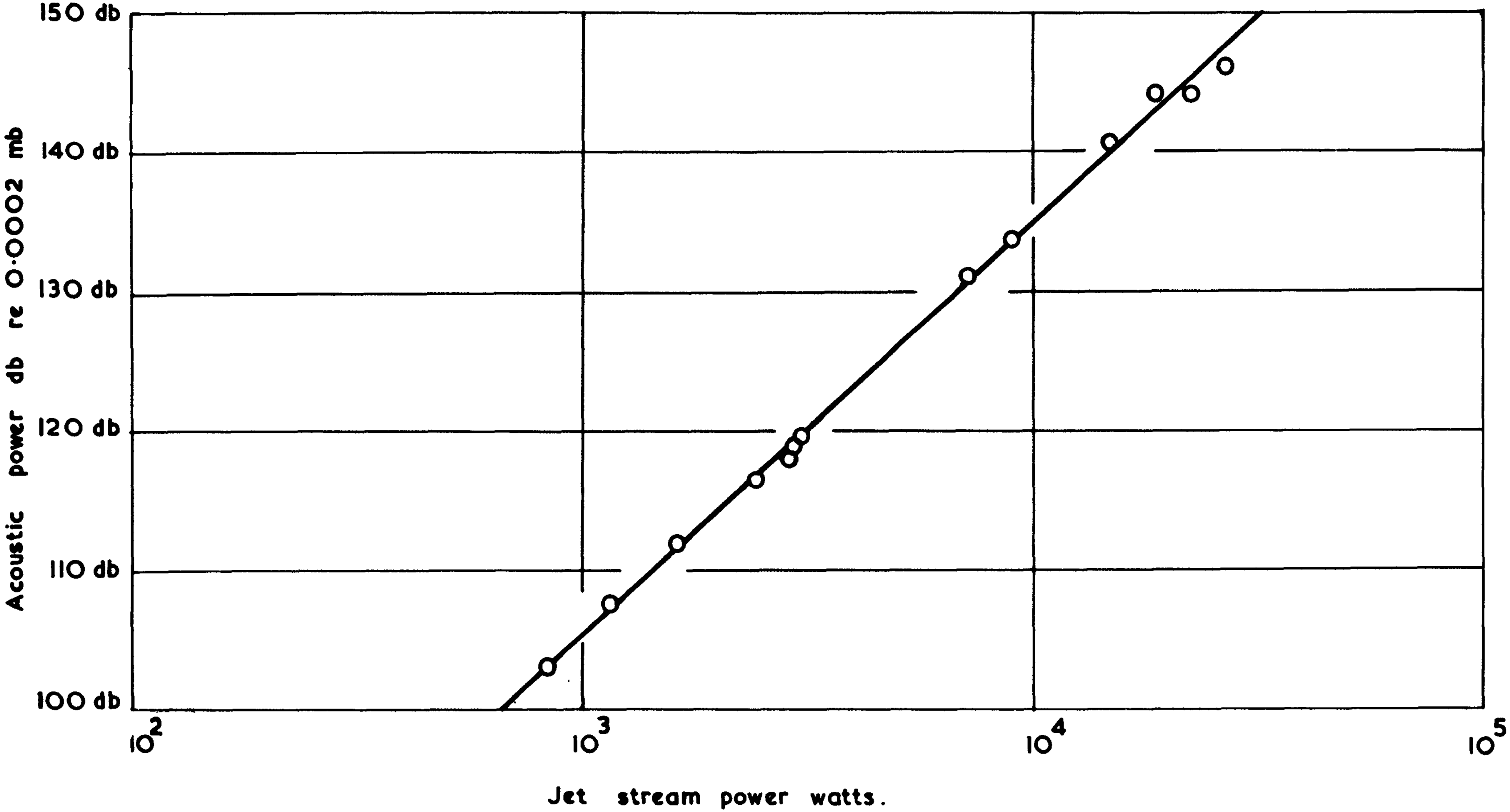
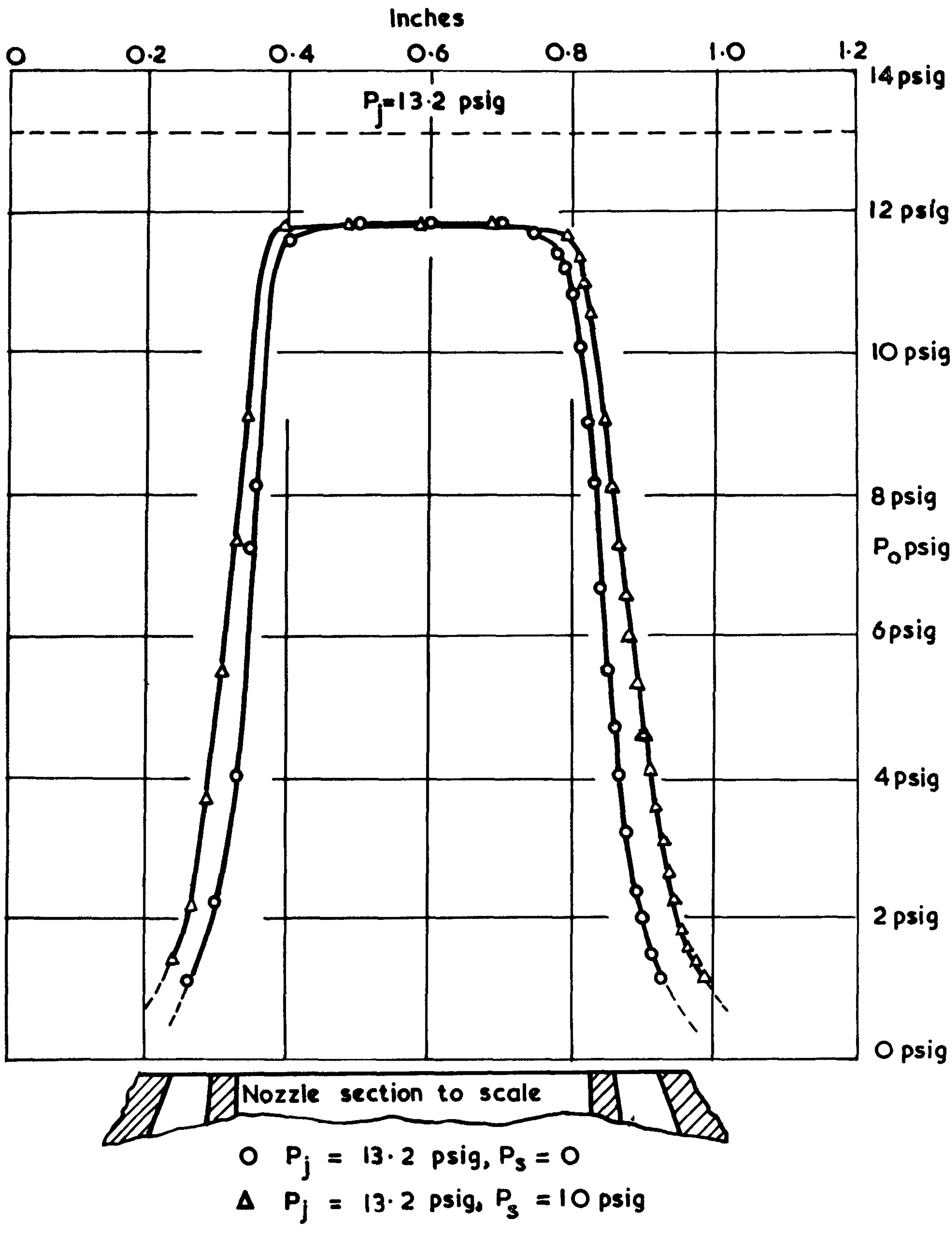


FIG. 21.

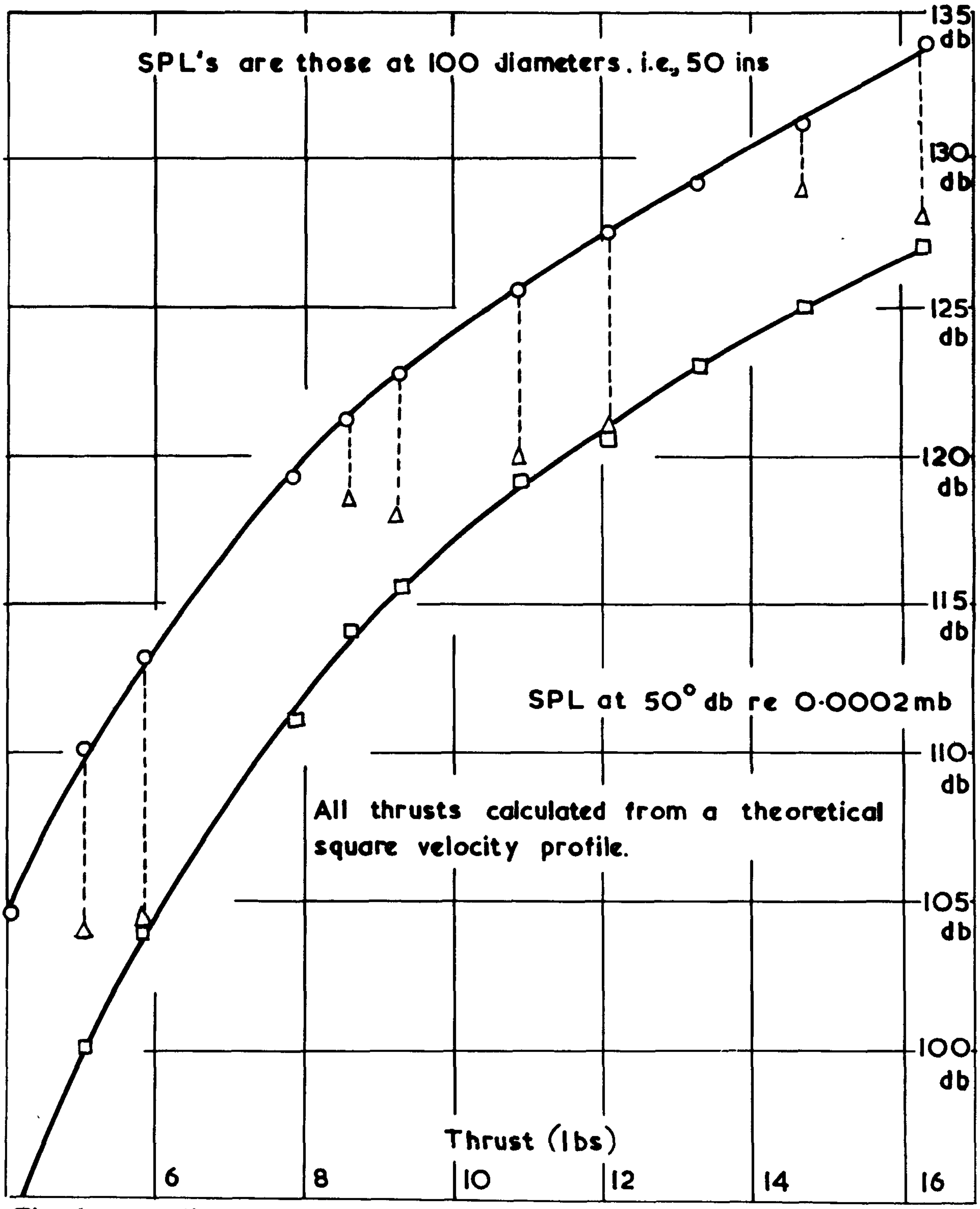
Traverses across jet exit, 1·8 diameters (0·9 ins) downstream of nozzle exit with the annular silencer fitted flush with the nozzle exit. P_0 is the stagnation pressure, psig, and P_j is the measured initial jet pressure from the tapping upstream of the turbulence screens. P_s is the measured stagnation pressure in the silencer entry section.



PITOT TRAVERSE 1·8 DIAMETERS DOWNSTREAM OF NOZZLE EXIT.

FIG.22

This figure demonstrates the effectiveness of the Annular Silencer. The top line, with the circled points is the actual sound pressure levels at 30° azimuth angles for the calculated thrusts. The triangular points represent the Silencer running at different pressure ratios. The circled points directly above the triangled ones represent the SPL at 30° if the nozzle produced the same thrust.



The bottom line represents the calculated SPL's at 30° for a circular nozzle of area equal to combined area of 1/2" nozzle and silencer exit.

- o SPL at 30° against calculated thrust for 1/2" diameter nozzle.
- Δ SPL at 30° against calculated thrust with silencer acting.
- □ SPL at 30° (calculated) against calculated thrust for a nozzle of area equal to combined exit area of silencer and 1/2" diameter nozzle.

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