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THE ACOUSTIC CHARACTERISTICS OF THE RAE 1.5M WIND TUNNEL.(U)
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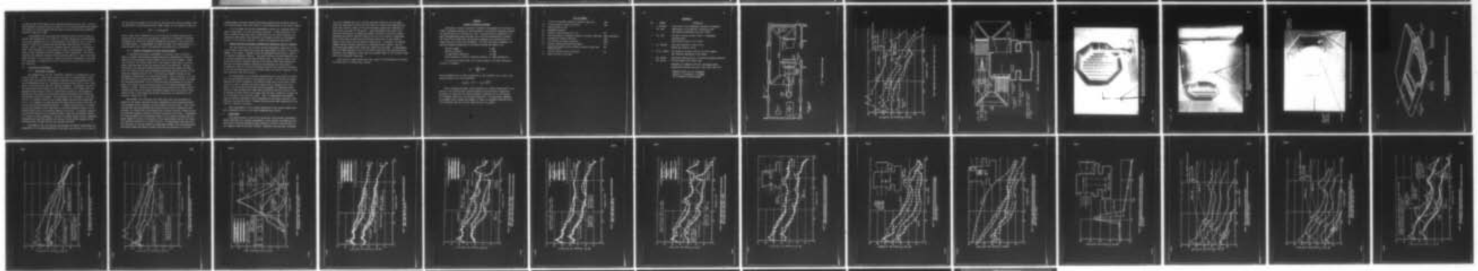

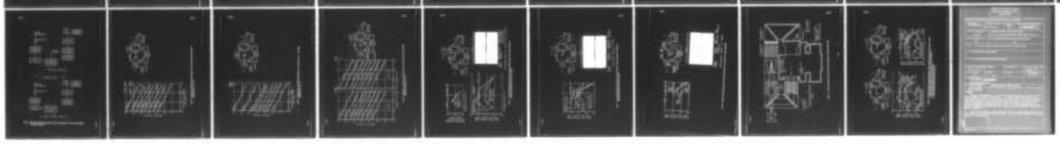

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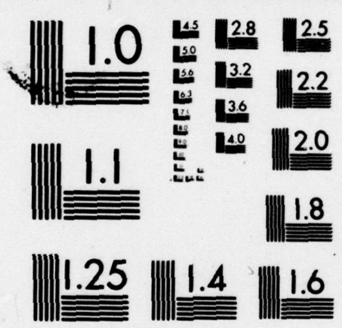

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THE ACOUSTIC CHARACTERISTICS OF THE RAE 1.5m WIND TUNNEL

by

(16) W.J.G. Trebble

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Procurement Executive, Ministry of Defence
Farnborough, Hants

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SUMMARY

Extensive modifications to the old 5ft tunnel at RAE have provided an acoustic tunnel capable of airspeeds up to 60 m/s. The drive-fan has been replaced by a seven-bladed unit which is now mounted in the return circuit and acoustic splitters have been installed in the circuit on both sides of the fan. An anechoic chamber lined with polyether foam has been built around the test-section to give good acoustic properties at frequencies above 1 kHz. The tunnel background noise level has been reduced by more than 15 dB for frequencies below 5 kHz with less benefit at higher frequencies.

Inside the airstream at 50 m/s the noise level for third-octave bandwidths now drops from 75 dB at 1 kHz to 70 dB at 20 kHz. The noise level outside the airstream is some 5-10 dB quieter.

Departmental Reference: Aero 3447

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1 INTRODUCTION

The 24ft wind tunnel at RAE, with acoustic treatment of the working chamber surrounding the open-jet test section[1], has proved to be a useful facility for experimental research on jet noise models at forward speed. However, the relatively high background noise levels associated with the closeness of the fan to the test-section implies that investigations of quiet engine installations and of airframe noise are precluded from the tunnel in its present state unless it becomes possible to develop a noise source discrimination technique such as the use of an acoustic mirror. Possible modifications to the tunnel have been considered including the replacement of the 40 year old fan by one of modern design repositioned in the return circuit, so that acoustic absorption material could be installed both upstream and downstream of the fan to reduce background noise levels in the test-section. Fortunately, since the RAE 5ft tunnel was built in 1930 as a scale representation of the 24ft tunnel to verify the initial design of the latter, it has been possible to make a design feasibility study at about 1/5 scale. Scaling the noise reduction requirements of the 24ft tunnel indicated that a reasonable target for the research programme should be to reduce the background noise levels in the smaller tunnel so that tests could be made there on an unheated jet, of pressure ratio of 1.4 from a nozzle of 25 mm diameter and at a wind speed of 50 m/s, with negligible interference from the background noise. A further requirement was that the anechoic properties of the small facility should be adequate to make acoustic measurements without significant reverberation at frequencies as low as 1 kHz, which would be equivalent to 200 Hz in the larger 24ft tunnel at the same Strouhal number.

The present Report is concerned mainly with the acoustic aspects of the tunnel design; the aerodynamics and engineering, including discussions on fan design and tunnel turbulence levels, are being presented separately in detail by T.B. Owen[2].

2 MODIFICATIONS TO TUNNEL CIRCUIT

An important constraint placed upon the redesign of the 5ft tunnel was the need to ensure that all changes to the circuit took place inside the existing tunnel shell. This was necessary to enable the designed modifications to be applicable to the 24ft tunnel which is a reinforced concrete structure.

The main constructional features of the old 5ft tunnel are illustrated in Fig 1; the acoustic spectra of the test section background noise as measured with a microphone on the tunnel centreline 1 m from the nozzle plane are shown in Fig 2. Naturally, the principal noise source at normal test speeds was the fan, located immediately downstream of the test-section, though the noise from the motor generator set predominated at speeds below 15 m/s. Additionally, eddy shedding from the safety net (1.2mm wire diameter), installed to protect the fan from model breakaway, gave some 'lift' in the spectra (Fig 2) which was most pronounced at wind speeds of 20-25 m/s when resonance gave a 20 dB lift in the background noise level due to this aeolian tone.

For the modified facility, which is known as the 1.5m acoustic tunnel, a new seven-bladed fan has been manufactured from laminated mahogany and is now positioned in the return-circuit (Fig 3). As a consequence of the constraint that the fan must fit within the existing shell its diameter is little changed from that of the old fan. The free-air cross-section at the new fan station has been reduced and so there has to be a more rapid rate of diffusion in the return circuit. It was therefore necessary to install a multi-passage diffuser immediately downstream of the fan to prevent flow separation from the walls.

An anechoic chamber (Figs 3 to 6) has been built around the 1.5m tunnel test-section, using 25mm plywood covered internally with 75 mm thick polyether foam intended to provide good anechoic properties at frequencies above 1 kHz. Care was taken to leave an air gap between this anechoic chamber and the return circuit so as to minimise sound transmission from the fan through the structure. Currently, two main support pillars for the roof of the building intrude into the chamber (Fig 3) but consideration is being given to the possibility of a building modification that will allow for their removal.

Acoustic splitters have been provided in the circuit on both sides of the fan to reduce the noise transmitted along the duct. The development of the splitter design, based on the theory of Cremer[3] (see Appendix), is described in detail in Ref 4. With attenuation being required over a large frequency range, it was decided to install two sets of splitters, offering maximum noise attenuation centred on 2 kHz and 6 kHz, and these are referred to as low-frequency splitters and high-frequency splitters respectively.

The low-frequency splitters (Figs 3, 4 and 7) essentially consist of slabs of 50 mm thick rockwool, with a flow resistance of 8 × 10^4 rayls/m, held in position by perforated steel sheets of 36% open area. The sheets have been cadmium-flashed, to prevent oxidation, and then covered with calico fabric to present a reasonably smooth surface to the airstream, so that the aerodynamic self-noise of the splitters should be kept to a minimum. A compromise became necessary in determining the size of the circular holes in the perforated sheet.

Small holes would imply that self-noise from the perforated sheet would occur only at high frequencies, but the need to glue the calico to the perforate without blocking the holes would require large sizes of hole. As a compromise, a hole diameter of 2.5 mm was selected. Since the splitters immediately downstream of the test-section are sited in a high velocity airflow, it is essential that they have a good aerodynamic shape so that they cause the minimum possible pressure drop in the tunnel. Thus the 1.5 m lengths of rockwool are installed in splitters with an overall length of 1.8 m which includes a 2:1 semi-elliptic wooden nose and a symmetrically chamfered wooden trailing edge of 9.5° included angle. There are nine splitters with air gaps of 0.16 m in the optimum design which has been used, but some investigations have been made with several splitters removed resulting in air gaps of 0.58 m and 1.88 m.

The high-frequency splitters (Figs 3, 5 and 7), though smaller in size, are of basically similar construction but felt material with a higher flow resistance (11×10^{4} rayls/m) is used for the acoustic blanket. These splitters have a thickness of only 16 mm and the overall length of 265 mm incorporates a blanket with a length of 147 mm. Separation between splitters is reduced to 63 mm.

Power supply for the new facility is provided by the same direct-drive electric motor which had driven the old tunnel fan and electric current limitations have restricted aerodynamic performance to a maximum airspeed of 58 m/s EAS. The tunnel design allows for higher airspeeds should a more powerful motor become available.

3 INSTRUMENTATION

For the investigations of the tunnel acoustics, the signals from ¼in condenser microphones were fed through preamplifiers and measuring amplifiers into a one-third-octave analyser (50 dB dynamic range) which gave a punched tape output. In the main, the signals were dominated by low-frequency noise but the effective dynamic range was extended by incorporating a universal filter between the measuring amplifier and the analyser. Measurements were then made after the selection of either a 4 Hz or a 400 Hz high-pass filter. The microphone inside the windstream was provided with an ogival nose cone which was aligned directly into wind. The microphone in the anechoic chamber outside the mainstream flow was provided with a standard protective grill and the axis was usually directed normal to the tunnel centreline; a foam windshield was placed over the microphone because there were significant secondary air currents in the chamber. At frequent intervals, the microphones were checked with a 94dB calibrator.

Initially, for measurements inside the airstream, the microphone was mounted from a long cylinder (with its axis along wind) which was firmly secured in position by six wires of 0.5 mm diameter (Figs 5 and 6). To reduce spurious noise, this rig was replaced as soon as possible with a mounting from a low-drag aerofoil strut (Fig 4); relative noise levels of various mounting systems are discussed in section 4.5. For measurements outside the airstream, the microphone was simply mounted on a tripod (Figs 4 to 6).

The assessment of the anechoic properties of the chamber at zero airspeed was made with a small loudspeaker mounted on the tunnel centreline facing the microphone which was in the same horizontal plane. This microphone was mounted vertically without any type of nose protection so that incident and reflected signals in this horizontal plane were all received at an incidence of 90° to the microphone axis.

No incidence corrections have been applied to the measurements as in most cases it would not be practical to determine the effective angle of incidence of the sound at the microphone. However, the microphone characteristics indicate that any correction would be negligible for frequencies below 10 kHz.

4 ASSESSMENT OF TUNNEL BACKGROUND NOISE

4.1 Improvements in acoustic performance compared with the original 5ft tunnel

Acoustic measurements were made, with a $\frac{1}{4}$in microphone mounted from the wire rig (Fig 6) on the tunnel centreline, at various stages of the reconstruction of the facility (Figs 8 and 9). The design of the new fan[2] assumed that splitters would cause a large increase in the pressure drop around the circuit and thus, to obtain representative fan operating conditions, it was necessary to represent splitter drag in the early tests with the new fan installed in the return circuit. A framework of wooden slats (each 32 mm wide), estimated to have the appropriate drag to represent the splitters but with self-noise estimated to be at least 10 dB below the tunnel background noise, was fitted in the tunnel downstream of the multi-channel diffuser. The noise measurements show that, over most of the frequency range, the new fan in the return circuit is significantly quieter than the old installation; the improvement being particularly marked at frequencies below 1 kHz.

The tunnel is housed in a highly reverberent room which also contains the electrical drive machinery. Consequently, the provision of an anechoic chamber around the test-section not only reduces acoustic reflections but also provides substantial attenuation of the machinery noise as well as reducing the levels of fan noise transmitted through the walls of the return circuit directly into the test-section.

The combined effects of the new fan installation and the provision of the anechoic chamber, without splitters in the collector, are to reduce noise levels at 50 m/s by 14 dB at 1 kHz and by 7 dB at 10 kHz (Fig 9) - somewhat less than had been hoped for[2].

4.2 Acoustic splitters

The design of the acoustic splitters (section 2) has been based on the theoretical work of Cremer[3] augmented by experimental research at RAE[4]. Attenuation was required for a wide range of frequency (*circa* 1 to 10 kHz) and it was quickly realised that this could only be achieved if banks of splitters, tuned to different frequencies, were used. Two banks with attenuation centred on 2 kHz and 6 kHz appeared to be sufficient and the splitters have been constructed to this specification.

The effectiveness of the splitters was initially investigated in the absence of mainstream flow (Fig 10). A 'pink' noise source* was used to drive a small loudspeaker mounted on the centreline just upstream of the first cascade corner of the tunnel circuit (Fig 3) and noise levels were recorded with a $\frac{1}{4}$in microphone mounted on the centreline of the working section 0.8 m from the plane of the nozzle. A digital voltmeter in the speaker circuit enabled adjustments to be made in the signal amplification to ensure that the source noise spectrum was maintained at the same level throughout the investigations. For all tested splitter configurations, the speaker signal picked up on the microphone was at least 10 dB above the background noise level for frequencies between 0.5 kHz and 16 kHz. To evaluate the attenuation effectiveness of splitters installed in the collector, noise measurements were made without splitters, with low-frequency splitters installed, and with both low-frequency and high-frequency splitters.

The results, illustrated in Fig 10, show that the low-frequency splitters, with air gaps of 160 mm, reduce noise levels in the test-section by about 30 dB at frequencies between 1 kHz and 2 kHz. At higher frequencies there is a gradual reduction in attenuation to about 4 dB at 10 kHz. Increasing the air gap to 585 mm reduces the peak attenuation to 10 dB and this is now attained over the frequency range 0.6-1.2 kHz. In both cases the maximum measured value of noise attenuation is only about half of the value predicted by the theory of Cremer but the experimental peaks tend to be rather broader, and at lower

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* 'Pink' noise is defined as having equal energy levels in each third-octave bandwidth.

frequencies the measured attenuation is greater than the predicted value. Similar trends were also observed in our preliminary research on splitter design techniques[4]. The addition of high-frequency splitters gives further attenuation so that noise levels are reduced by over 30 dB for frequencies between 1 kHz and 5 kHz, when they are used in combination with low-frequency splitters with air gaps of 160 mm. With this combination, the attenuation at 10 kHz, is increased to 10 dB.

For an assessment of the splitter performance in the presence of air flow one microphone was mounted on the centreline from a wire rig while a second microphone was stationed outside the stream some 1.6 m from the tunnel centreline. Measurements were made at six air speeds up to 55 m/s but, for clarity, results are shown only for 30 m/s and 50 m/s in Figs 11 to 14.

Splitter attenuation is now seen to be significantly less than that found in the absence of air flow, though the measurements are affected by noise emanating from the wire rig (section 4.5). The low-frequency splitters with 160 mm air gaps now only give noise reductions of 10 dB at 1 kHz reducing to zero at 10 kHz. The reason for this impaired performance is considered to be mainly self-noise generated from the splitter surfaces as the fast moving air flows past them. Unfortunately, the splitters ahead of the fan had to be installed in a very high velocity part of the circuit because design constraints with regard to feasible modifications to the 24ft tunnel precluded the possibility of modifications which would allow significant diffusion of adequate length ahead of the fan*.

The effectiveness of the high-frequency splitters in the airflow has proved to be very disappointing (Fig 13). Actually, because of their high self-noise, high-frequency splitters in the collector increase the tunnel noise levels though some benefit is observed from those positioned in the return circuit. For the time being, it has therefore been decided to operate the tunnel without high-frequency splitters in the collector though they will remain installed in the return circuit. Thought has been given to redesigning the covering of the splitters with a view to reducing their self-noise in the airstream and further tests are planned.

Throughout this Report, the standard splitter configuration comprises the

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* In this connection, it should be noted that the transverse leg of the circuit is too short on its inner wall and that the cross-section area here is little different from that in the collector (compare stations A and B on Fig 3). Also in the 24ft tunnel, the thick corner vanes are part of the concrete structure and acoustic treatment to them would not be practical.

low-frequency and high-frequency splitter combination in the return circuit together with only the low-frequency splitters in the collector.

4.3 Variations in noise level within the anechoic chamber

The acoustic field inside the chamber has been investigated employing a wide range of microphone positions, both inside and outside the airstream, over a range of wind speed up to 50 m/s and with the standard splitter configurations installed in the tunnel circuit. In general, little change in noise spectra occurs with movement along the tunnel centreline (Fig 15) though some increase in splitter self-noise is observed at the aft measuring position, which is only 1 m ahead of the leading edges of the splitters. Outside the stream there are two noteworthy features (Fig 16). The first is the substantially lower noise levels at the forward measuring station where the microphone is shielded from noise emitted at the nozzle exit. Also of interest is the reduced level of the splitter self-noise at the aft station caused by the shadow effect of the collector ring at this position. The combined effect of excess noise from the nozzle and splitters leads to the highest overall noise levels in the middle of the traverse which is, unfortunately, the region most likely to be used for positioning microphones during acoustic research in the facility. The source of the noise emitted from the nozzle has not yet been identified though there is some evidence of air leakage between timbers of the tunnel circuit in the vicinity of the maximum section and this could indicate a possible point of entry of noise from the reverberant room which houses the drive machinery as well as the main part of the tunnel structure.

Lateral microphone traverses have been made 0.82 and 1.82 m downstream from the nozzle plane (Figs 17 and 18). As expected, the very high turbulence in the mixing region at the edge of the tunnel airstream causes very large increases in microphone signal level and this region is enlarged with downstream movement from the nozzle. Acoustic measurements for noise-model tests should not be attempted with microphones immersed in this turbulent flow region, which forms a triangle with its apex at the nozzle perimeter and with internal and external slopes of about 5^o and 10^o respectively to the streamwise direction.

In the anechoic chamber outside the mixing region, there is a slow but steady reduction in noise level with movement away from the tunnel centreline. To a first approximation, the reduction in sound pressure level is linear with distance from the centreline as is illustrated for the 5 kHz third-octave bandwidth in Fig 18. At the time, no measurements were made beyond 3 m from the tunnel centreline where the noise levels are some 10 dB lower than those observed inside the airstream. Basically similar trends are observed at other frequency bandwidths as can be deduced from consideration of Fig 17.

4.4 Overall acoustic performance of the tunnel

The acoustic calibration of the tunnel, with the standard splitter configuration installed, is given in Figs 19 and 20 for microphones mounted inside and outside the airstream at wind speeds between 10 m/s and 50 m/s. At the lowest speed, the backbround noise of the electrical drive machinery predominates but, at the higher speeds the noise intensity is seen to be varying with U_0^6 at constant values of f/U_0 ; *ie* there is approximately an 18 dB increase in noise level for a doubling of air speed.

Some indication of the usefulness of the facility is demonstrated from a comparison of these background noise levels with the predicted noise from 25 mm and 50 mm diameter unheated jets on the assumption that in-stream noise measurements would be made 0.5 m from the jet and out-of-stream measurements at 1.5 m distance. The comparison shows that, at a pressure ratio of 1.4, the 25 mm jet could be acoustically tested with confidence at frequencies above 1 kHz for wind speeds up to 40 m/s and that the speed could be increased to 50 m/s for the 50 mm jet.

4.5 Noise of microphone mounting systems

Various mounting systems have been used for noise investigations inside the airstream of the 24ft tunnel and there has been little evidence of significant increases in background noise caused by the type of mounting system employed, other than the expected discrete tones produced by vortex shedding from wires. Nevertheless, noise from such support systems might be detectable in the quieter 1.5m tunnel, so a new low-drag strut of aerofoil cross-section was designed for this facility (Fig 4). Unfortunately, manufacturing delays precluded the use of this strut for most of the acoustic assessment of the 1.5m tunnel but, when it became available, comparisons were made of the self-noise levels of three rigs as measured by a microphone outside the stream (Fig 21). Each of these rigs was positioned so that it could hold a ¼in microphone on the tunnel centreline at 1.8 m from the nozzle face; the noise measurements were made on a further ¼in microphone 1.6 m from the centreline. Investigations were completed at 10, 20, 30, 40 and 50 m/s but, for clarity, only the results at 30 m/s and 50 m/s are shown on Fig 21 though similar effects were observed at other speeds.

The elliptic strut had the same section (50 mm × 20 mm) as that frequently used for microphone mountings in the 24ft tunnel. It is now seen that, in a quiet tunnel, this section gives substantial increments in noise level over a three-octave bandwidth, with a peak increment of about 20 dB at a Strouhal number of 0.3 based on the strut thickness (20 mm).

Wire rigs produce aeolian tones at a Strouhal number of 0.18 based on wire diameter and there is an additional lower frequency tone associated with the 4mm signal cable which has to be attached to one of the wires. Thus at 30 m/s, a rig using wires of 0.5 mm diameter gives a tone 10 dB above the background noise level at 12.5 kHz and there is also a 5 dB 'lift' in noise level produced by the cable over the frequency range from 1-2 kHz.

The new aerofoil strut (Figs 4 and 21) is much quieter with its noise level less than 1 dB above the tunnel background level throughout the investigated frequency range (0.1-40 kHz), and similar designs are recommended for use as microphone mountings inside the airstream for all future work.

For measurements outside the airstream of an open-jet tunnel, a foam windshield should be fitted over the microphone as there are significant secondary air currents generated in the surrounding chamber.

5 ASSESSMENT OF THE ANECHOIC CHAMBER

The acoustic reflection limitations of the anechoic chamber have been assessed using two techniques, 'inverse-square' law and 'tone-burst'. For noise-model testing any interference effects can be regarded as being negligible provided that the reflected signal is at least 10 dB below the level of the direct signal. In the following sections limiting frequencies are established and the effects of remedial treatment are discussed. The 'inverse-square' law technique can be used quickly to determine spatial limitations for the positioning of noise measuring equipment; the 'tone-burst' technique can then be profitably used to determine sources of significant reflections so that surfaces in need of ameliorating treatment can be identified.

5.1 'Inverse-square' law

In an anechoic environment, the sound intensity is reduced to a quarter for each doubling of distance from a noise source; *ie* there is a corresponding 6 dB reduction in the sound pressure level, ignoring atmospheric attenuation effects. The apparatus used for checking this 'inverse-square' law capability in the 1.5m tunnel is shown schematically in Fig 22b. Using the digital voltmeter as an indicator, a pink-noise driving voltage to the speaker is held constant as the microphone is moved away from the noise source. The microphone signal is fed through a filter to remove any low-frequency background noise of high intensity so that the full 50 dB range of the third-octave analyser can be used. From the data obtained, curves are plotted in Figs 23 to 25 of sound pressure level against the distance of the microphone from the source for each third-octave bandwidth between 0.5 kHz and 2.5 kHz.

Investigations have been made both along the tunnel centreline (Figs 23 and 24) and perpendicular to it (Fig 25). At high frequencies the measurements are in good agreement with the 'inverse-square' law prediction, but, as the frequency is reduced, the sound levels become higher than expected at the more distant points. Thus the facility has good anechoic properties at frequencies above 2 kHz irrespective of the positions of source and microphone but limitations on their separation should be imposed at lower frequencies. The acoustic properties are adequate along the tunnel centreline down to 0.5 kHz if the microphone is within 1 m of the source. Outside the stream, measurements can be made with confidence at frequencies as low as 0.8 kHz even 4 m away from a source on the centreline.

5.2 'Tone-burst' measurements

5.2.1 'Tone-burst' technique

The equipment used for the 'tone-burst' technique is schematically illustrated in Fig 22a. A short burst of pure tone noise is radiated from a source on the tunnel centreline and the signal is detected with an appropriately positioned microphone and fed to a calibrated oscilloscope which has its trace triggered at the instant that the noise emission commences. Photographic records of the oscilloscope traces (Figs 26 to 28) show the direct noise signal after the appropriate time delay for noise to travel from the source to the microphone, followed by other signals as sound waves reach the microphone after reflection from surfaces within the chamber. For work within the 1.5m tunnel, a time base of 0.05 s is normally chosen as this allows signals from reflected sound paths up to 17 m in length to be observed while the direct path is only of the order of 1 m for the selected microphone positions. It should be noted that it is essential for the duration of the 'tone-burst' to be short enough for there to be no overlap between direct and reflected signals on the trace. In general, bursts of 4 cycles were emitted at tone frequencies above 1 kHz with the duration reduced to 2 cycles at lower frequencies. In order to improve signal clarity, background broadband noise should be removed with the aid of third-octave bandpass filters inserted between the amplifier and the analyser (Fig 22a).

The height of the oscilloscope trace measures the signal voltage which is proportional to the pressure amplitude of the sound wave and thus, if (a) and (b) are the respective heights on the trace of the direct and reflected signals, then the difference in sound pressure level (ΔdB) between the two signals is given by:

$$\Delta dB = 20 \log_{10}(b/a) \quad .$$

From a single trace, differences of up to 25 dB can be readily detected from analysis of the records, but even greater resolution is attainable if separate photographs are taken with different voltage gain settings for the direct and reflected signals. The measurement of signal strength can be made absolute on a sound pressure level scale if the system is calibrated with a pistonphone.

5.2.2 Anechoic performance of tunnel working chamber

In assessing the acoustic performance of a facility from 'tone-burst' tests, we regard installations as being acoustically substandard if reflected signals have sound pressure levels within 10 dB of the direct signal. Using this criterion, the results (Figs 26 to 28) indicate lower limits to the frequency range that may be used for acoustic tests in the facility. The main reflections occur from the acoustically hard collector and nozzle face (Figs 4 and 6) but there are also some troublesome reflections from the end wall of the tunnel at frequencies below 1 kHz. The reflection problems increase as the microphone is moved nearer to a reflecting surface. Thus, in Fig 26, it is seen that the facility is acoustically acceptable at all frequencies above 1 kHz when the centreline microphone is 0.75 m from the source but movement of the microphone 0.75 m nearer to the collector results in the limiting frequency being raised to 2.5 kHz. Nozzle-face reflections are less severe than those from the collector and, even in the severe constraints imposed by the test set-up illustrated in Fig 27, both nozzle and end wall reflections are acceptable at frequencies in excess of 1 kHz.

The severest test conditions occur when both source and microphone are mounted on the tunnel centreline as this configuration allows focussing effects to be produced by the octagonal collector ring and circular nozzle. This arises from the fact that the multiplicity of paths from the source reflected by the collector (or nozzle) onto the microphone are of almost identical length and thus the reflected acoustical energy is received in phase at any instant. Consequently it is even possible for the reflected signal to be of greater strength than the direct signal as is seen, for instance, on the oscilloscope trace for the reflection from the collector at 1.25 kHz in Fig 26. For measurements made away from the centreline, as is more normal for noise model testing, this focussing phenomenon would become less severe as there would then be differences in the path length between the waves reflected from various parts of the collector ring and the resulting phase shift would result in some cancellations in the overall signal.

It is envisaged that acoustic measurements outside the airstream would normally be made some 1.5 m from the tunnel centreline. A check using the 'tone-burst' technique shows that, with a noise source on the tunnel centreline, no significant reflections would interfere with signals received by a microphone mounted in this vicinity (Fig 28) - at least for frequencies above 800 Hz.

5.3 Improved anechoic performance obtained with additional acoustic treatment

The work reported in the previous sections highlighted those parts of the circuit which caused significant echoes when measurements are made in the working chamber of the tunnel. Remedial action has subsequently been taken to improve the anechoic performance (Fig 29). The solid collector has been replaced by one of identical geometry but made from polyether foam. The foam treatment of the nozzle face has been extended right up to the nozzle itself while leaving the 36% open area metal perforate covering to the auxiliary air inlet (Fig 6). In addition a layer of 75 mm thick polyether foam has been installed internally on the end wall upstream of the test section leg of the circuit (Fig 29), *ie* the wall upstream of the fourth corner.

The improvements in the anechoic characteristics of the facility attributable to these modifications are illustrated in Fig 30. The end wall no longer presents any acoustic problems; the reflected sound level on the tunnel centreline is at least 15 dB below the direct signal even at frequencies as low as 300 Hz. The nozzle-face reflections are now acceptable at frequencies above 800 Hz but some problems still remain with reflections from the collector ring at frequencies below 1600 Hz even though there has been a reduction of some 8 dB in the strength of the reflected signal. Thus, if experimental requirements imply the need for measurements with a microphone on the tunnel centreline, they should not be made more than 1 m behind the noise source when frequencies of the order of 1 kHz are of interest.

These improvements to the anechoic properties of the working chamber have had no measurable effect on the tunnel background noise levels.

6 CONCLUSIONS

These modifications to the old 5ft tunnel have thus provided experimental design information for possible improvements to the acoustic performance of the 24ft tunnel, involving background noise reductions of about 15 dB over most of the frequency range of practical interest. Moreover, the resulting 1.5m tunnel can now be regarded also as an acoustic research facility in its own right; inside the airstream at 50 m/s the noise level for third-octave bandwidths now drops from 75 dB at 1 kHz to 70 dB at 20 kHz while outside the airstream the noise levels are some 5-10 dB quieter. Lower background noise levels could have been achieved but the design philosophy (in respect of the 24ft tunnel), requiring the acoustic splitters ahead of the fan to be sited in a high-speed part of the tunnel circuit and the resulting 'self-noise' of the splitters impairs their overall noise attenuation capabilities. In general, the working chamber has good anechoic properties at frequencies down to about 1 kHz for noise model measurements both inside and outside the airstream. If measurements have to be made especially close to the tunnel centreline, the limiting acoustic constraint still appears to arise from the focussing effect of the collector ring (even with a polyether foam ring).

This acoustic tunnel should prove most useful for investigating the effects of forward speed on various noise sources.

Appendix

DESIGN OF ACOUSTIC SPLITTERS

The design of acoustic splitters is based on developments of the theory of Cremer[3] reported by Beranek for which blankets of acoustically absorbent material are mounted parallel to the axis of a duct. The splitters are considered to be made from homogeneous porous material and it has been demonstrated by Delaney and Bazley[5] at the NPL that the acoustical impedance for such materials is a unique function of their flow resistance. For this theoretical treatment, the important physical parameters of the splitter design are taken to be:

Splitter length	ℓ (mm)
Splitter thickness	$2t$ (mm)
Air gap between splitters	$2h$ (mm)
Flow resistance of splitter absorbent material	R_1 (mks rayls/metre) .

It can then be deduced that, for a given geometry, the peak attentuation occurs at a frequency

$$f_0 = \frac{101.6}{\sqrt{ht}} \text{ (kHz)}$$

and the maximum level of noise attenuation at this frequency (f_0) occurs if the blanket material has a flow resistance

$$R_1(\text{OPT}) \times 10^{-4} = 66.75\sqrt{h/t^3}\ .$$

Such a design would limit sound attenuation to a rather narrow band of frequencies but the band width can be increased if material with a higher flow resistance is chosen for the acoustic blanket, though this is at the expense of a somewhat lower level for the peak attenuation. For wind-tunnel purposes, the optimum overall design would appear to require an absorbent material with a flow resistance some two to three times the value of R_1(OPT).

LIST OF SYMBOLS

ℓ	length of absorbent blanket in acoustic splitters	(mm)
2h	air gap between acoustic splitters	(mm)
P	total pressure in jet	
P_0	atmosphere pressure	
R	radius of tunnel nozzle (0.76 m)	(m)
R_1	flow resistance of absorbent blanket in acoustic splitters	(mks rayls/metre)
2t	thickness of acoustic splitter	(mm)
U_0	air velocity on tunnel centreline	(m/s)
X	distance downstream from nozzle plane	(m)
Y	horizontal distance from centreline, positive away from return circuit	(m)
Z	vertical distance above centreline	(m)
θ_J	angle relative to jet axis	

REFERENCES

No.	Author	Title, etc
1	J. Williams T.B. Owen	Some acoustic and aerodynamic analysis for proposed improvements to the RAE 24ft low-speed tunnel RAE Technical Memorandum Aero 1669 (1976)
2	T.B. Owen	The RAE 1.5 metre acoustic tunnel - Aerodynamic considerations. RAE Technical Report to be issued
3	L.L. Beranek	Noise and vibration control, Ch 15. McGraw Hill Book Co (1971)
4	W.J.G. Trebble	The design of acoustic splitter for wind tunnels. RAE Technical Memorandum to be issued
5	M.E. Delany E.N. Bazley	Acoustical characteristics of fibrous absorbent materials. NPL Aero Report Ac37, March 1969
6		Estimation of subsonic far-field jet-mixing noise. Engineering Sciences Data Unit, Item 74002, June 1973

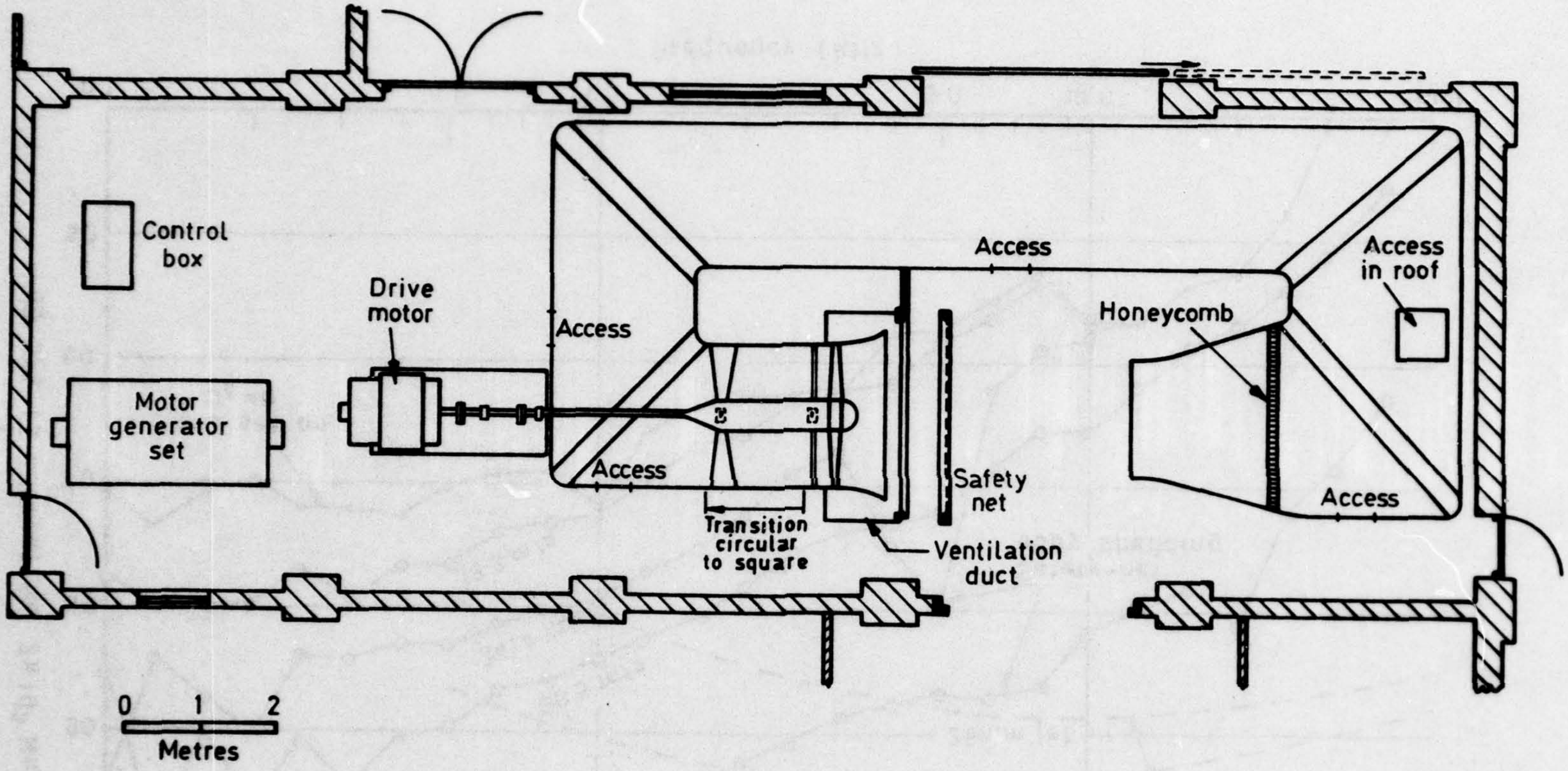


Fig 1 Original circuit of 5ft tunnel

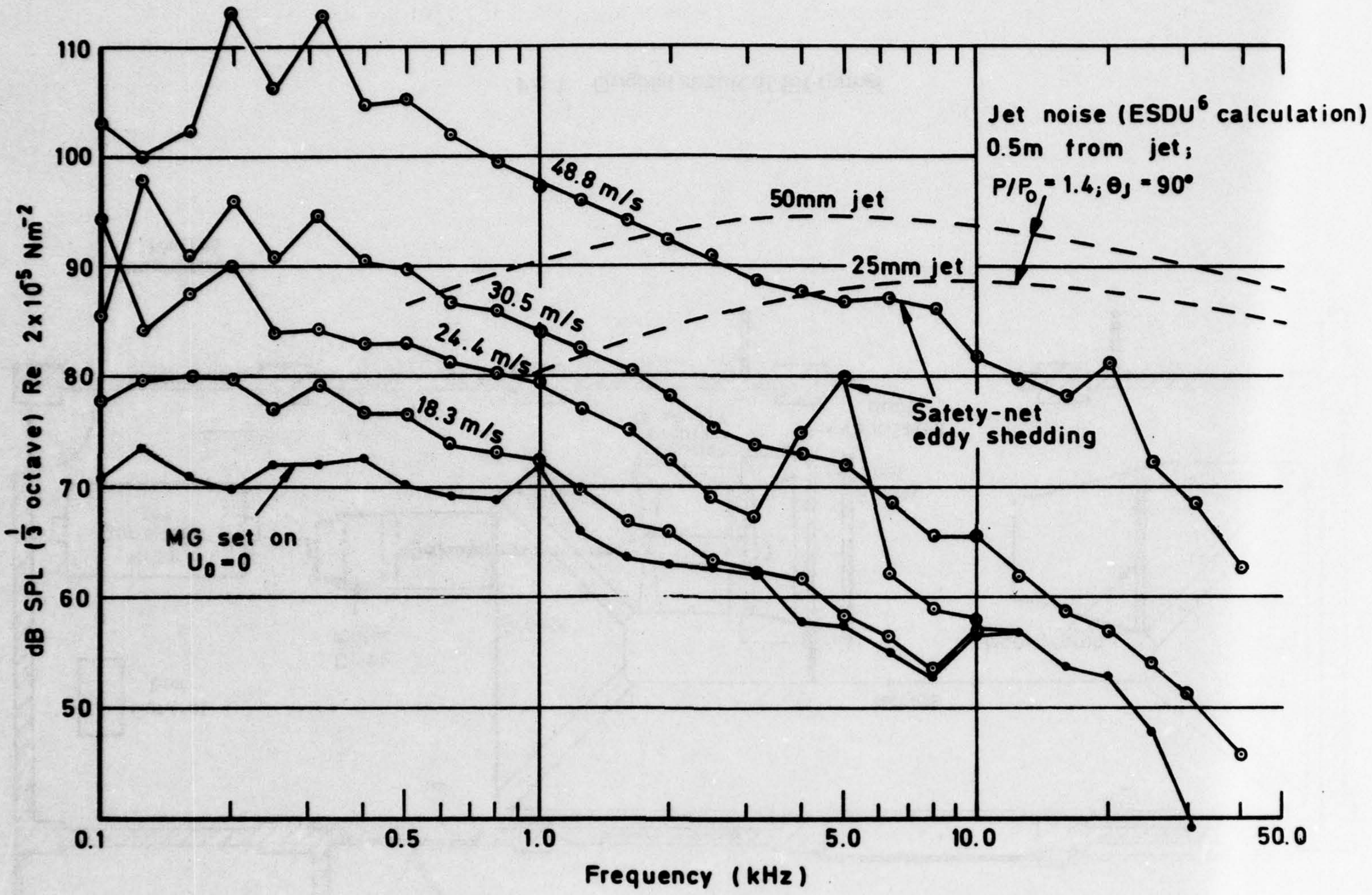
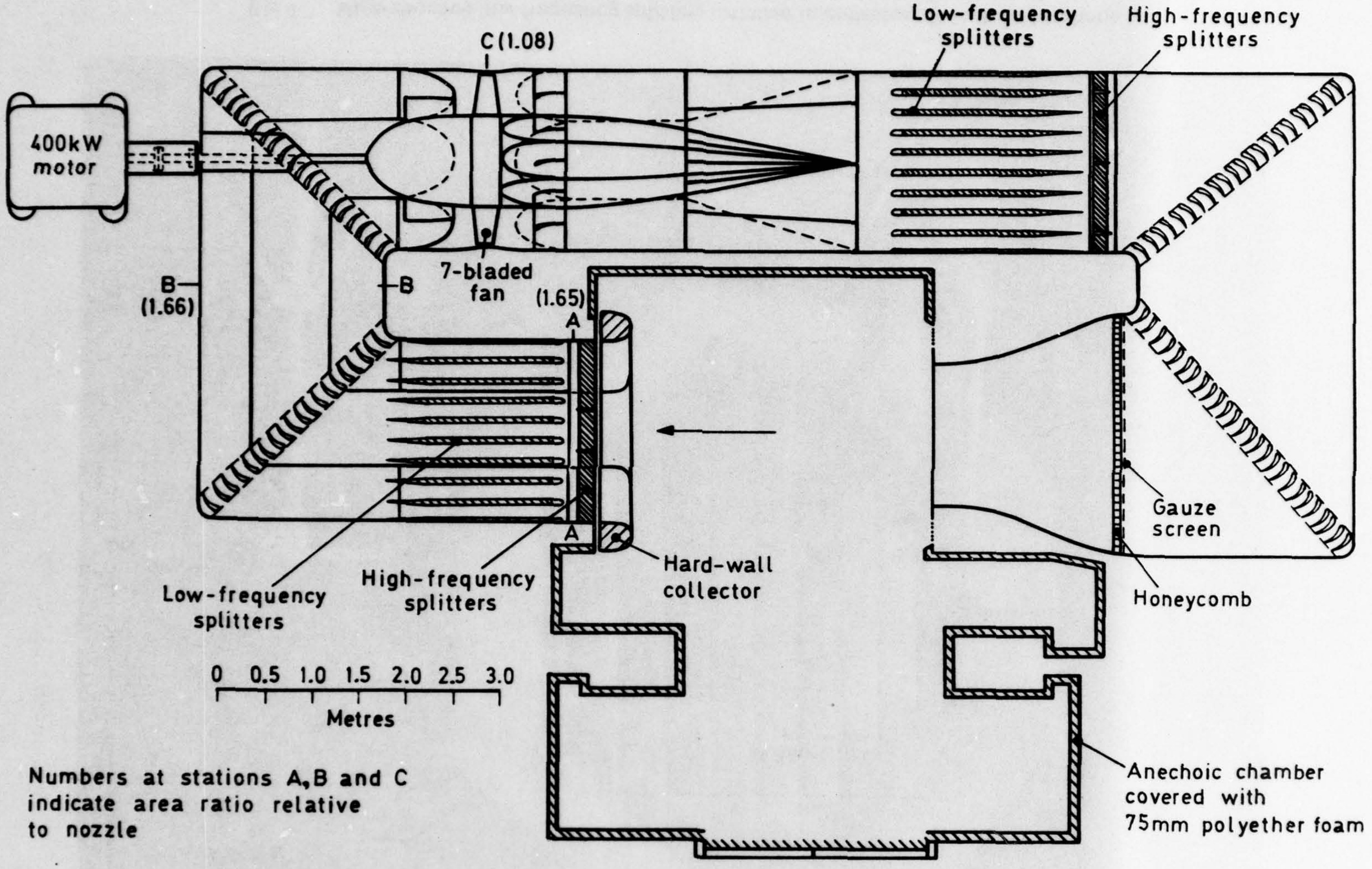


Fig 2 Noise levels in old 5ft tunnel (X/R = 1.30; Y/R = 0; Z/R = 0)



Numbers at stations A,B and C indicate area ratio relative to nozzle

Fig 3 1.5 metre tunnel with initial acoustic treatment

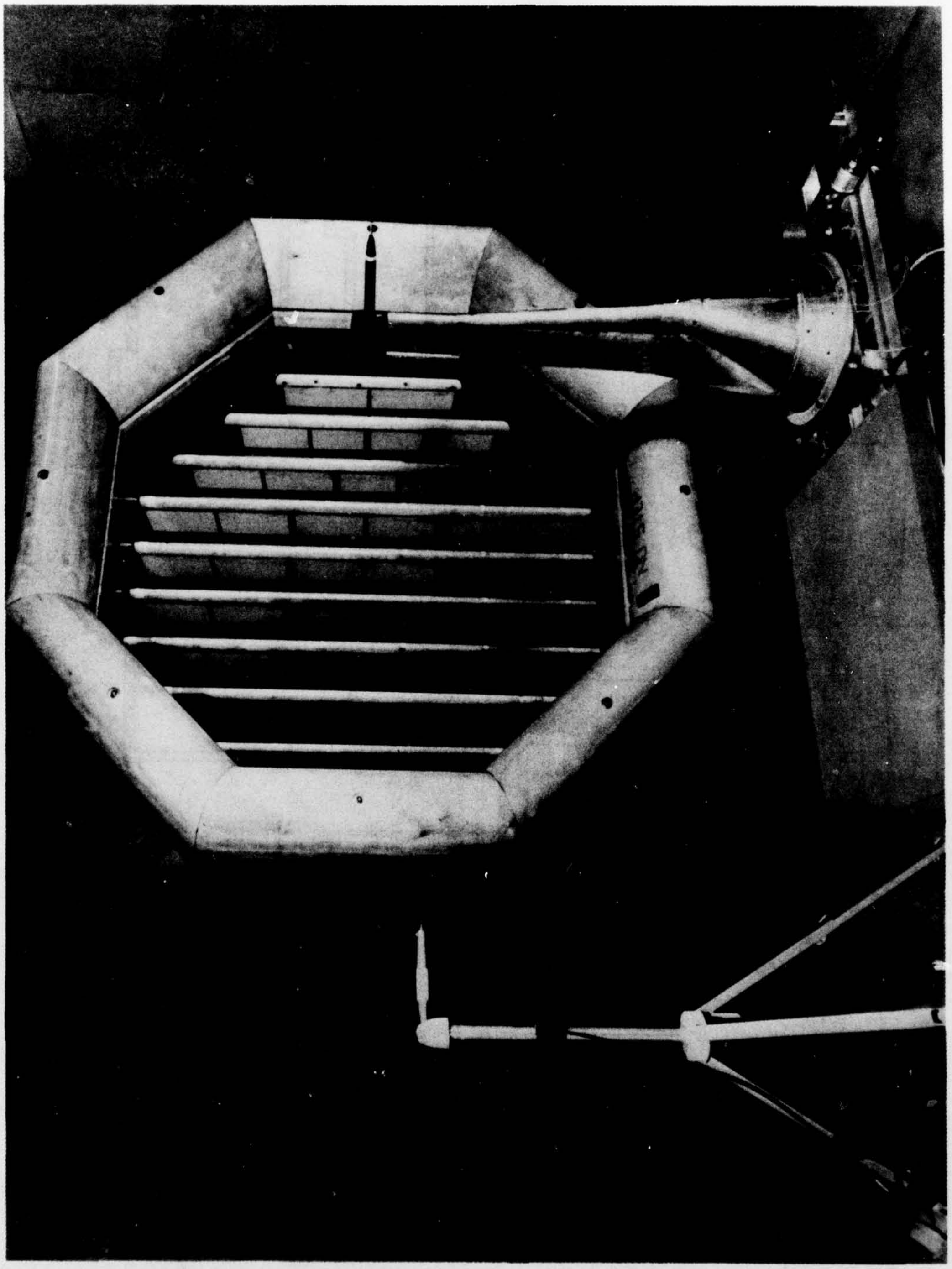


Fig 4 View showing low frequency splitters installed in collector. ¼ inch microphone with ogive nose cone mounted from aerofoil strut carried on track

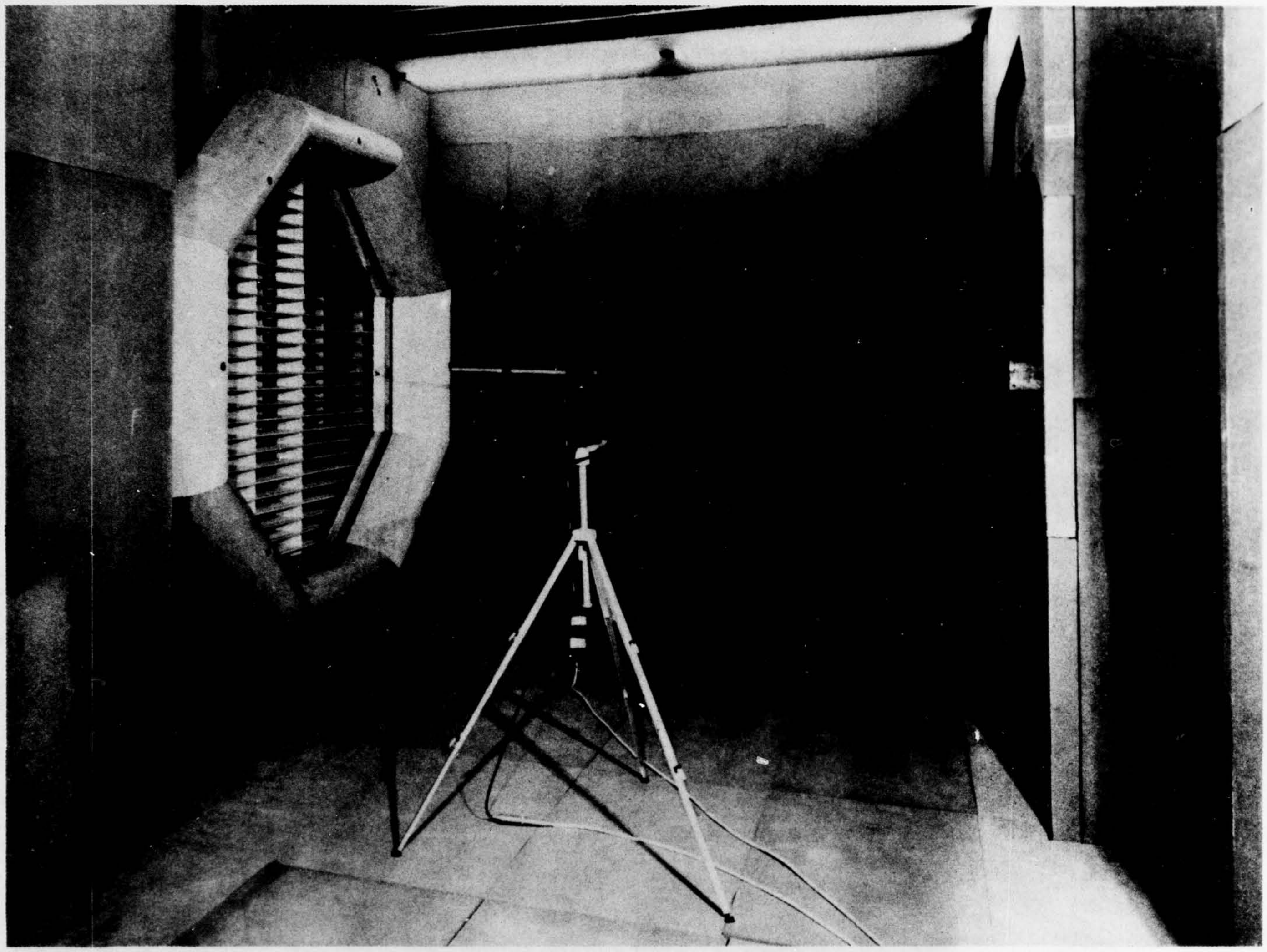
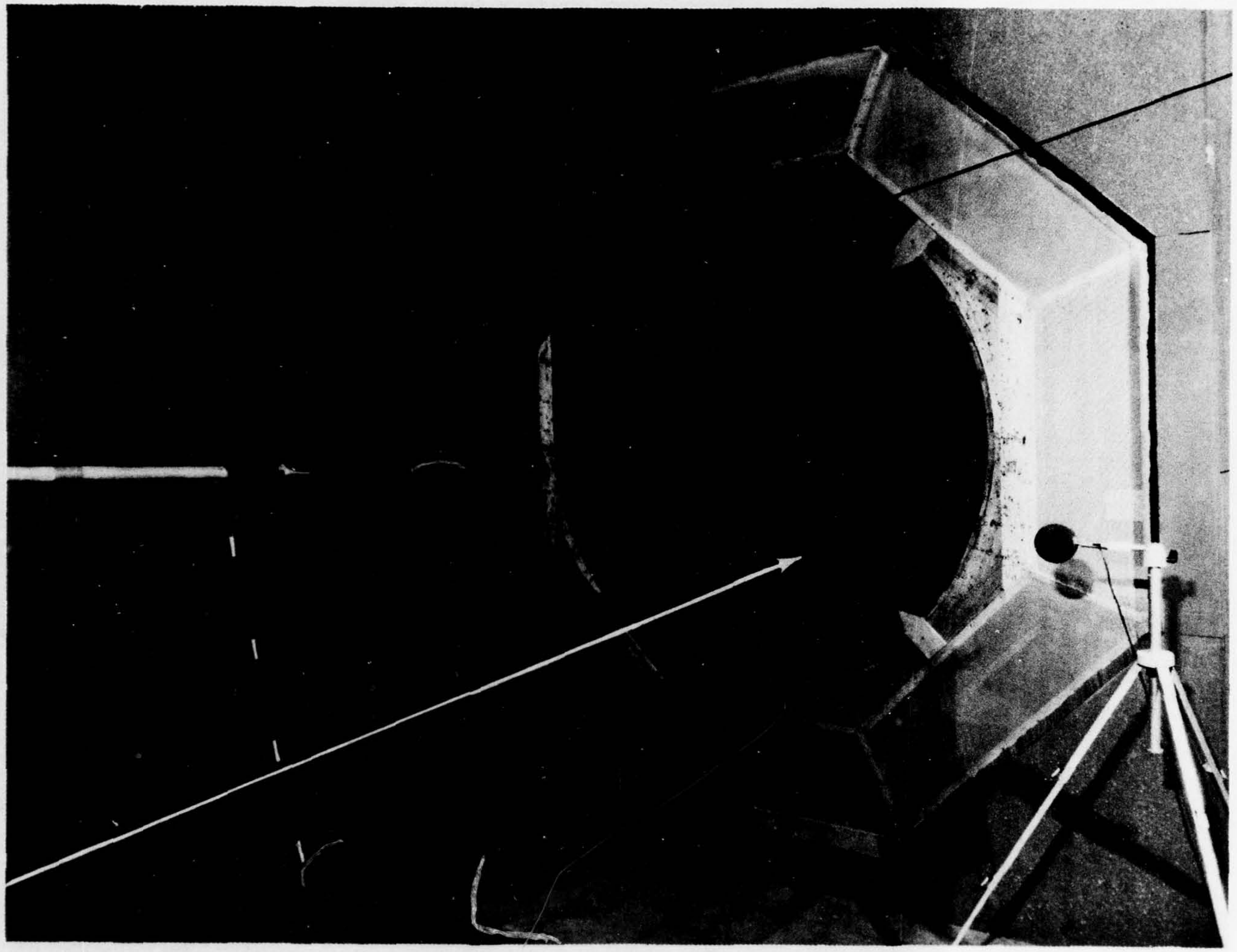


Fig 5 View of tunnel with high frequency splitters installed in collector. ¼ inch microphone with ogive nose cone mounted from wire rig in stream



No acoustic
treatment on
nozzle face

Perforated
face of
inlet for
cooling air

Honeycomb

Fig 6 View of tunnel nozzle also showing honeycomb in maximum section

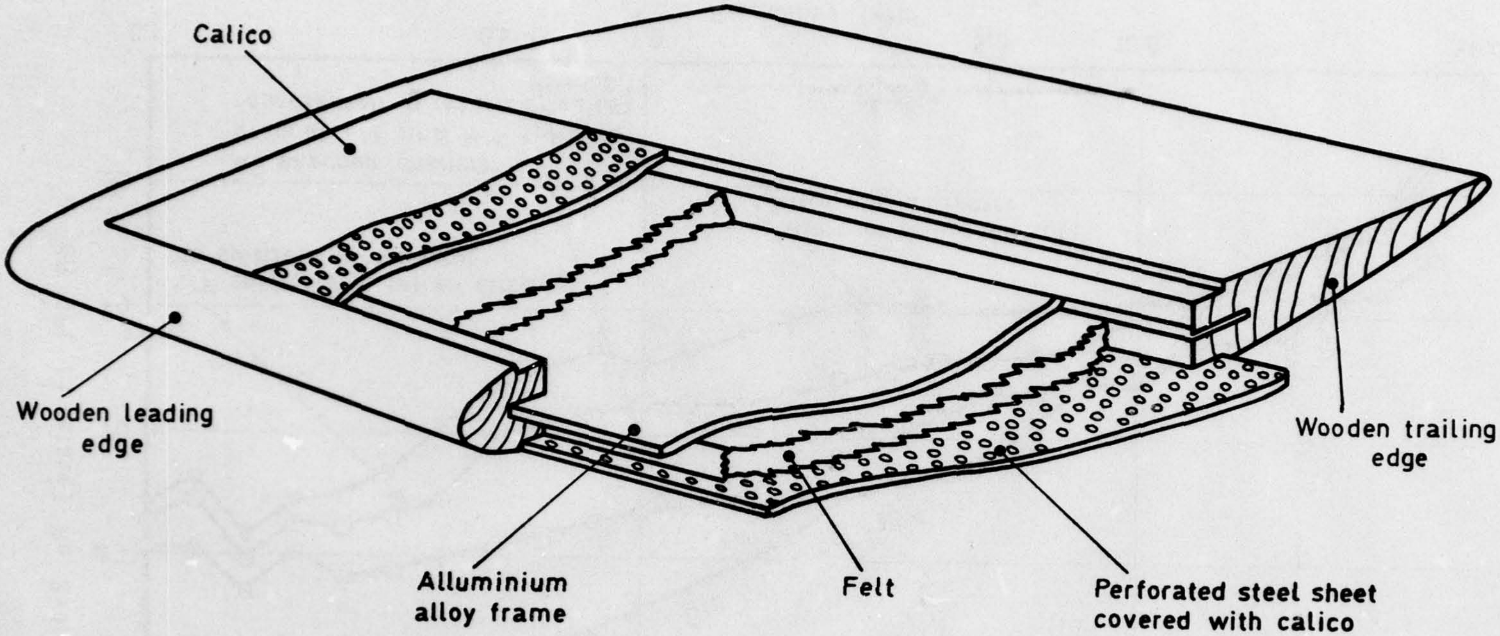


Fig 7 Sketch showing construction of high-frequency splitters.
N.B. Low-frequency splitters basically similar but felt replaced with Rockwool and no aluminium frame

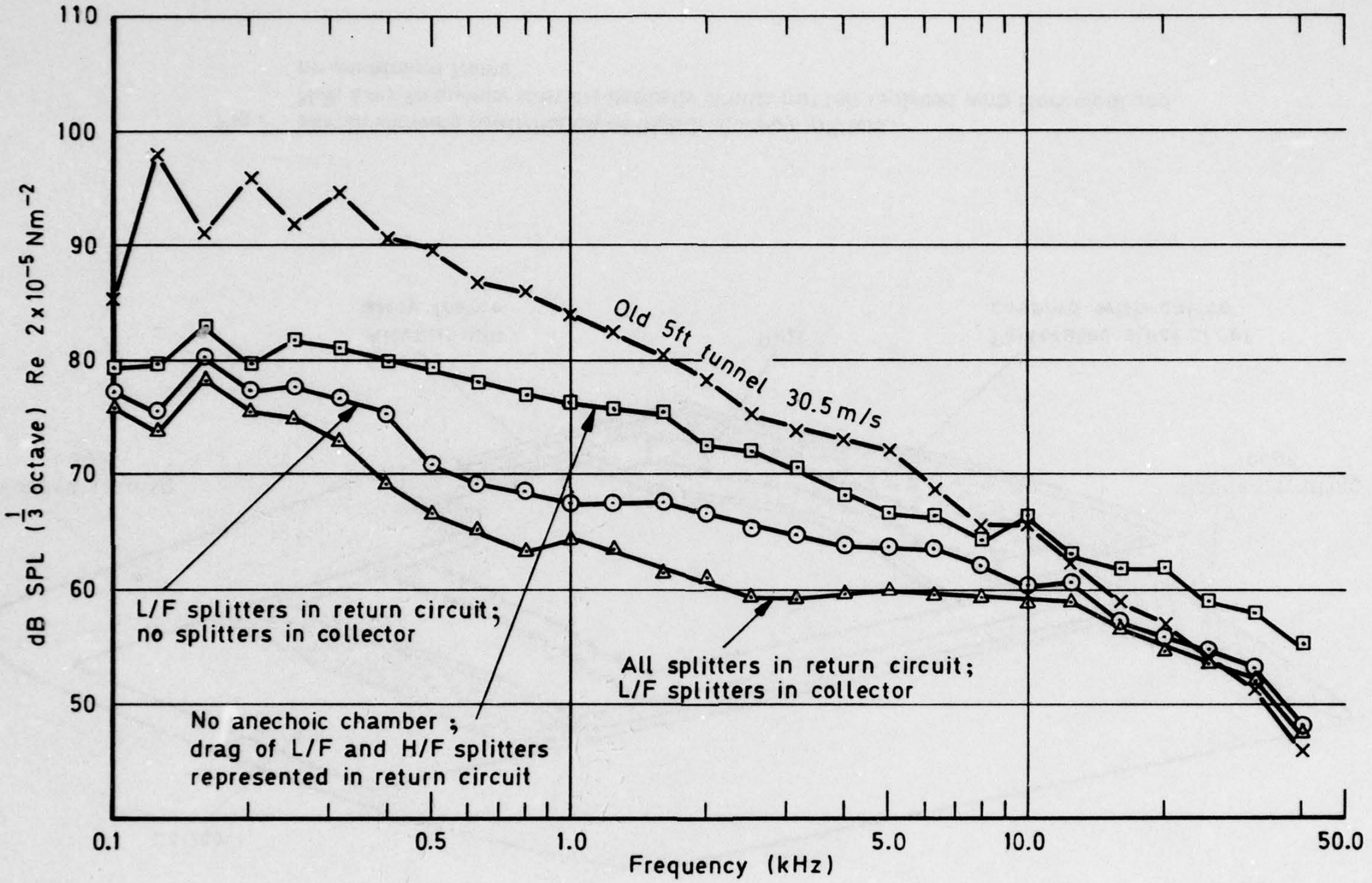


Fig 8 Improvements to acoustic performance obtained from modifications to facility $U_o = 30$ m/s; $X/R = 1.30$; $Y/R = 0$; $Z/R = 0$

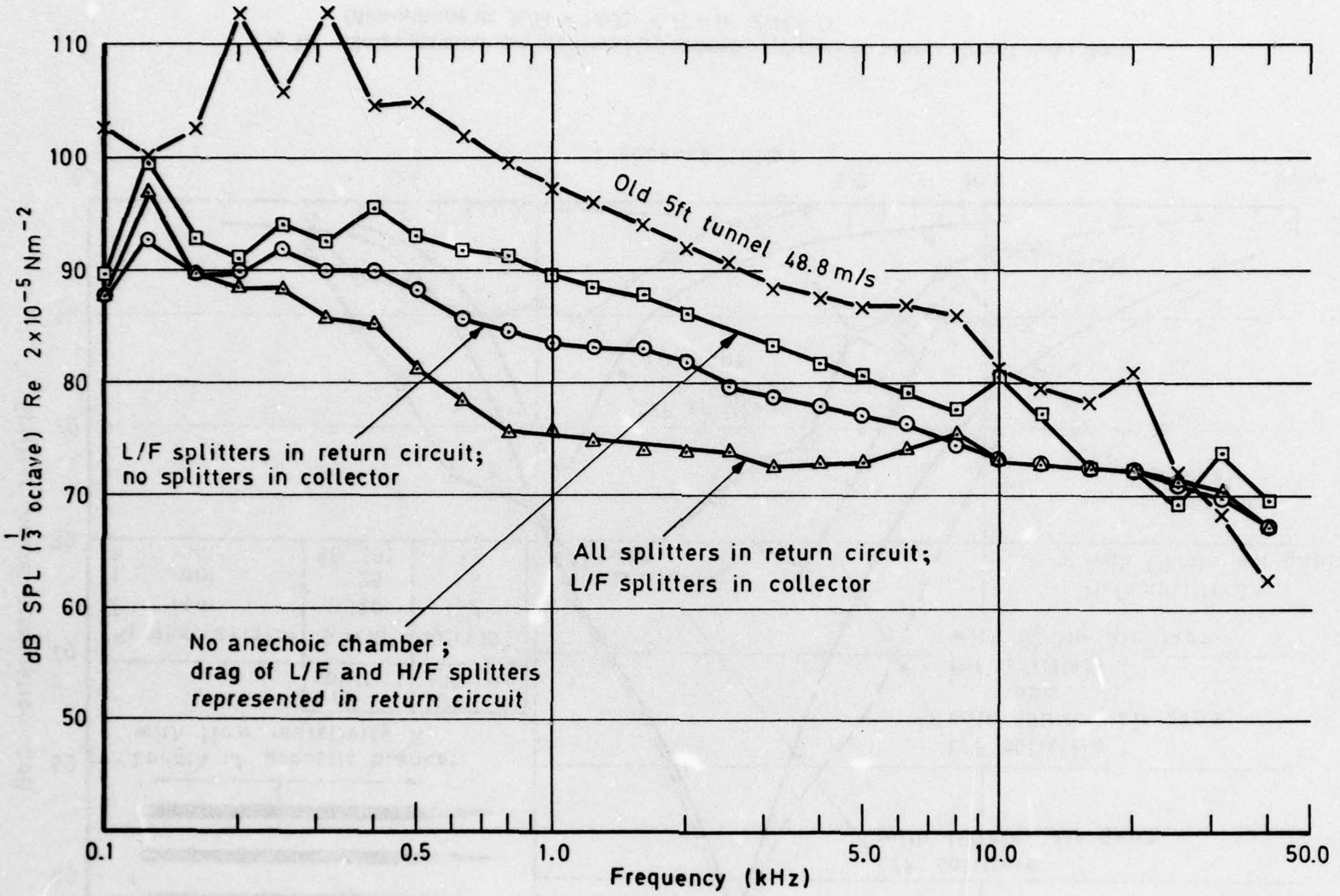


Fig 9 Improvements to acoustic performance obtained from modification to facility
$U_o = 50$ m/s; $X/R = 1.30$; $Y/R = 0$; $Z/R = 0$

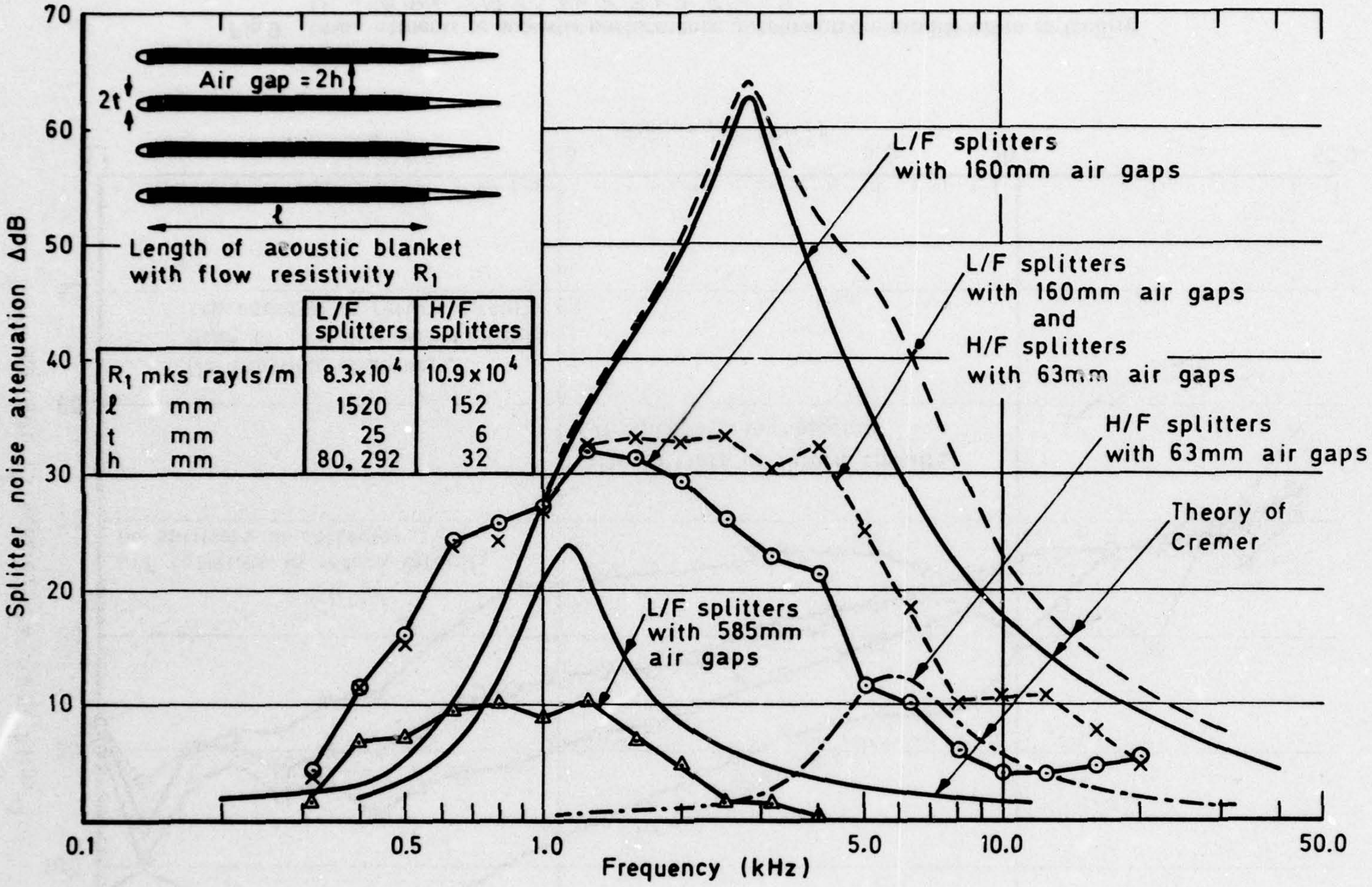


Fig 10 Noise attenuation produced by acoustic splitters in tunnel circuit – no flow. Microphone at X/R = 1.07; Y/R = 0; Z/R = 0

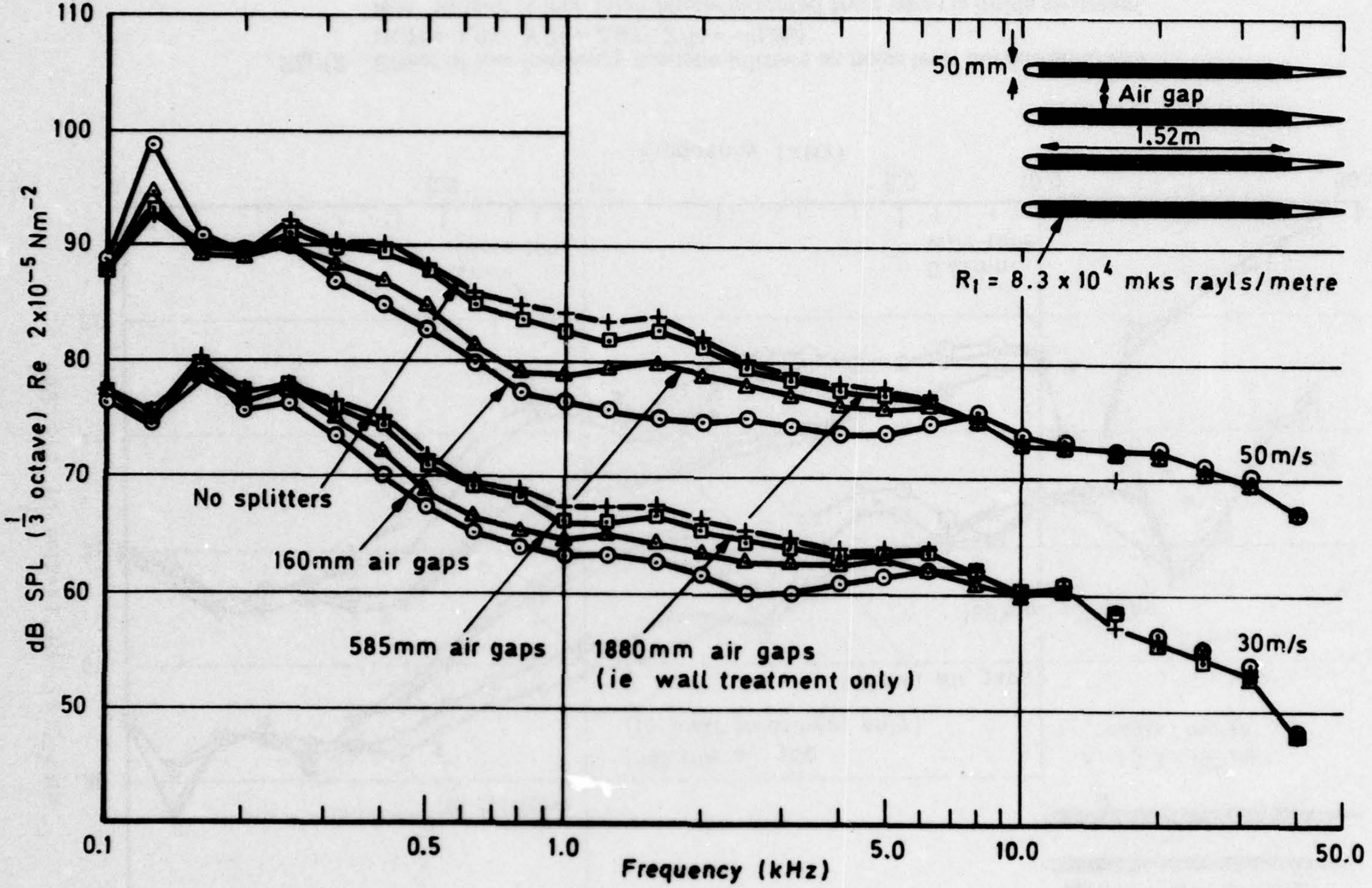


Fig 11 Effect of low-frequency acoustic splitters on noise level inside stream (X/R = 1.05; Y/R = 0, Z/R = 0)

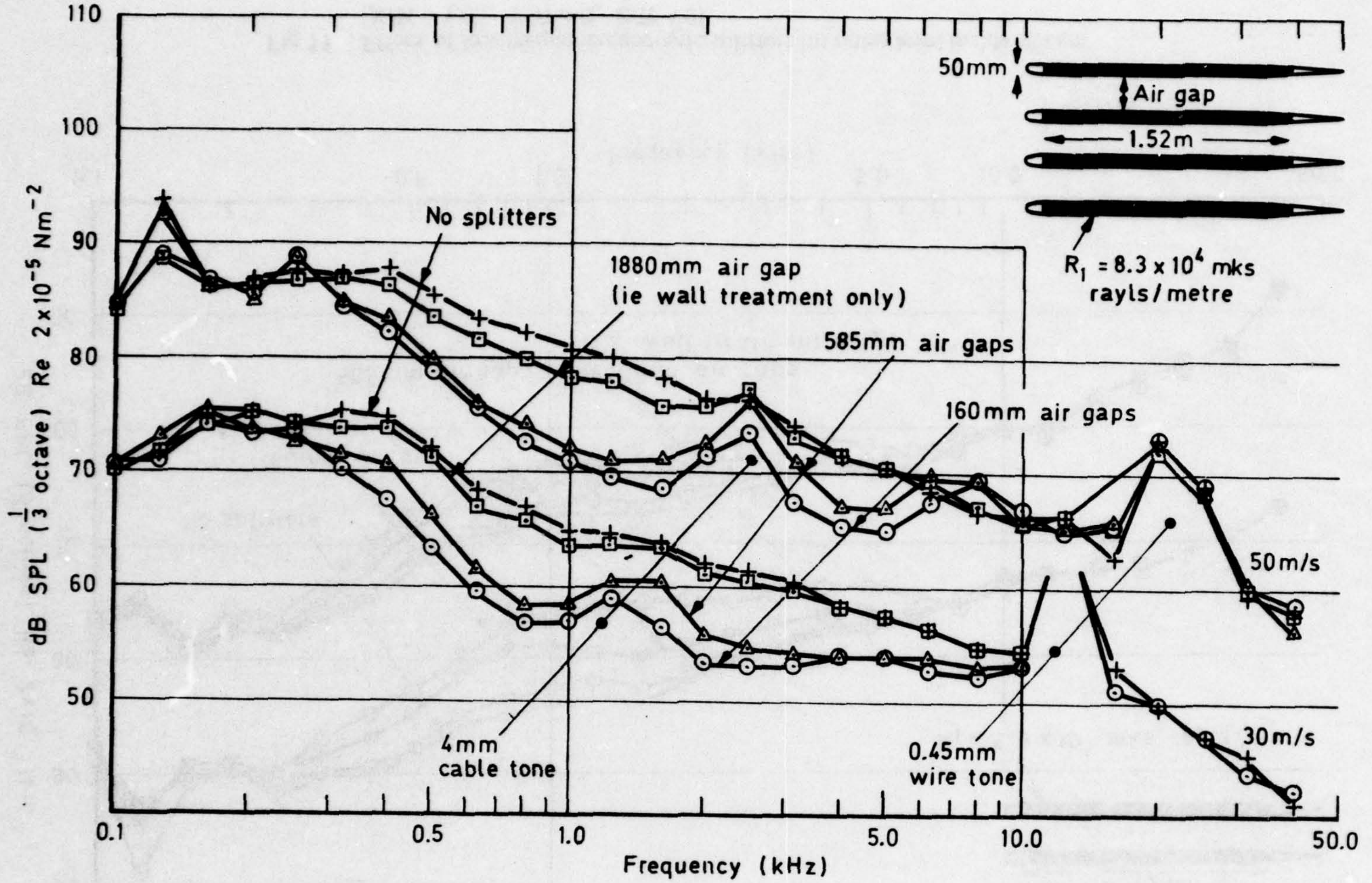


Fig 12 Effect of low-frequency acoustic splitters on noise level outside airstream (X/R = 1.97; Y/R = 2.07; Z/R = –0.35)
N.B. Second ¼-inch microphone mounted from wire-rig inside airstream

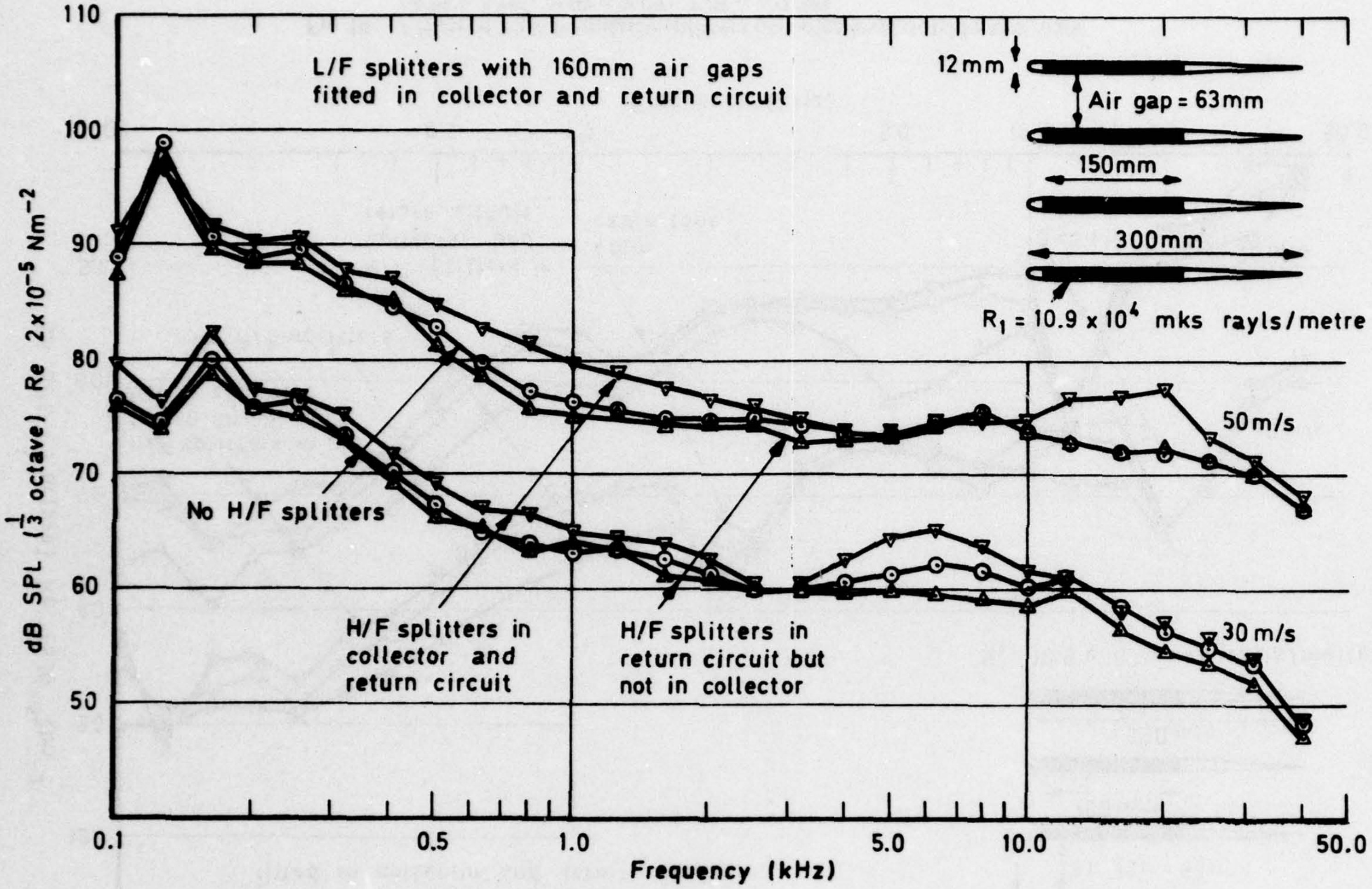


Fig 13 Effect of high-frequency splitters on noise level inside stream (X/R = 1.05; Y/R = 0; Z/R = 0)

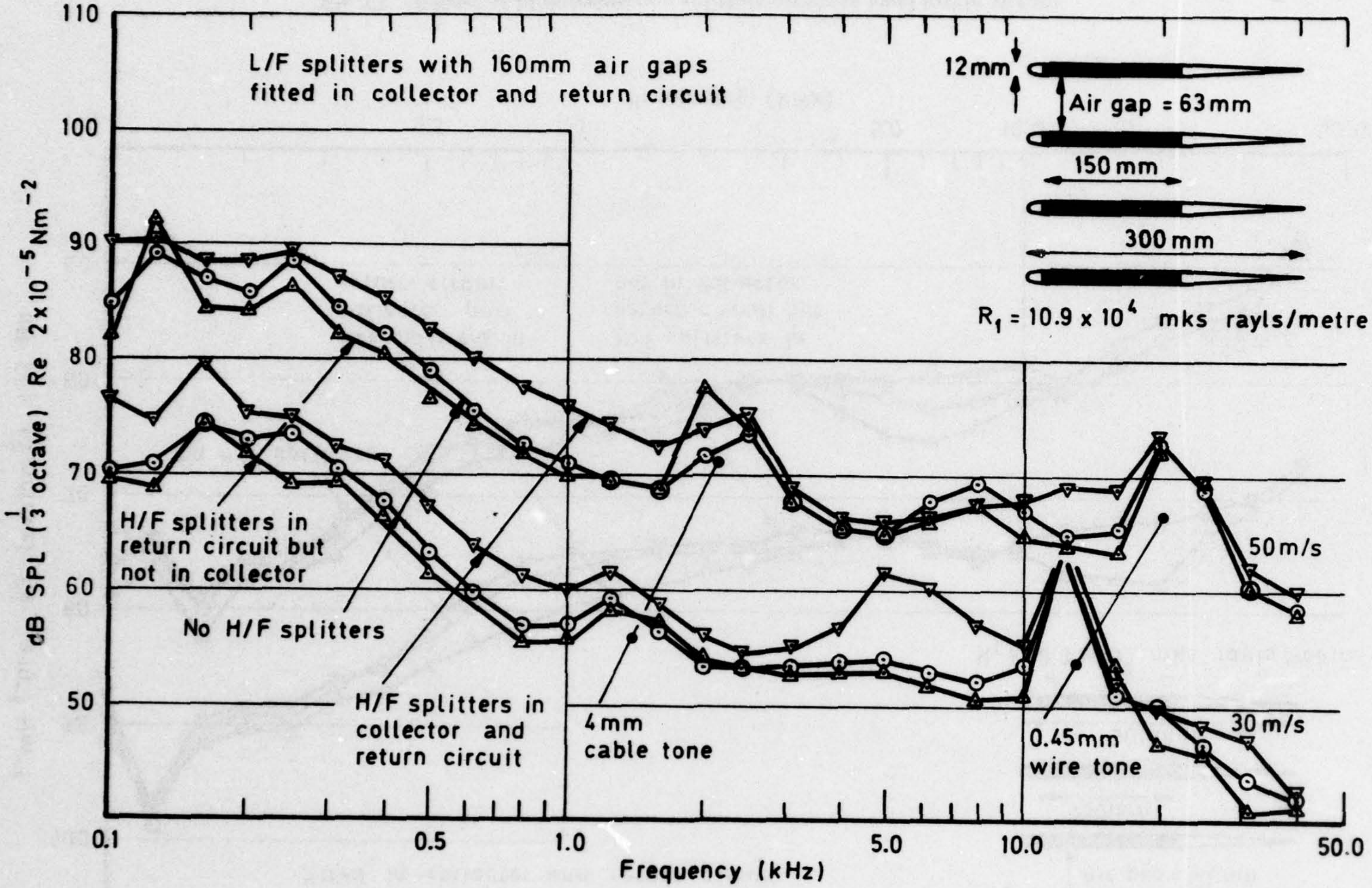


Fig 14 Effect of high-frequency splitters on noise level outside airstream (X/R = 1.95; Y/R = 2.07; Z/R = –0.35)
N.B. Second ¼-inch microphone mounted from wire-rig in airstream

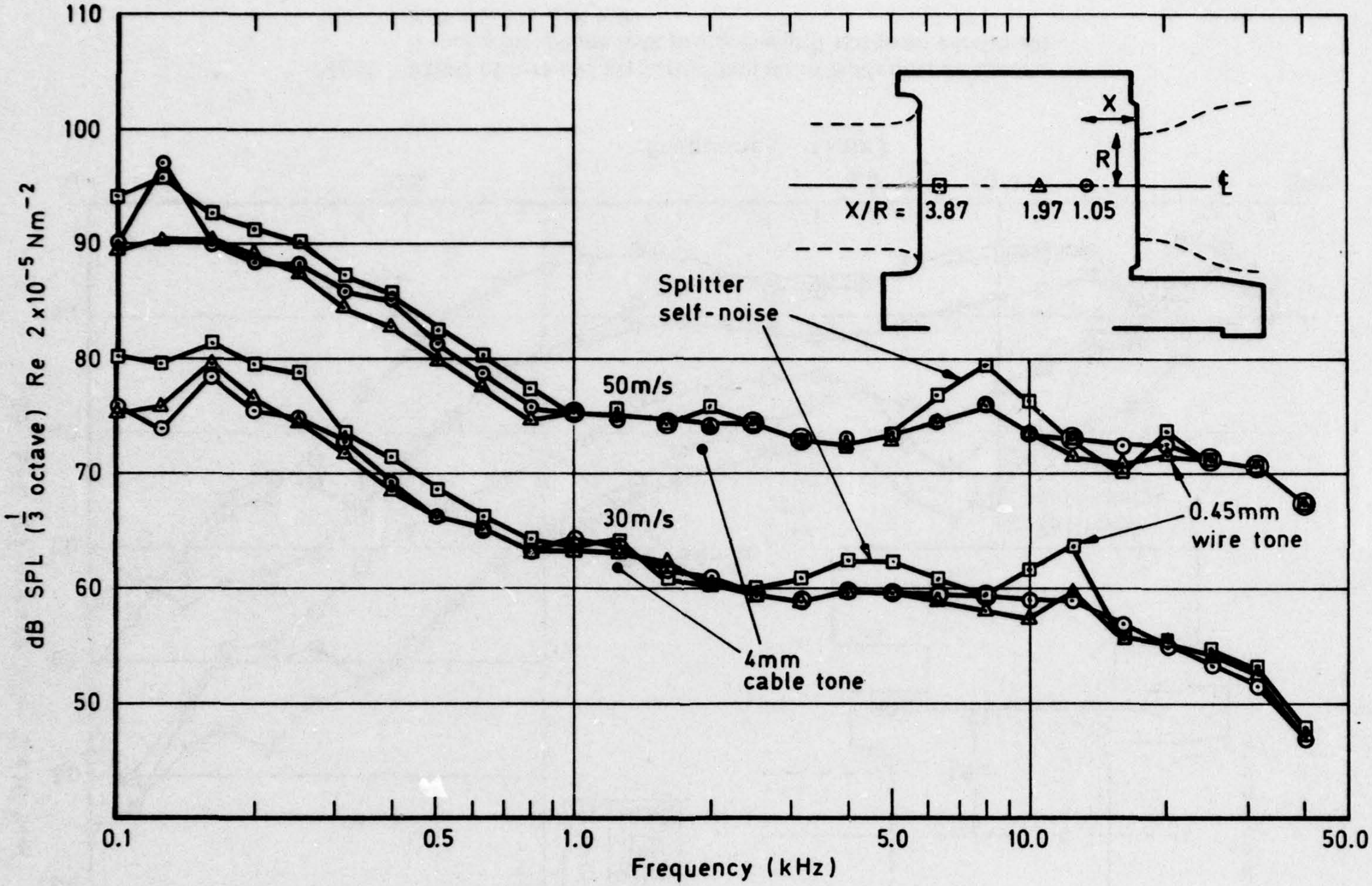


Fig 15 Effect of streamwise position on noise levels along tunnel centreline. ¼-inch microphone with ogive noise cone mounted from wire-rig

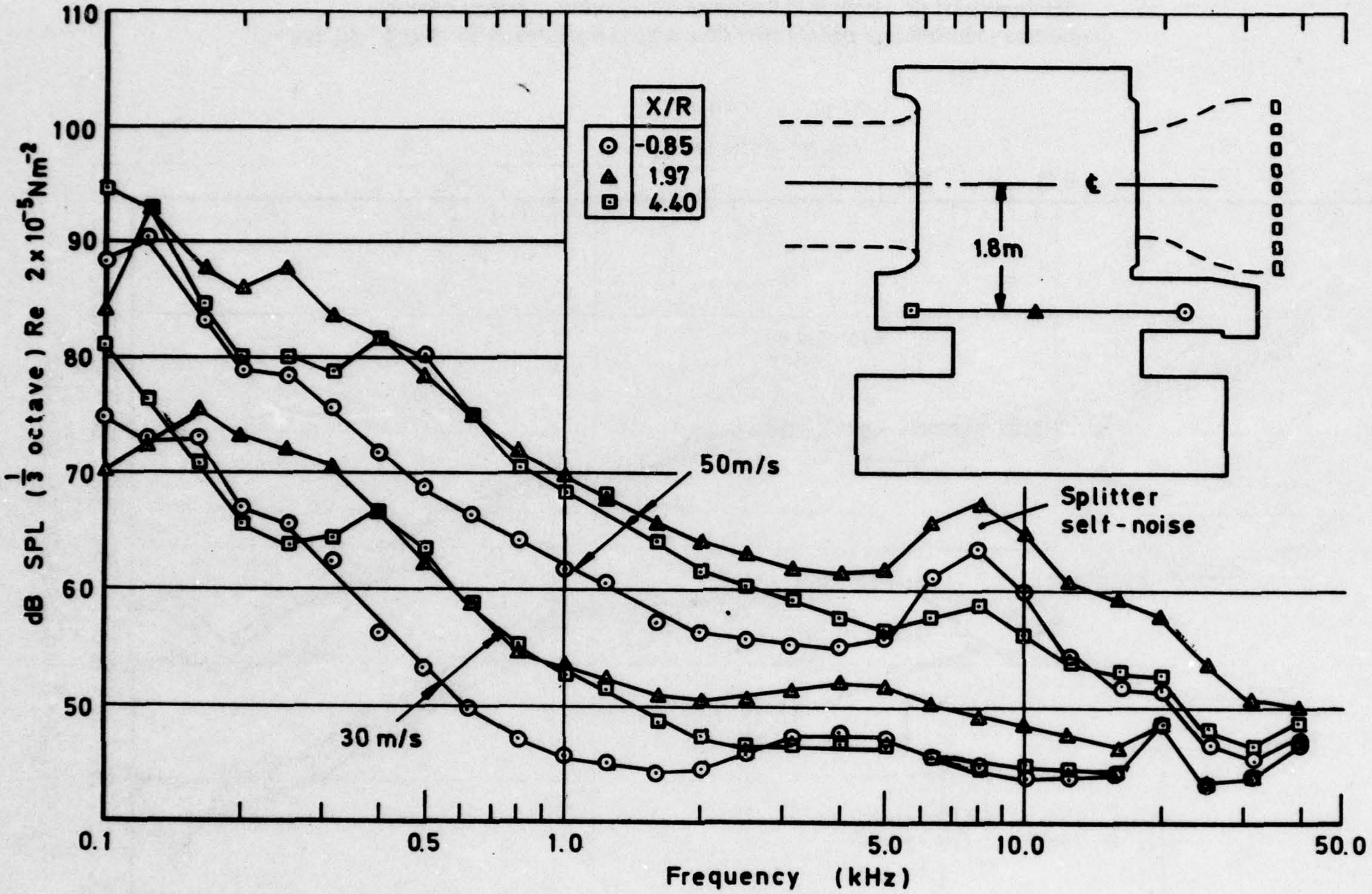


Fig 16 Effect of fore and aft position on noise levels outside stream.
¼-inch microphone with protective grill and foam windshield.
Y/R = 2.27; Z/R = 0

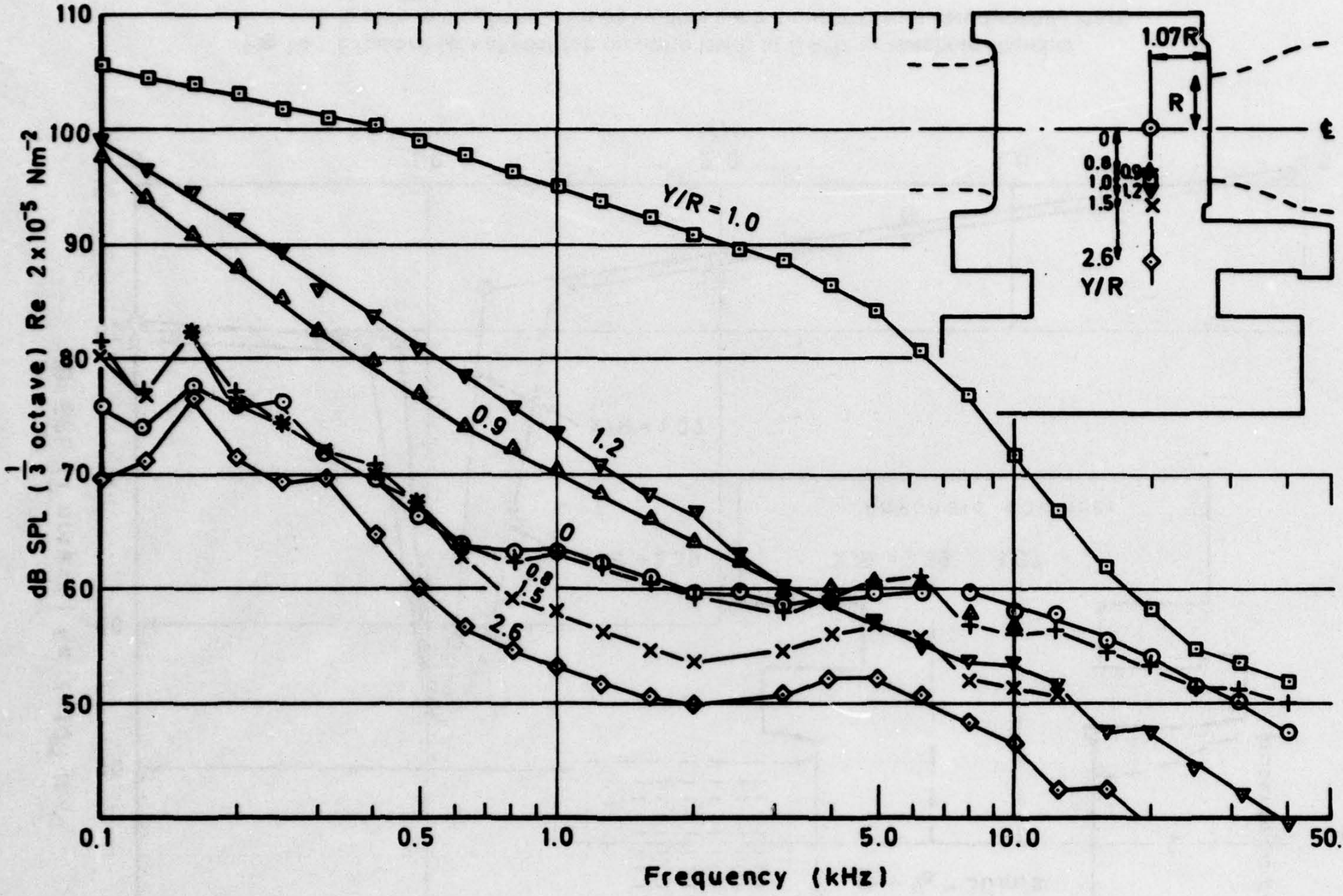


Fig 17 Variations in noise spectra with spanwise position in anechoic chamber. ¼-inch microphone with ogive nose cone mounted from aerofoil strut. $X/R = 1.07$; $U_o = 30$ m/s

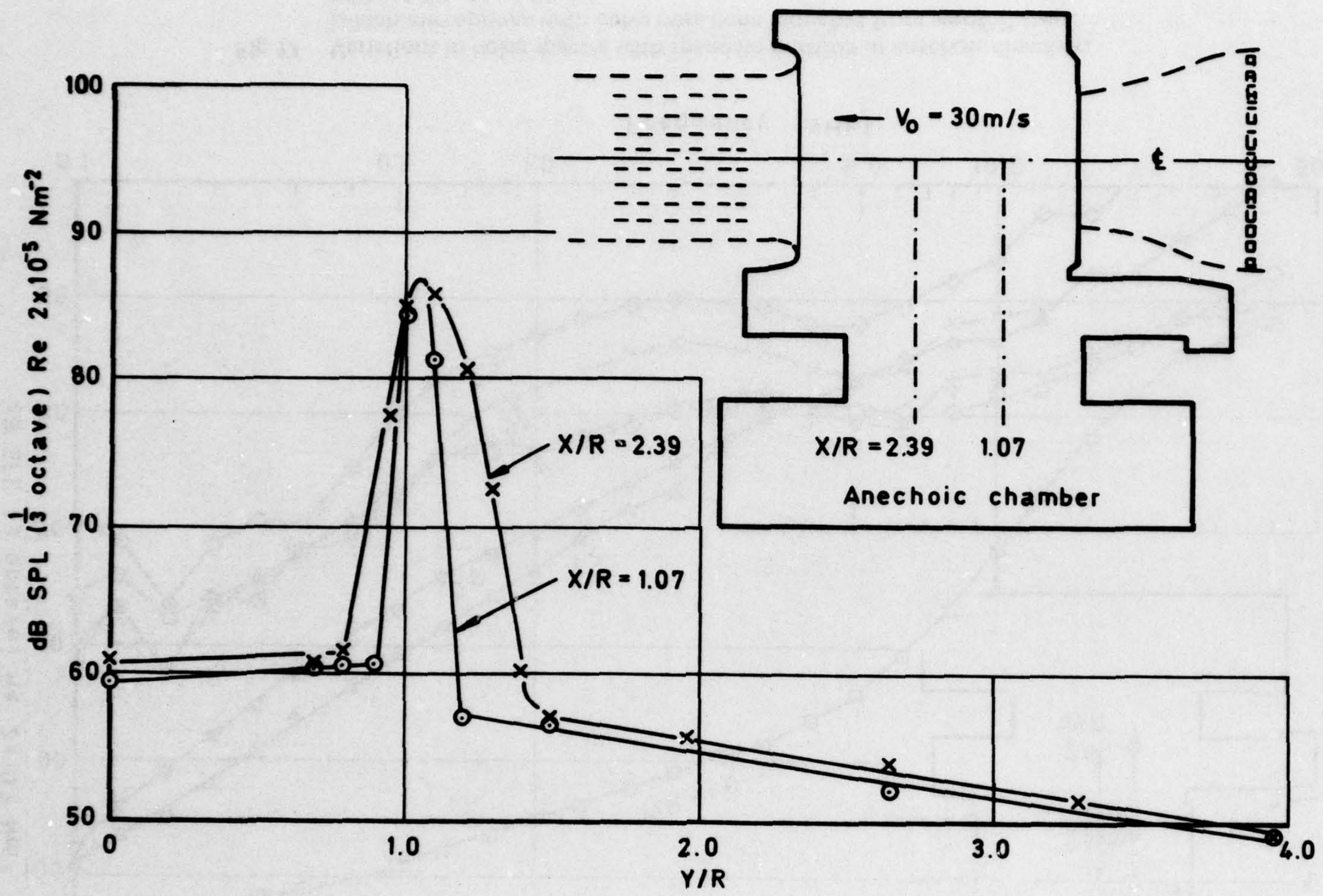


Fig 18 Effect of lateral position on noise levels at 5 kHz in anechoic chamber. ¼-inch microphone with ogive nose cone mounted from aerodynamic strut. U_o = 30 m/s

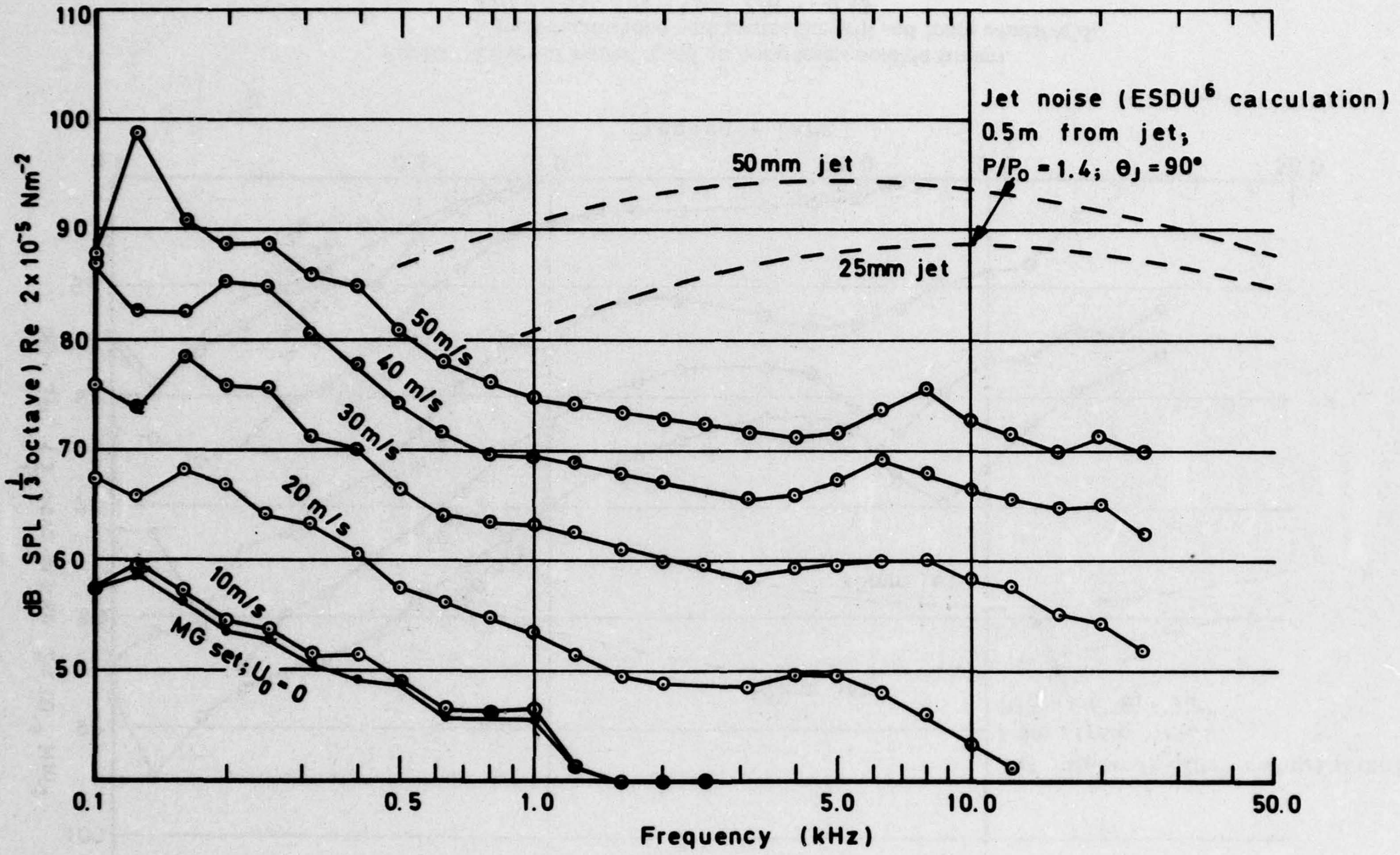


Fig 19 Effect of tunnel speed on noise levels inside stream.
¼-inch microphone with ogive nose cone mounted from aerodynamic strut.
X/R = 1.07; Y/R = 0; Z/R = 0

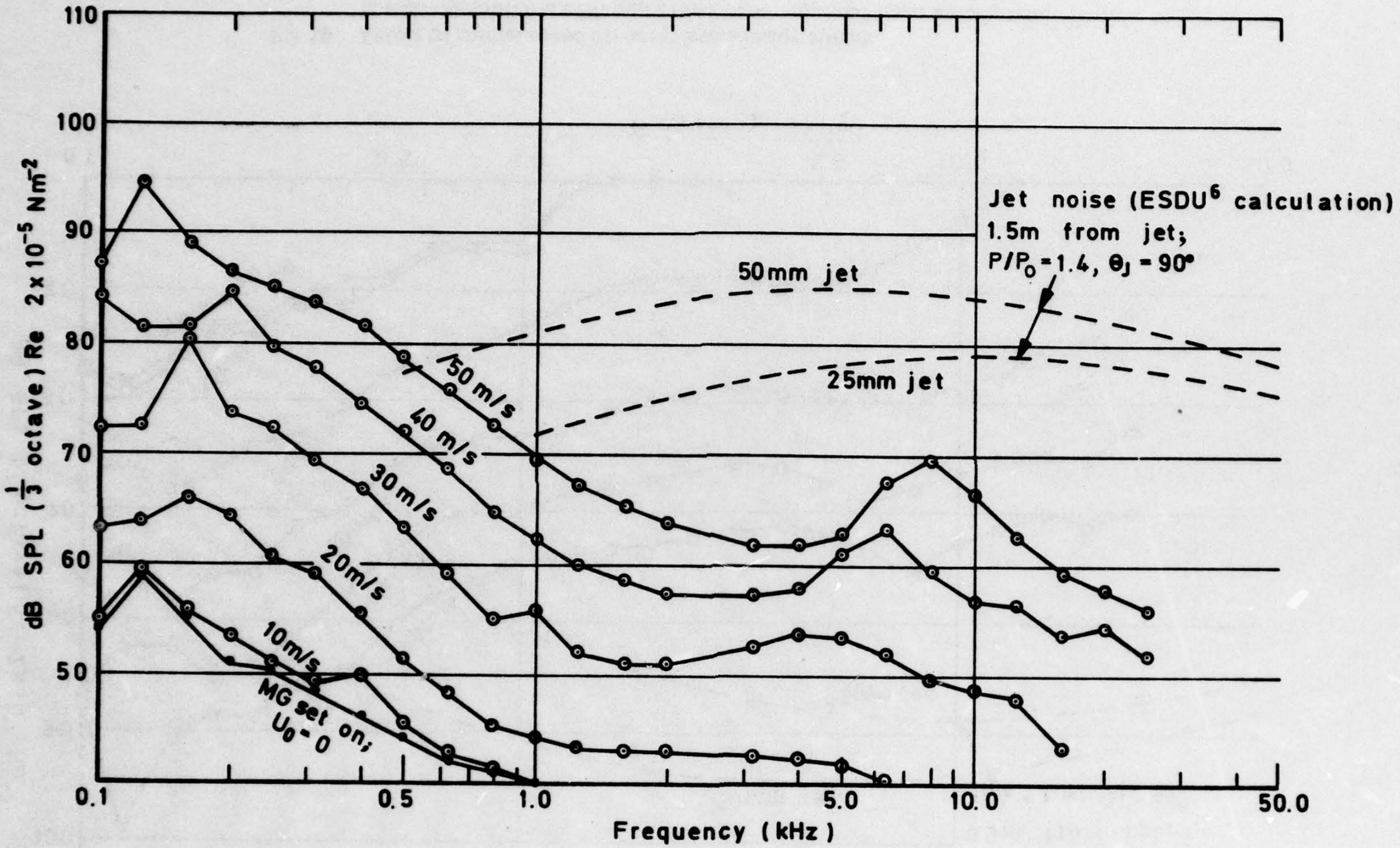


Fig 20 Effect of tunnel speed on noise levels outside stream.
¼-inch microphone with protective grill and foam windshield.
$X/R = 2.63$; $Y/R = 1.97$; $Z/R = -0.13$

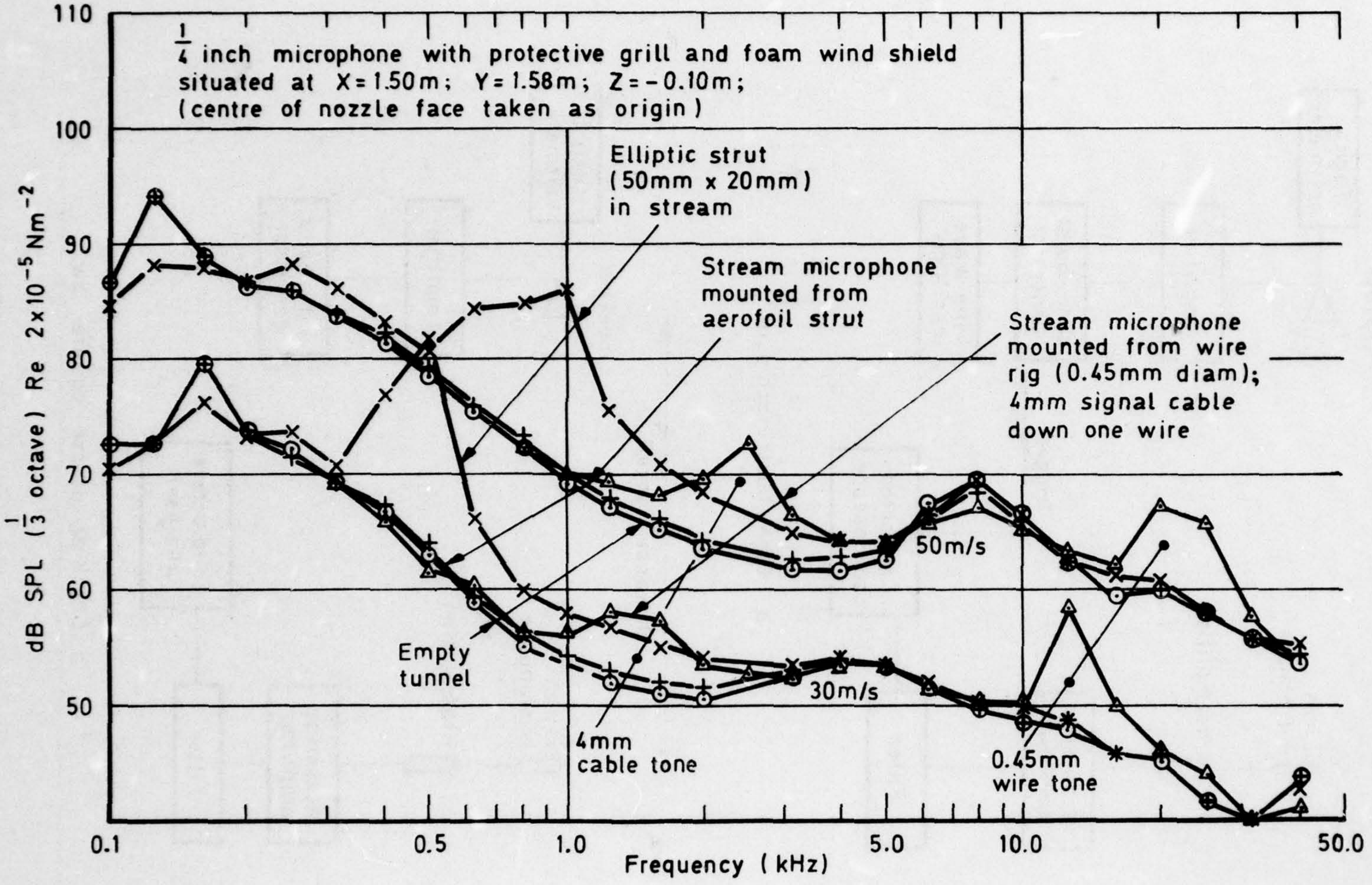
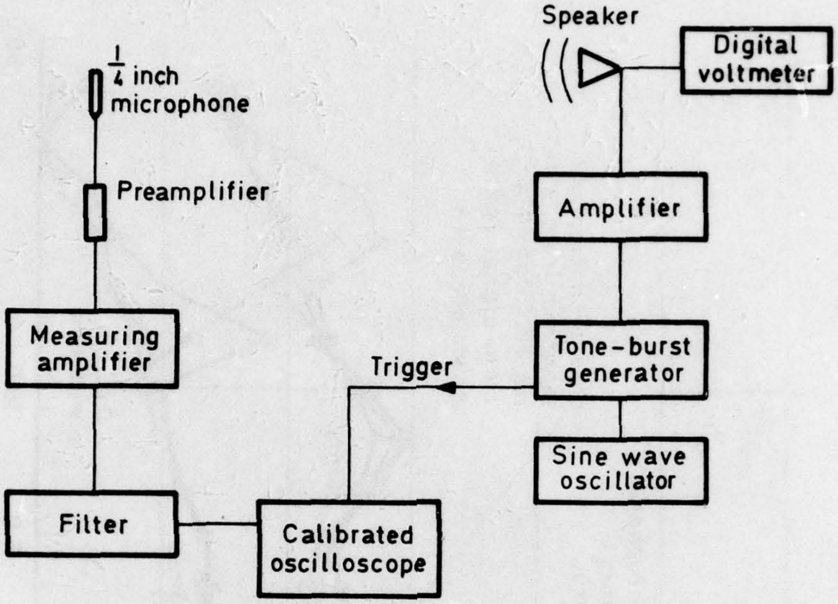
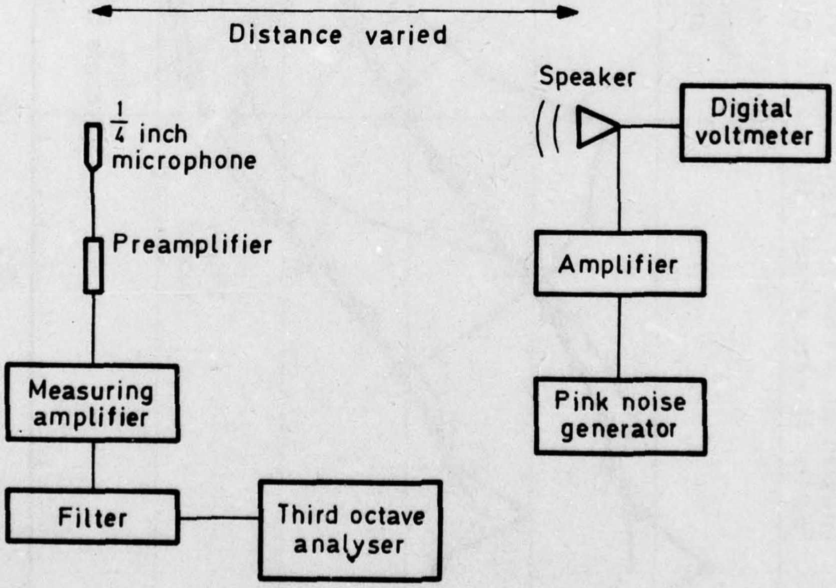


Fig 21 Noise arising from microphone support systems.
All L/F splitters in collector and return circuit; H/F splitters in return circuit only



a Tone-burst technique



b Check of inverse-square law

Fig 22 Schematic layout of equipment used for investigation of acoustic properties of anechoic chamber

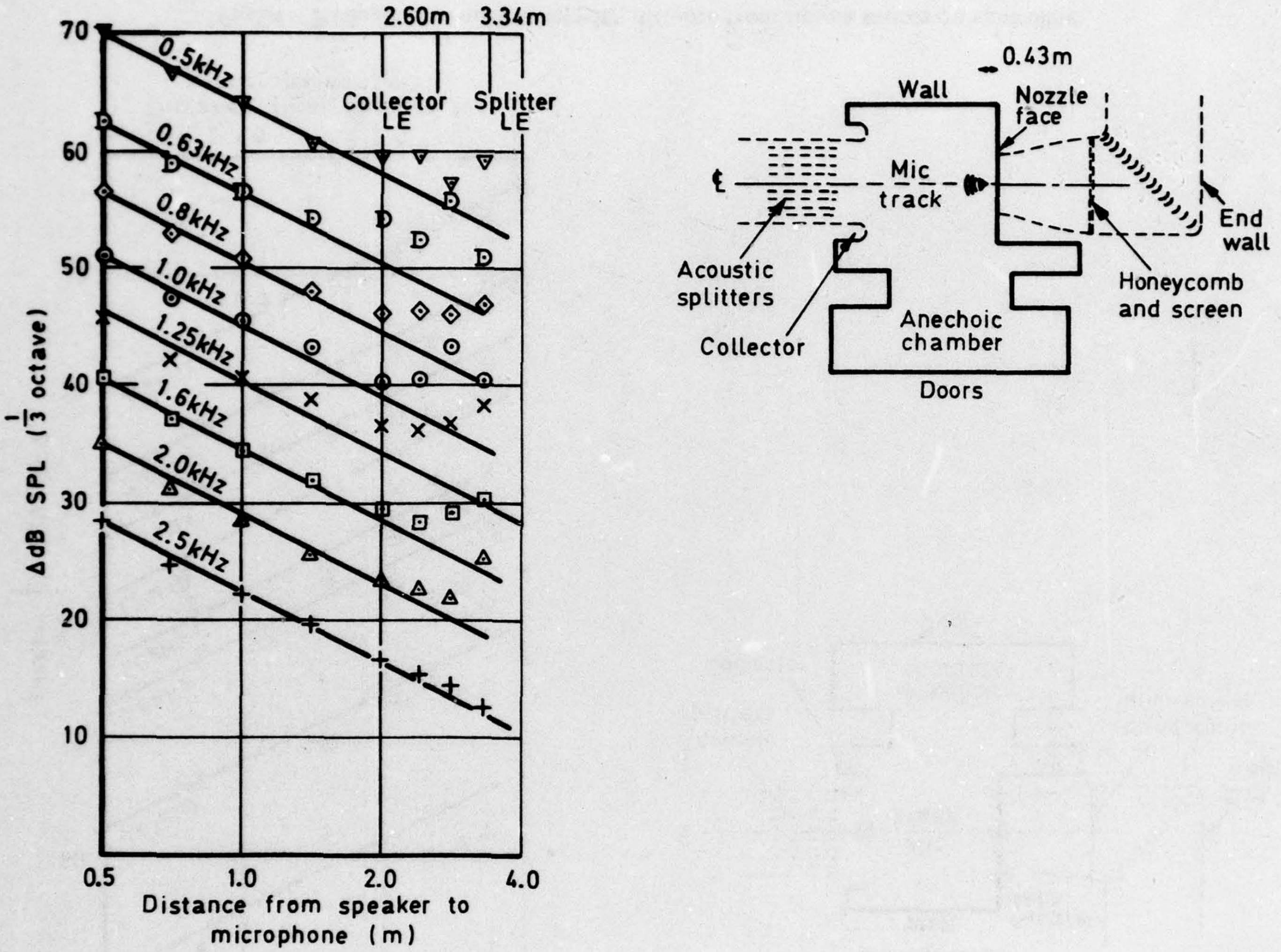


Fig 23 Reduction in noise level with distance from simple source on centreline facing collector. $U_o = 0$

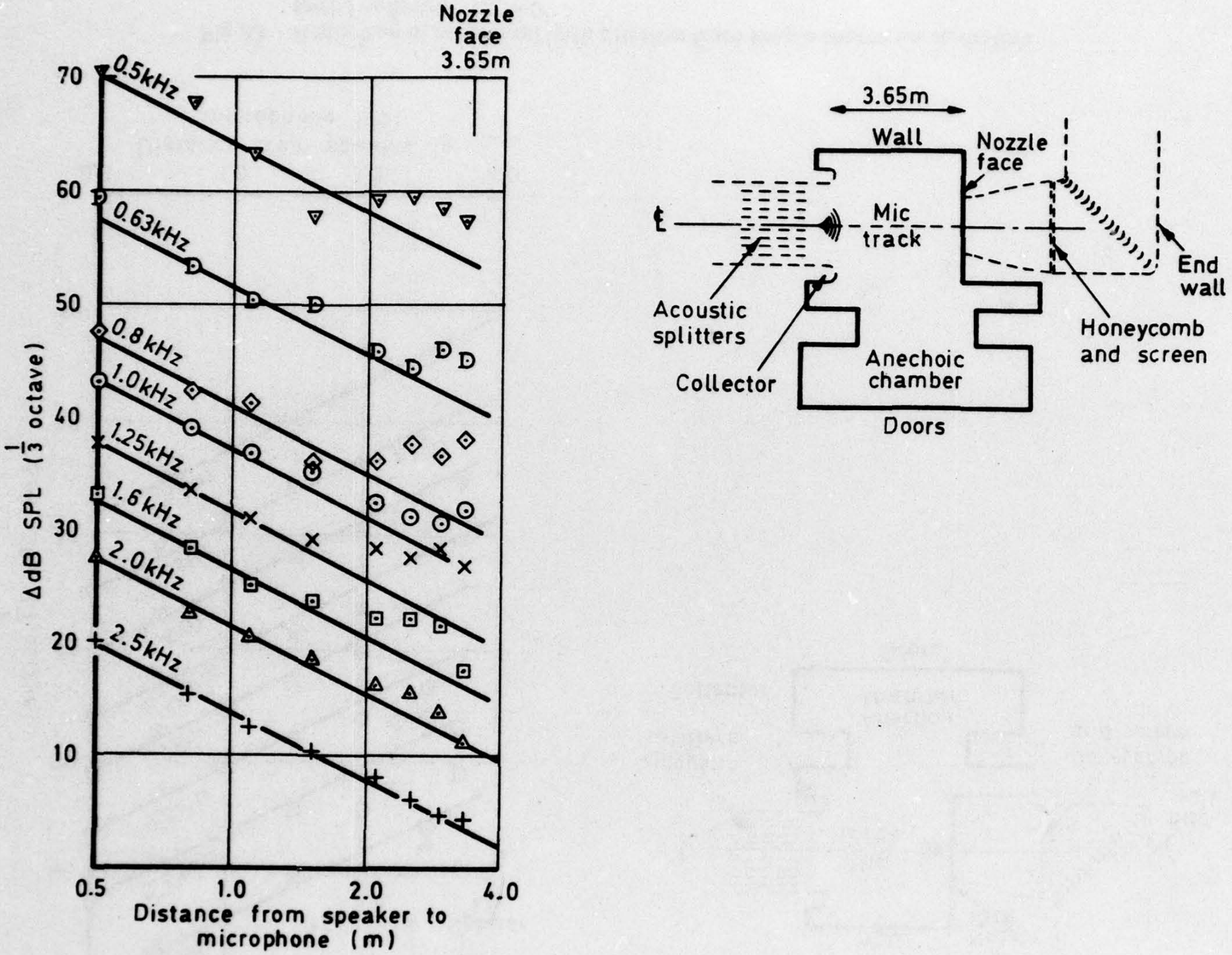


Fig 24 Reduction in noise level with distance from simple source on centreline facing nozzle. $U_0 = 0$

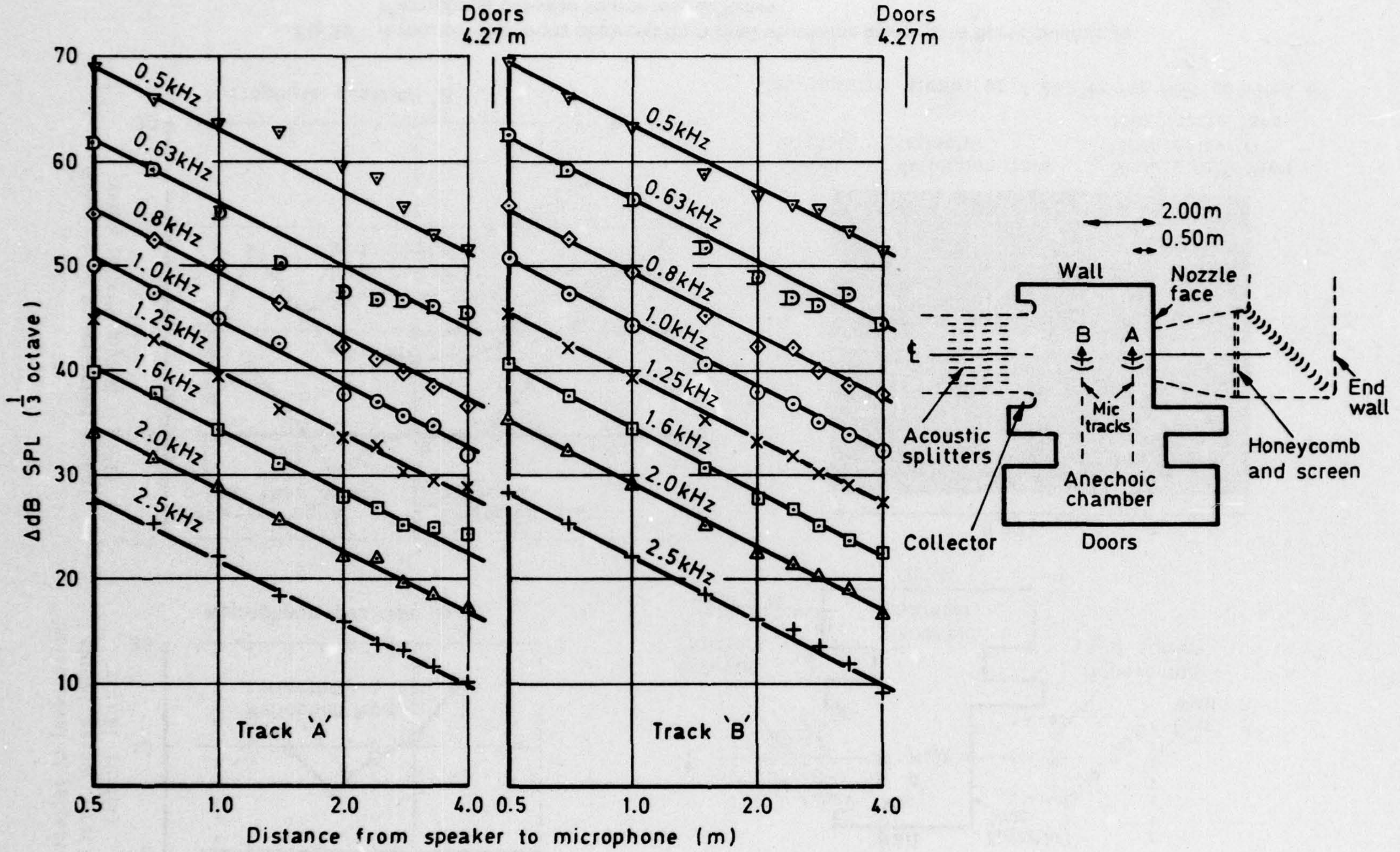


Fig 25 Reduction in noise level with distance from simple source on centreline facing across stream. $U_o = 0$

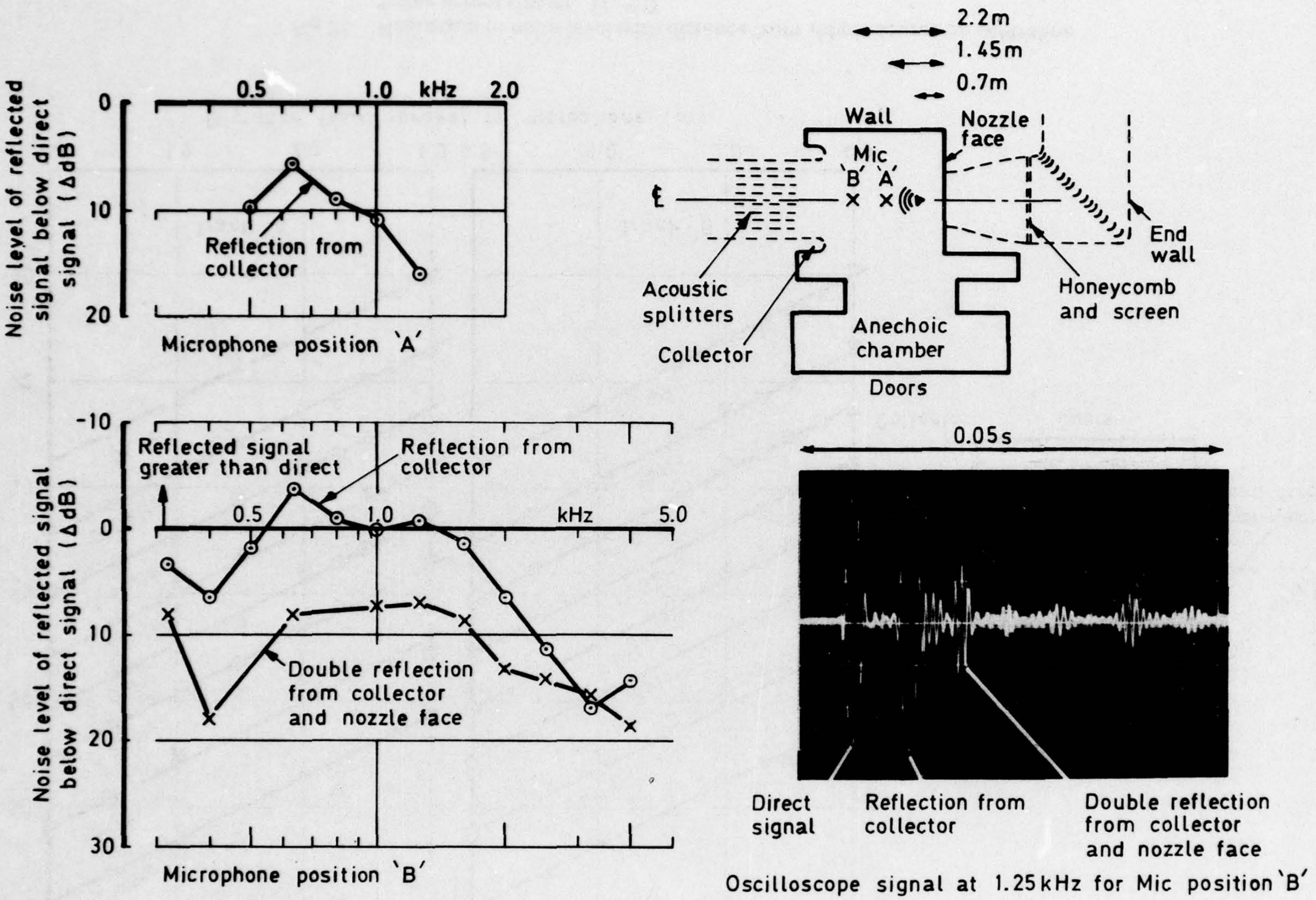
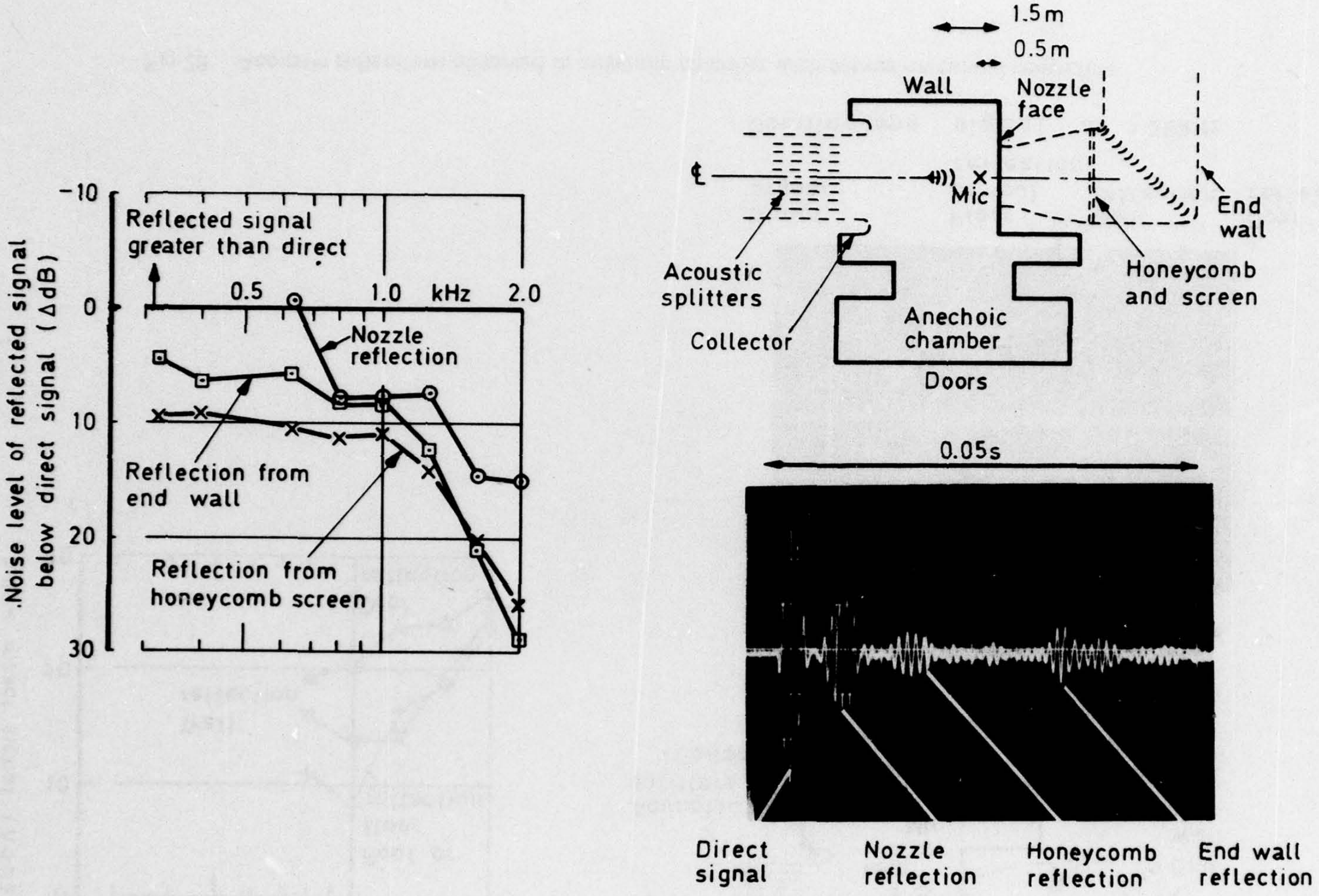


Fig 26 Acoustic reflections observed on tunnel centreline using 'tone burst' technique. Microphone between source and collector



Oscilloscope signal at 1.25 kHz

Fig 27 Acoustic reflections observed on tunnel centreline using 'tone burst' technique. Microphone between source and nozzle

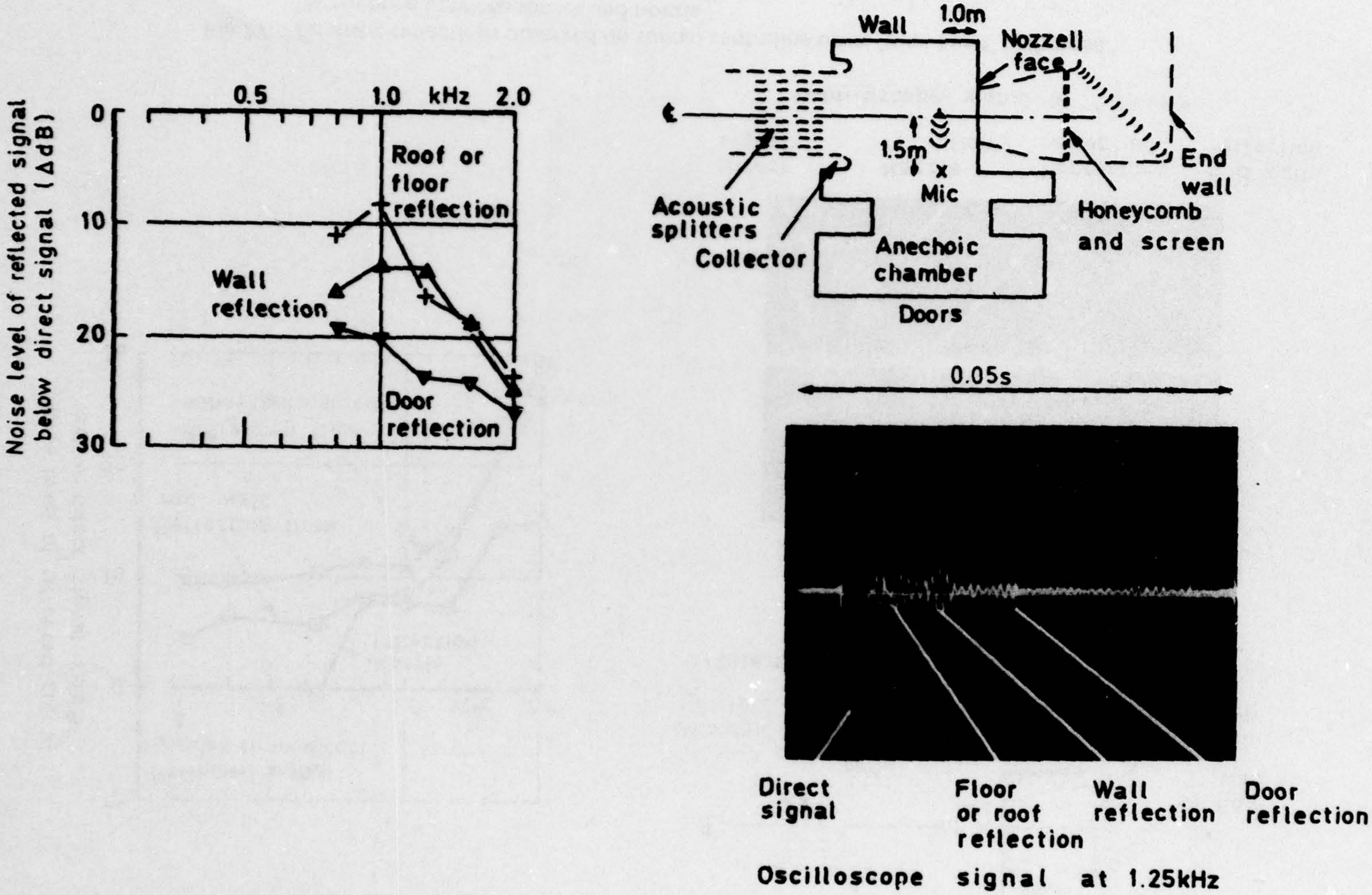


Fig 28 Acoustic reflections observed in anechoic chamber with source on tunnel centreline

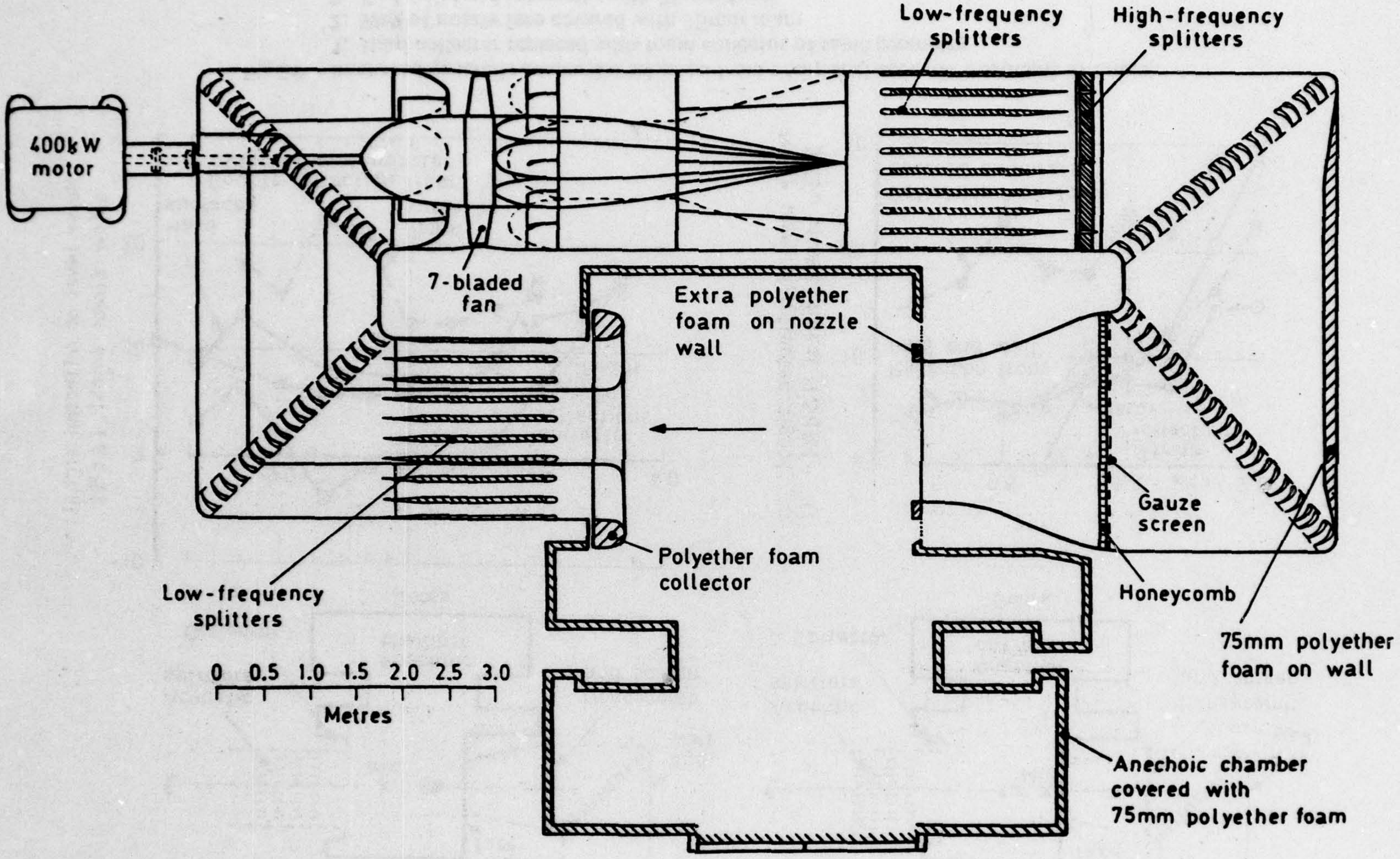


Fig 29 1.5 metre tunnel with improved acoustic treatment (compare with Fig 3)

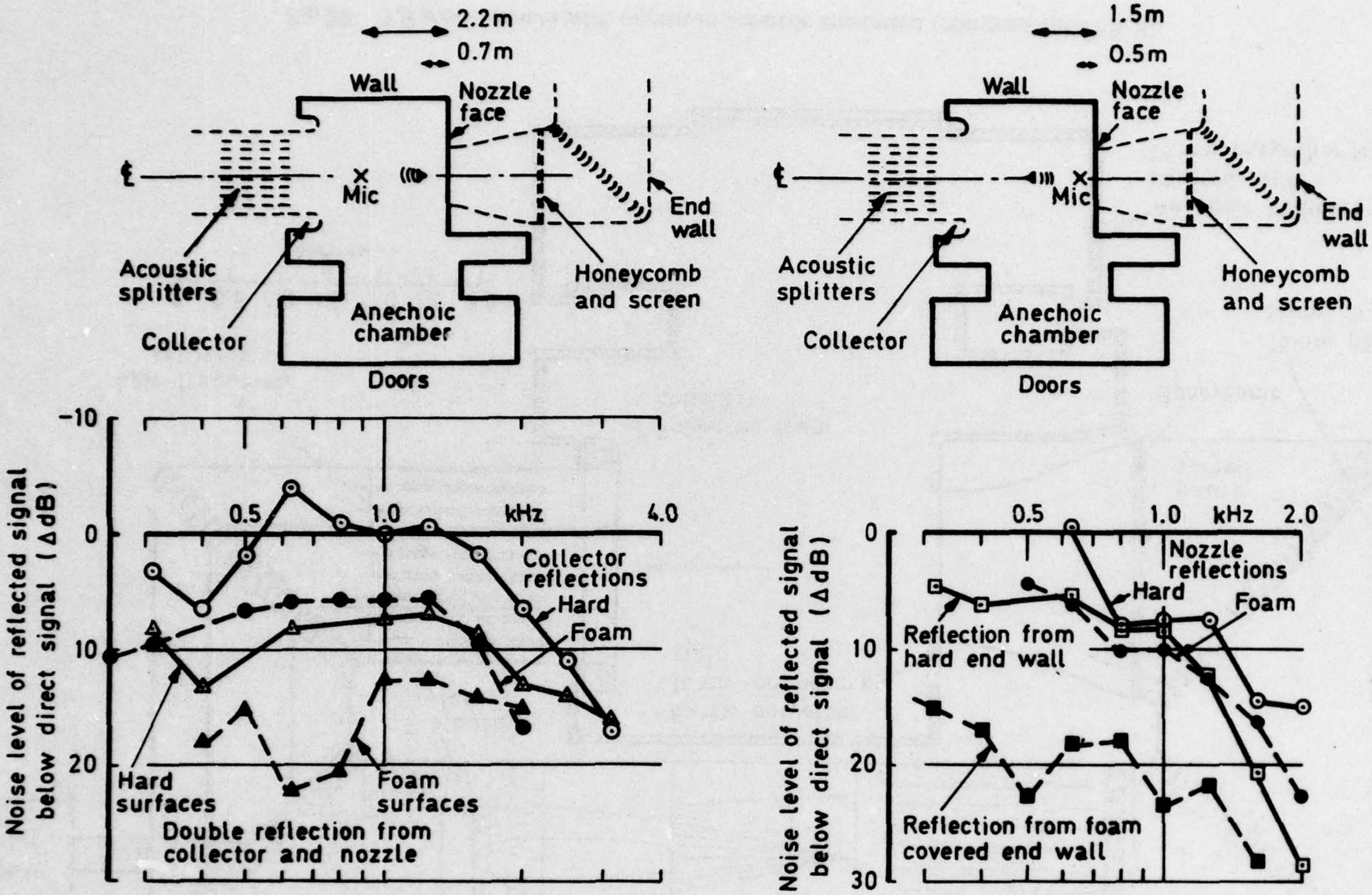


Fig 30 **Improved anechoic properties achieved from additional acoustic treatment to tunnel.**

1. **Hard collector replaced with foam collector of same geometry**
2. **Wall of nozzle face covered with 75mm foam**
3. **End wall lined internally with 75mm foam**

REPORT DOCUMENTATION PAGE

Overall security classification of this page

UNCLASSIFIED

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Acoustic tunnel. *Acoustic attenuation. Wind tunnel tests. *Noise measurement. Noise reduction.

17. Abstract

Extensive modifications to the old 5ft tunnel at RAE have provided an acoustic tunnel capable of airspeeds up to 60 m/s. The drive-fan has been replaced by a seven-bladed unit which is now mounted in the return circuit and acoustic splitters have been installed in the circuit on both sides of the fan. An anechoic chamber lined with polyether foam has been built around the test-section to give good acoustic properties at frequencies above 1 kHz. The tunnel background noise level has been reduced by more than 15 dB for frequencies below 3 kHz with less benefit at higher frequencies.

Inside the airstream at 30 m/s the noise level for third-octave bandwidths now drops from 75 dB at 1 kHz to 70 dB at 20 kHz. The noise level outside the airstream is some 5-10 dB quieter.

RAE Form A143