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The Effect of Temperature on Subsonic Jet Noise

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Summary

The noise levels produced by hot and cold subsonic jets have been measured using a convergent circular nozzle in an anechoic chamber. This report presents the effects of jet temperature on the sound power, the overall sound-pressure levels and the spectra of the jet noise.

The results show an unexpected increase in noise with increasing jet temperature at low jet velocities. The possibility of this observation arising from sources upstream of the nozzle exit is considered and discounted.

It is concluded that both the spectral shapes and the overall sound-pressure level of a hot jet are significantly affected by refraction of the sound by the jet.

The overall sound-pressure levels have been correlated to form the basis of a method for the prediction of the noise from static jets.

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* Replaces N.G.T.E.R. 331-A.R.C.35 575

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1. Introduction

The steady increase in public concern over the levels of aircraft noise since the advent of the first generation of turbojets has resulted in manufacturers making every effort to produce quieter engines. Indeed, the problem is so acute that the overall engine design is strongly influenced by noise considerations. Although the relationship between jet velocity and jet noise has been well established, there remained until the early 1970s uncertainty as to the effect of jet temperature on the noise output. In an attempt to clarify this effect, so that the jet noise prediction methods could be improved, a series of tests was conducted at NGTE during 1971 using a simple convergent nozzle run over a range of jet temperatures and with subsonic velocities down to 500 ft/s (150 m/s). At about this time, a similar test programme was carried out independently by SNECMA but the velocity range was higher and 650 ft/s (200 m/s) was the lowest jet velocity used.

The major result of the NGTE tests was that although the expected trend of a reduction in noise with heating was noted at jet velocities above 800 ft/s (245 m/s), at lower velocities than this the noise increased. Consultations with SNECMA revealed that their data showed a similar effect, and the major results of the two programmes were published in a joint paper.[1] Since that time other experimenters[2,3] have observed the same trend. The present Report presents the NGTE data in more detail than Reference 1, and discusses possible explanations for certain of the observed effects.

2. The Situation Prior to the Tests

2.1. Outline of Previous Work

As late as 1969, in a review of the status and general problem areas in jet noise research, Ribner[4] stated that 'the effect of jet temperature on jet noise needs to be resolved'. The following brief summary of work prior to the tests described here illustrates the confused situation which formed the incentive for the investigation.

The theoretical aspects had been studied by Lighthill[5] and Ribner,[6] who indicated three possible changes to the noise sources due to heating:

(a) Increasing the jet temperature at constant velocity reduces the jet density. This weakens the quadrupole source strength and hence reduces the power emitted by the jet. In fact, according to Lighthill's analysis, the acoustic power of a jet is proportional to the square of the jet mixing-region density, which can be taken as an average of the ambient and jet densities.

(b) According to the analysis by Ribner, the entropy fluctuations arising from the turbulent nature of the movement of the hot gas from the centre of the jet to the colder outside region can create noise.

(c) Further analysis by Lighthill suggested that the inhomogeneities of temperature existing in the mixing region of a jet can also be the cause of an additional source of sound because of the difference in the velocity of sound inside and outside the jet. It was argued that if this source is ever significant it is likely to affect only the high-frequency sound emanating from the heavily-sheared mixing region.

Published prediction methods showed that the reduction in noise accompanying the density change outlined in (a) was believed to be the dominating effect, but the experimental evidence was inconsistent. For instance, Rollin[7] showed no sensible change in noise even though the jet total temperature was changed by 550 K. He suggested that the reduction in noise due to the lowering of density is cancelled by some other effect which Ribner[6] argued is the increase in noise due to the entropy fluctuations. However, other work by Lassiter and Hubbard[8] on cold jets showed that when the density in the mixing region was reduced by changing the gas, larger reductions in noise were measured than would be expected from Lighthill's ρ^2 relationship. These reductions could be taken to support the argument that the entropy fluctuations only cause a cancelling effect with hot jets. Later work by Plumblee et al[9] indicated that reductions in noise do accompany jet heating and it was suggested that these could be considerable at high jet temperatures.

Data obtained from engines did not help to clarify this picture. Studies made by Howes[10] and Coles and Callaghan[11] indicated that jet temperature was an unimportant parameter but correlation work by Mawardi and Dyer[12] showed that more noise was produced by an engine than by a cold model jet at the same velocity. It was acknowledged however that other sources of noise, such as combustion, may have been influencing the measured data.

2.2. Prediction Methods

Fig. 1 shows the nature of a typical jet-noise-prediction curve at a given angle to the jet axis. The relationship between the overall sound-pressure level and the jet velocity is obtained from measurement, while the normalising parameter

$$\mathrm{OASPL}_{\mathrm{NORM}} = \mathrm{OASPL}_{\mathrm{MEAS}} - 10\log_{10}\left[\left(\frac{\rho_j}{\rho_0}\right)^{\omega} \cdot \frac{\rho_0}{\rho_{\mathrm{ISA}}} \cdot \frac{A_j}{R^2} \cdot \left(\frac{t_0}{t_{\mathrm{ISA}}}\right)^2\right] \tag{1}$$

is used to correct from the conditions in the jet and surrounding atmosphere to ISA conditions. The form of this normalising parameter is approximated in some publications, but such approximations make only slight differences to the predicted noise level for aircraft engines. The only term in this equation which is affected by jet heating is the fully-expanded jet density, ρ_j. All the factors in the normalising parameter, except for jet density, are accurately incorporated and the value of the jet-density exponent, ω, has been taken as either 1 or 2 in the literature[13–17] published prior to 1971. Bushell[16] used ω equal to unity, Hooker[17] used ω equal to 1 or 2 depending on the jet speed, while the others used ω equal to 2 even though there was considerable evidence, as mentioned in the previous Section, for a weaker dependency than this. Further support for this weaker dependency had been given in a later paper by Lighthill,[18] and by Minner[19] who had obtained better agreement between some measured and predicted noise when no dependency on density was assumed. Indeed, it seems that the only support for ω being greater than unity was the work of Lassiter and Hubbard.[8] The magnitude of the difference in the predicted noise resulting from the use of $\omega = 2$ and $\omega = 0$ (i.e. assuming no dependency on jet density) can be around 7 or 8 dB for a turbojet operating at normal conditions.

3. Test Facility and Programme

3.1. Test Facility and Rig

The configuration of the anechoic jet chamber at NGTE is given in Fig. 2. The floor area of the working chamber is 17 ft (5·18 m) square and its height from wedge-tip to wedge-tip is 15 ft (4·57 m). The wedges of glass-fibre and plastic foam lining the walls make the chamber anechoic down to approximately 250 Hz. Exhausting the hot jet flow through the hole in the roof, combined with the openings for entrained air, keep the working section at ambient conditions and allow hot jets to be run continuously.

The nozzle air supply at a maximum pressure of 3·5 atm from the compressor is heated by a novel arrangement that burns hydrogen injected into the main airstream a short distance below the point where the jet rig is positioned. Although temperatures may be limited by the rig materials, a temperature of 1200 K can readily be obtained.

The noise measurements are taken by a polar-traversing microphone controlled remotely. The analysis instrumentation allows 1/3-octave real-time analysis to be performed up to 100 kHz with the digitised levels being punched onto paper tape for subsequent computer processing. In parallel with the analyser is a high quality multi-channel tape recorder using either a frequency-modulated or direct recording system which, with suitable calibrations, can record signals accurately up to 100 kHz. To improve the accuracy of the overall sound pressure level (OASPL), especially at low angles to the jet axis where low frequency buffeting and pseudo-sound can mask the signal level, the normal procedure is to calculate it from the 1/3-octave levels at frequencies above 250 Hz rather than to use the direct measurement.

All the instrumentation and control systems for the chamber are installed in a control room situated close to the chamber and a closed-circuit television system allows visual observations of the interior of the chamber while tests are in progress.

The general configuration of the rig used for this study is shown in Figs. 3 and 4; this assembly formed the primary section of a coaxial jet rig. The plenum chamber, which incorporated a 'pepper-pot' silencer, was lined on the interior with a high-temperature sound-absorbent material to reduce any rig or upstream noise and enabled the turbulence levels at the nozzle exit to be kept to a low level. The 1·78 in. (0·045 m) diameter convergent nozzle was connected to the plenum chamber using the smooth jet-pipe illustrated.

3.2. Test Programme

The test programme was conducted within a velocity range from 500 ft/s (150 m/s) to 1250 ft/s (380 m/s) and at jet total temperatures from 300 K to 900 K. Testing was restricted to subsonic jet Mach numbers to avoid shock or shock-associated noise. The noise measurements were taken at equal logarithmic intervals of jet velocity and at temperatures of 300 K, 500 K, 700 K and 900 K.

At each test condition the microphone was traversed around the jet from 15 to 120 degrees to the jet axis at a distance of 7·08 ft (2·16 m) from the nozzle exit. The microphone used was a Bruel-and-Kjaer 1/2 in. free-field type. The real-time analyser was set to cover the frequency range from 250 Hz to 40 kHz and in the subsequent data analysis, appropriate corrections were made for atmospheric attenuation and microphone non-linearity. The corrections ranged from zero at the lowest frequencies to no more than 3 dB at 40 kHz.

In addition to the separate calibration of the electronic analysis equipment, calibrations of the complete system were carried out at regular intervals during testing, using both Bruel-and-Kjaer and variable-level Hewlett-Packard pistonphones.

The aerodynamic parameters at the nozzle exit were calculated using the measured plenum conditions and as all tests were at subsonic Mach numbers the nozzle-exit static pressure was assumed to be equal to the barometric pressure. Confidence in the use of the plenum pressure was confirmed by checks on the total pressure at the nozzle exit.

At low jet velocities, over-heating of the burner tubes occurred at first but this problem was eliminated by fitting a restrictor plate just below the burner to increase the air velocity over the tubes.

4. Results and Discussion

4.1. Overall Power and 1/3-Octave Power Spectra

Although a knowledge of the acoustic power (PWL) of an air jet is not of direct use in the prediction of aircraft noise, it is an extremely useful analytical parameter since it is independent of factors such as refraction and scattering which alter the directivity of the sound without changing the energy emitted by the source.

Fig. 5 shows how the power varies with jet velocity at various jet total temperatures. The most interesting and surprising result is that at velocities below 800 ft/s (245 m/s) there is a progressive increase in power with increasing total temperature. The reduction in noise at the higher velocities follows the expected trend based on the concept of a density reduction weakening the quadrupole source strength. It would be expected, based on this model, that reductions in noise with jet heating should occur at all jet velocities; consequently the increase in noise power that occurs at the lower velocities implies that modifications are needed to the quadrupole model produced by Lighthill.

It is considered that the noise produced at all temperatures and velocities originates in the mixing region of the jet and that it is not associated with rig or other internal noise sources. Evidence supporting this belief will be presented in Section 5.

The 1/3-octave power spectra at velocities of 500, 700 and 1000 ft/s (150, 215 and 305 m/s) are shown in Figs. 6, 7 and 8. The increase in power with increasing temperature at 500 ft/s (150 m/s) can be seen to occur at all frequencies with the increase at the peak noise frequencies being the most marked. As the jet temperature increases, the peak frequency shifts to a lower value, the shift being approximately two 1/3-octaves when the jet total temperature changes from 300 K to 900 K. When the velocity is increased to 700 ft/s (215 m/s) the low frequency noise levels become less dependent on jet temperature, while the high frequency 1/3-octave power levels now reduce with heating. These trends continue as the jet velocity is increased to 1000 ft/s (305 m/s) and, as Fig. 8 shows, the levels of the low and peak frequencies are now independent of jet temperature while considerable reductions with heating occur at the high frequencies.

These spectra also show that when a jet is heated at constant velocity the high-frequency noise levels reduce relative to the levels at the peak frequencies and the reductions become larger as the temperature is increased. This effect is observed at all the jet velocities tested.

4.2. Field Shapes

If the changes in the noise power observed with jet heating arose only from modifications to the strength of an omnidirectional source, then equal variations in the noise levels would be expected at all points in space, even though source convection produces a non-spherical directivity pattern. Although the similarity of the field shapes at 500 ft/s (150 m/s) shown on Fig. 9 could be explained on such a basis, Figs. 10 and 11 show that it cannot be generally true. Consider for example Fig. 11, which refers to 1000 ft/s (305 m/s) velocity. There is a reduction in the OASPL of approximately 5 dB at 15 degrees to the jet axis when the temperature is raised from 300 K to 900 K, while no change in level is observed around 60 degrees. Clearly an effect other than a change in the strength of an omnidirectional source is needed to explain this observation. Such an effect could arise either from acoustic-aerodynamic effects (e.g. refraction and scattering) and/or from a change in the strength of a directional source.

At present it is extremely difficult to state categorically which of the possible acoustic-aerodynamic interaction effects has the main influence. But experiments conducted with a small sound source placed in the mixing region of a jet at various temperatures has shown that refraction of the sound is considerable.

The expected effect of refraction is to lower the noise levels at narrow angles to the jet axis in the rear arc and to reinforce the levels at the higher angles, and this is consistent with the observation on Fig. 11.

Although refraction, or other interaction effects may explain the difference in the observed field shapes it is necessary to discuss the noise changes that occur with jet heating in more detail to determine if they arise from changes to the strength of any lateral quadrupoles that are present.

At a jet velocity of 700 ft/s (215 m/s) (Fig. 10) there is no significant change in the OASPL with heating at either 90 or 15 degrees to the jet axis but an increase is noticed at approximately 45 degrees. It is difficult to decide what causes this change; but the data at a jet velocity of 1000 ft/s (305 m/s), shown on Fig. 11, suggest strongly that refraction is a predominant factor: at this velocity, the large reductions in noise level with heating at small angles to the jet, appear to be reinforcing the noise levels at the wider angles to such an extent that they become independent of the jet temperature. The slight reduction in noise level with heating at 90 degrees at 1000 ft/s (305 m/s) would be expected since there is a slight reduction in noise power with jet heating at this velocity. Indeed, it is generally true that the changes in the noise levels with jet heating at 90 degrees are consistent with the changes in the noise power at the same jet velocity (*see* Fig. 5). Figs. 9, 10 and 11 also show that the field-shape distortion increases with increasing velocity as the jet is heated—another effect expected of refraction. The distortion is sufficient to move the angle at which the peak noise occurs from approximately 20 degrees for a cold jet to 30 degrees for a hot jet at 1000 ft/s (305 m/s).

4.3. Overall Sound Pressure Levels

The variation of the OASPL with jet velocity at jet angles of 90, 45 and 15 degrees are shown in Figs. 12, 13 and 14. At 90 degrees, as has already been noted, the variation in the OASPL with temperature is similar to the variation in the PWL; the increase in noise at the lower velocities due to heating and the reduction at the higher velocities being clearly shown. At this angle, the average velocity exponent over the jet velocity range from 500 to 1000 ft/s (150 to 305 m/s) decreases with heating from a value of 7·5 for cold air to 5·5 at 900 K.

At 45 degrees to the jet axis, the noise at the higher velocities becomes independent of jet temperature. Hence at these velocities the velocity index is constant, having a value of 8·5. The increase in the index at this angle from the 90 degree value is to be expected from the effect of convective amplification. At the lower velocities, however, the increase in noise with jet heating produces a different velocity index at each temperature; with the value changing from 8·5 at 300 K to 6·0 at 900 K.

At 15 degrees to the jet axis (Fig. 14) large reductions in noise with increasing temperature occur at the higher velocities; at 1000 ft/s (305 m/s) there is a reduction of 4·5 dB when the temperature is raised from 300 K to 900 K, although no change in noise level with heating is observed at 45 degrees. Again, jet heating changes the velocity index at 15 degrees and the value of 9·0 at 300 K falls to approximately 6·0 at 900 K.

A comparison of the data at 45 and 15 degrees on Figs. 13 and 14 respectively highlights the changes in noise level observed in the field shapes. The contention that refraction is significant in heated jets is supported by the observation that at high velocities much larger reductions in noise with heating occur at 15 than at 90 degrees where they are thought to be due mainly to source strength changes.

4.4. 1/3-Octave Spectra

The 1/3-octave spectra for jet velocities of 500, 700 and 1000 ft/s (150, 215 and 305 m/s) are shown in Figs. 15 to 23 and these show that the spectral shape alters significantly at a given angle when a jet is heated. Not only, as has already been discussed, are the changes in the field shape dependent on jet temperature and jet velocity in a manner which is consistent with refraction, but the spectra also show an effect with increasing frequency which is consistent with refraction.

At a jet velocity of 500 ft/s (150 m/s) the peak noise levels at all angles show similar increases with increasing jet temperature. The main observation at this velocity, however, is that the high frequency levels, although showing an increase with heating at 90 degrees, actually fall with respect to the cold datum as the angle moves towards the jet axis where large reductions in level are noted. The net result is an increase in the power spectrum levels as shown in Fig. 6.

When the jet velocity is increased to 700 ft/s (215 m/s)—where the sound power level is nearly independent of the jet temperature— the increases in noise level with heating at the low and peak frequencies are greater at 45 degrees than at 90 degrees or 15 degrees. The high frequencies reduce in level at all angles with jet heating, the reductions becoming progressively larger as the jet axis is approached.

Figs. 21, 22 and 23 for 1000 ft/s (305 m/s) show that within the experimental scatter there are reductions of varying magnitude at the angles and frequencies shown except at the low and peak frequencies at 45 degrees to the jet axis.

Again, it is considered that the general character of the results described above can be explained in terms of refraction. The factors governing the spectral levels differ at low and high frequencies and hence these two regions will be discussed separately.

It can be seen from the spectra (particularly at 1000 ft/s (305 m/s)) that noise reductions with heating at low angles and at the low frequencies are accompanied by increases at 45 degrees. Such an effect is symptomatic of refraction. As a result of convective amplification there is a progressive increase in the low frequency noise levels as the jet angle reduces from 90 degrees to 15 degrees, hence any refraction is from a high energy to a lower energy region. Because of the use of the logarithmic energy scales, a small change in noise level at the narrow angles can considerably reinforce those at the wider jet angles.

The directivity of the high-frequency noise is, however, very different to that at the low frequencies. As expected, the noise levels of the cold air jets at high frequencies are lower at 15 degrees to the jet axis than at the wider angles. The reason for this high-frequency 'cut-off' is not clear from published literature: refraction is thought to have a prominent effect according to Ribner,[6] but Lush[21] concludes that it results from a lack of convective amplification. It is possible to attribute the further reductions in high-frequency noise with jet heating to a strengthening of the effect described by Lush, but as there seems to be considerable refraction of the low frequency sound, it is to be expected that even stronger effects would be observed at the higher frequencies. The 'cut-off' characteristic ensures that refraction of the high-frequency sound in a hot jet is always towards a region of higher energy and the use of the decibel scale means that the redirected energy will not significantly affect the much higher noise levels at the wider jet angles. Hence, at the high frequencies, it appears that although the lack of convective amplification is playing an important part in explaining the observed behaviour for cold jets, the changes due to jet heating can be explained qualitatively by refraction alone and an extrapolation of the low-frequency refraction effects tends to support this explanation.

5. The Question of Internally-Generated Noise

The surprising observation from the experiments described here that at low velocities there is an increase in both the PWL and the OASPLs with increasing temperature, raises the question of whether the effect could arise from the hydrogen-burning air heater. The following four pieces of evidence are cited in support of the belief that the combustion noise is insignificant:

(a) Because of overheating problems in the early test runs, an annular restrictor plate was fitted immediately below the burner so that, for a given mass flow, the velocity over the burner grids was increased by a factor of four. A typical example of the spectra produced is shown on Fig. 24 for a jet velocity of 500 ft/s (150 m/s) and temperature of 500 K. It can be seen that when the restrictor plate is in position the changes in spectrum levels are insignificant compared to those due to jet heating.

(b) Fig. 22 shows an increase in the low-frequency noise with increasing temperature at a jet velocity of 1000 ft/s (305 m/s) and although the levels at this angle (45 degrees) are believed to be reinforced by refraction from the lower angles, it is unlikely that 1/3-octave levels of nearly 100 dB could arise from burner noise propagating through the silencer. It is estimated[22] that the silencer should reduce the upstream noise by at least 20 dB in the 1 to 2 kHz frequency range. Hence, without silencing, the far-field levels would have to be 120 dB in each 1/3-octave band around the 1 to 2 kHz frequency range if the burner was responsible for the low-frequency noise. In the light of existing data on combustion noise this is extremely unlikely.

(c) The field shape at 500 ft/s (150 m/s) (Fig. 9), shows that approximately the same increase in OASPL is noted at 90 degrees as at 30 degrees when the temperature is increased to 900 K. This indicates that the noise levels of the hot jet and the cold jet are receiving the same convective amplification (the convective amplification from 90 degrees to 30 degrees is 6·5 dB for the cold jet). It appears inconceivable that the combustion noise sources could exhibit convective amplification that could be detected in the far-field since the silencer and plenum chamber would act as a diffuser of sound. The existence of convective amplification shows that the noise is produced by a moving source and hence the agreement between the hot and cold field shapes indicates that the noise-generating mechanisms are similar.

(d) Further evidence of the lack of combustion noise was obtained when tests were performed with an electrical heater replacing the hydrogen burner. This heater was constructed by inserting elements of the 'immersion heater' type into a steel box 4 ft (1·22 m) in length and 2 ft by 2 ft (0·61 m by 0·61 m) in cross-section. The large cross-sectional area of the heater ensured low velocities over the elements—about 1/200 of the jet velocity—so that the noise generated from this source was negligible. The limited temperature rise from this heater only allows comparison with the hydrogen burner at 500 K and 500 ft/s (150 m/s) jet velocity. But, as Fig. 25 shows for jet angles of 15 degrees and 90 degrees, the changes in the noise levels are very similar for each heater.

The evidence outlined above strongly supports the view that the observed increases in noise are not associated with combustion but originate within the jet mixing region.

6. Normalisation of PWL and OASPL

Since the test environment is near ISA sea level conditions, the form of the normalising parameter given in Section 2.2 can be closely approximated by

$$\mathrm{OASPL_{NORM}} = \mathrm{OASPL_{MEAS}} - 10\log_{10}\left[\left(\frac{\rho_j}{\rho_{\mathrm{ISA}}}\right)^{\omega}\frac{A_j}{R^2}\right]. \tag{2}$$

At each velocity and angle to the jet axis, the value of the density exponent can be calculated from a re-arrangement of the above equation to

$$\omega = \frac{\mathrm{OASPL_{HOT}} - \mathrm{OASPL_{COLD}}}{10\log_{10}(\rho_{j\mathrm{HOT}}/\rho_{\mathrm{ISA}}} \tag{3}$$

since the cold jet conditions are close to the ISA values. In some publications ρ_{ISA} is substituted by ρ_0 but the use of either value is acceptable.

Fig. 26 shows how the value of ω varies for the PWL and for the OASPL at 90 and 15 degrees. The density exponent required to correlate the data can be seen to depend on both the velocity and the angle to the jet axis, with the effect of refraction at the higher velocities at 15 degrees to the jet axis increasing the value of ω above that at 90 degrees. A negative value of ω is obtained over the velocity range where heating the jet increases its noise.

Fig. 27 shows the measured levels for the PWL and for the OASPL at 15 and 90 degrees normalised by using the value of ω taken from the lines drawn through the data on Fig. 26. These results show that, within a reasonable experimental scatter, the definition of a density exponent varying with velocity is an effective means for normalising hot jet data at any one angle. This does not, or course, necessarily imply that the noise generation is controlled by the jet density changes when a jet is heated at constant velocity but only that jet density is a convenient correlating parameter for prediction purposes. Although refraction causes the density exponent to vary with direction, this effect is only significant at low angles to the jet axis and it can be shown that taking the average value of ω from 30 to 120 degrees, a close approximation of the density exponent is given by

$$\omega = 4{\cdot}6\log_{10}\left(\frac{V_j}{a_0}\right) + 0{\cdot}44 \tag{4}$$

7. Concluding Remarks

It has been observed from these measurements of jet noise at subsonic Mach numbers that the effect of jet density differs from that previously believed. The results have shown the expected reductions in noise power with reducing density at velocities above 800 ft/s (245 m/s), but they have also demonstrated the existence of a low velocity regime in which heating at constant velocity increases the acoustic radiation from a jet. This latter effect is evident mainly at the low and peak noise frequencies.

In arriving at this finding, the author is fully aware of the danger of being misled by the presence of extraneous noise sources in the jet rig. However, considerable care has been exercised in the rig design and this, together with the measurements obtained from additional special tests and the recently published reports,[2,3] has supported the validity of the data.

Recent analytical work on the noise from heated and unheated jets by Lush and Fisher[2] suggests that the noise depends on Lighthill's[5] original V_j^8 component which decreases in strength when the jet is heated, together with a V_j^4 component which increases in noise output with increasing temperature. Their simple theoretical arguments to support the analysis are based on the suggestion by Ribner[6] that entropy fluctuations may be important in heated jets. On the other hand, recent theoretical work by Morfey[23] using Lighthill's acoustic analogy shows that convected variations of compressibility or density, on a scale which is small compared with a typical acoustic wavelength, can scatter hydrodynamic pressure fields of a similar scale and thus radiate sound. Morfey's analysis predicts a V^6 dependency for low Mach number jets if the jet fluid differs in density from the surrounding fluid.

In addition to these theoretical studies, work by Mani[24] suggests that the radiative efficiency of a moving source due to the mismatch of the velocities, densities and temperature inside and outside the jet has an important part to play in explaining the observed trends. Clearly, further work is needed to clarify which of these competing models produces the correct explanation.

It is also concluded from the work described here that the basis of an improved prediction method for jet noise can be formulated by defining a velocity-dependent function of the jet density. Such a method has recently been detailed.[25] However it should be emphasised that the proposed density correlation may well only hold for heated jets and may not be applicable when using gases of different density.

The results not only show how the noise power of the jet is affected by heating but also indicate that the spectral shapes and hence the OASPLs are changed by jet refraction. Indeed, the resulting effects give strong support to the view that the position of the peak in the polar field shape for hot subsonic jets arises from refraction and not from a lateral quadrupole distribution.

LIST OF SYMBOLS

PWL	Total acoustic power
OASPL	Overall sound pressure level
SPL	1/3-octave sound pressure level
A_j	Jet nozzle area
a_0	Speed of sound in ambient air
$\mathrm{OASPL}_{\mathrm{NORM}}$	Normalised overall sound pressure level
$\mathrm{OASPL}_{\mathrm{MEAS}}$	Measured overall sound pressure level
$\mathrm{OASPL}_{\mathrm{COLD}}$	Measured overall sound pressure level from cold jet (at nominally ISA conditions)
$\mathrm{OASPL}_{\mathrm{HOT}}$	Measured overall sound pressure level from hot jet
R	Microphone measuring distance from centre of jet exit
t_0	Temperature of ambient air
V_j	Jet velocity, fully-expanded condition
ρ_0	Density of ambient air
ω	Exponent of density ratio
ρ_j	Jet density, fully-expanded condition
$\rho_{j\mathrm{HOT}}$	Density of a hot jet, fully-expanded condition
ρ_{ISA}	Density of air at ISA conditions = $0{\cdot}0765$ lb/ft^3
θ	Angle to jet axis
T	Jet total temperature

Suffices

0	Ambient
j	Jet
ISA	International Standard Atmosphere conditions

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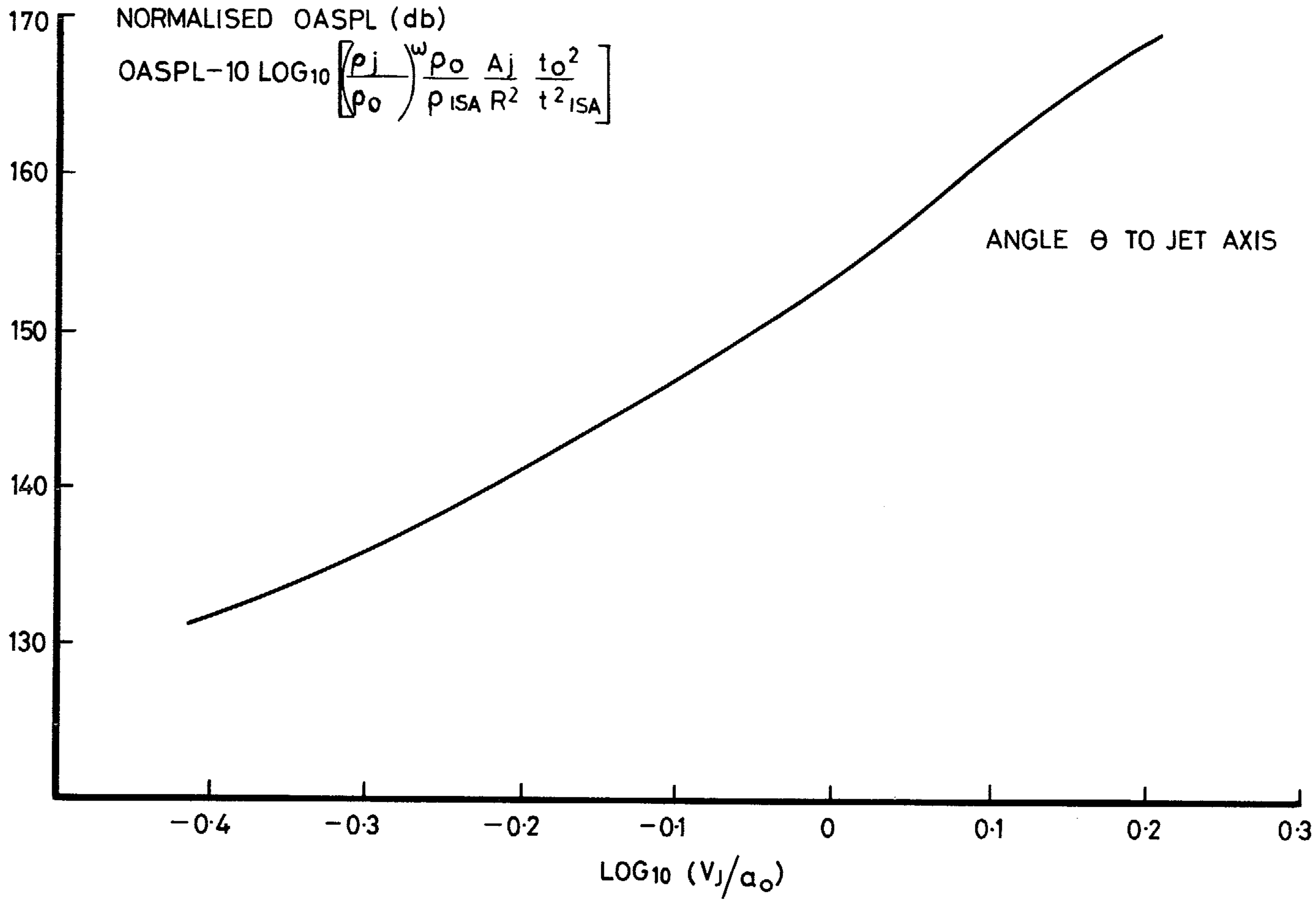

FIG. 1. Typical polar jet noise prediction curve.

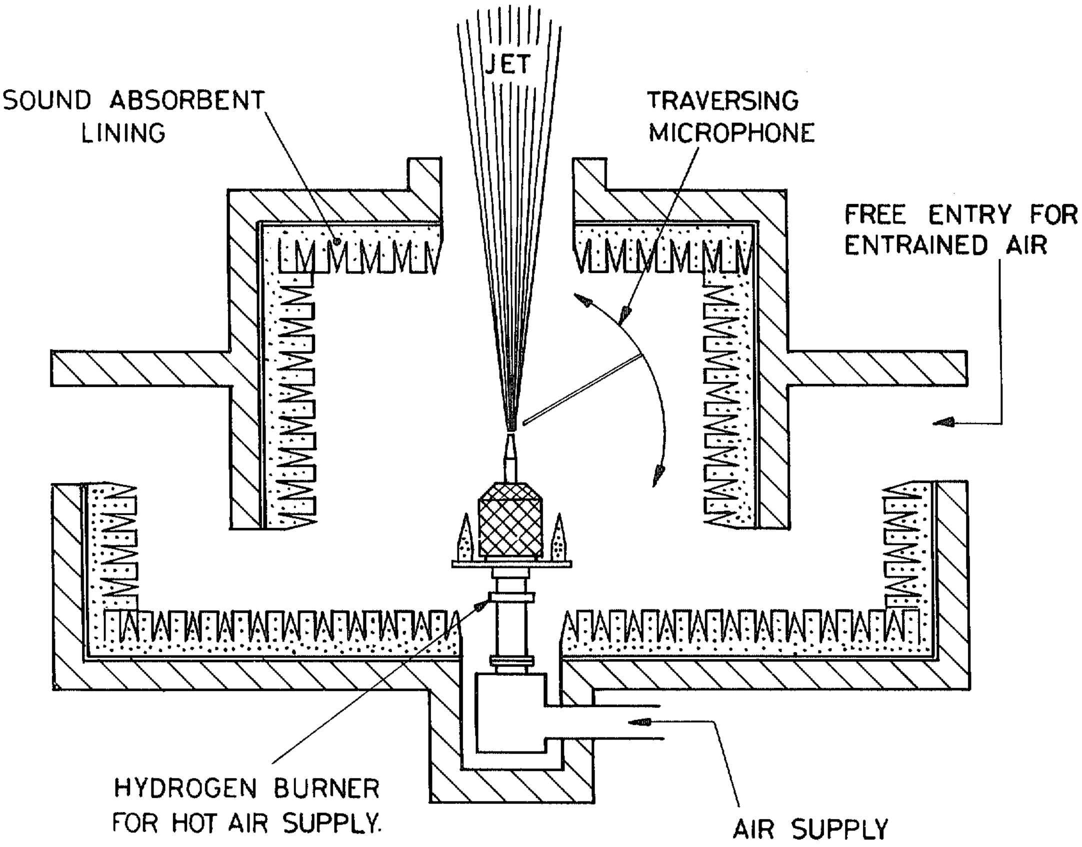

FIG. 2. Anechoic chamber section.

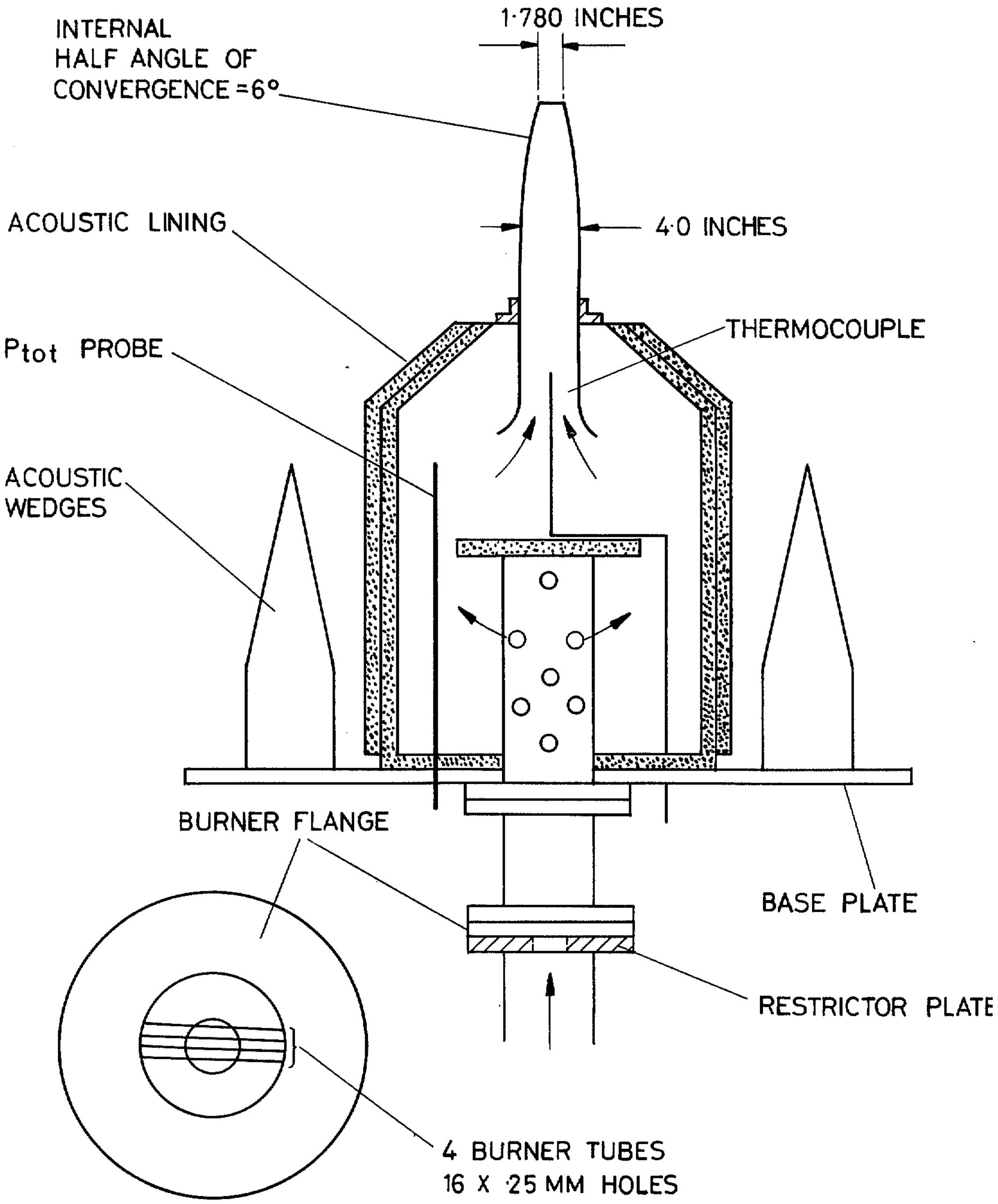

FIG. 3. Nozzle and silencer assembly.

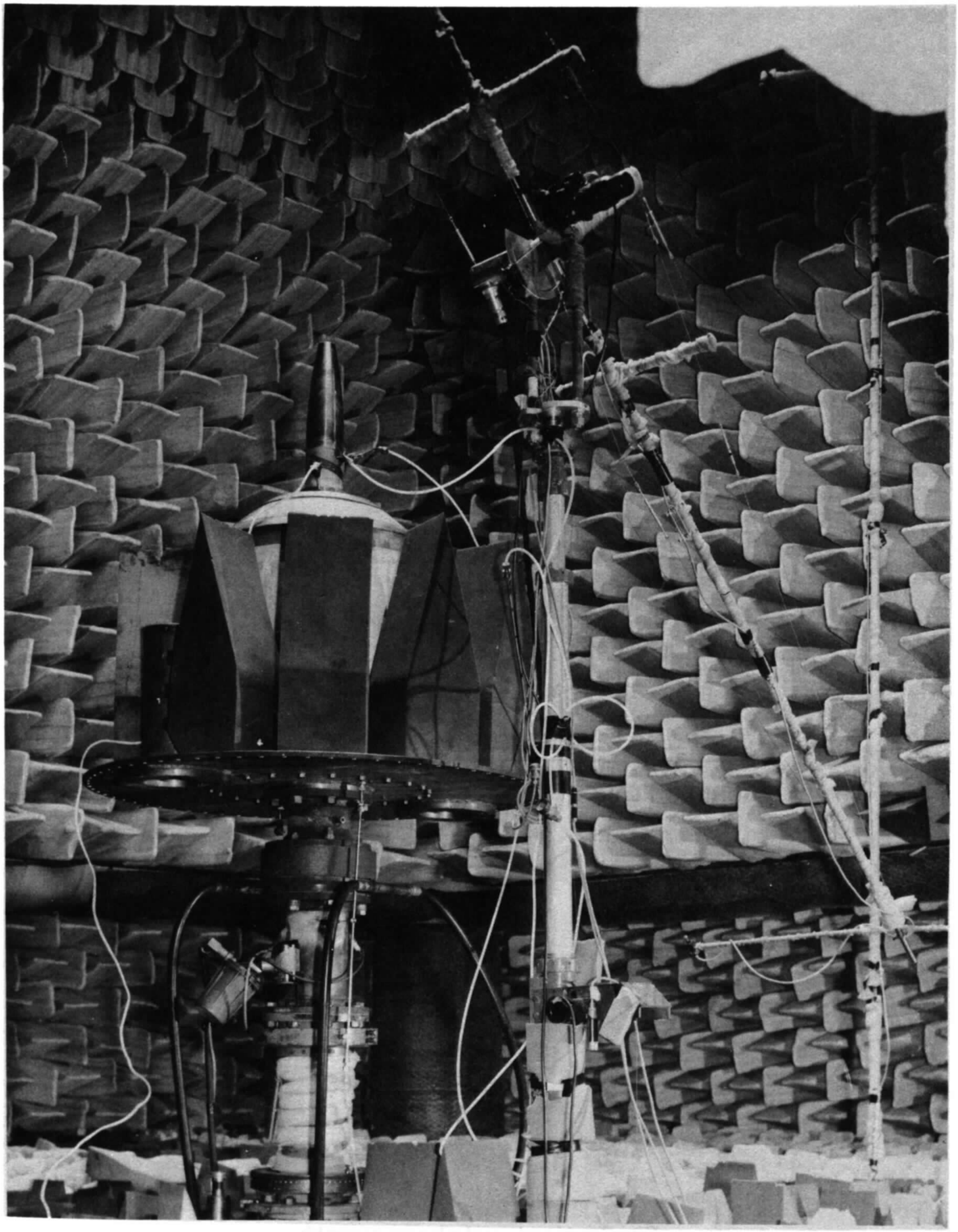

FIG. 4. Jet rig in anechoic chamber.

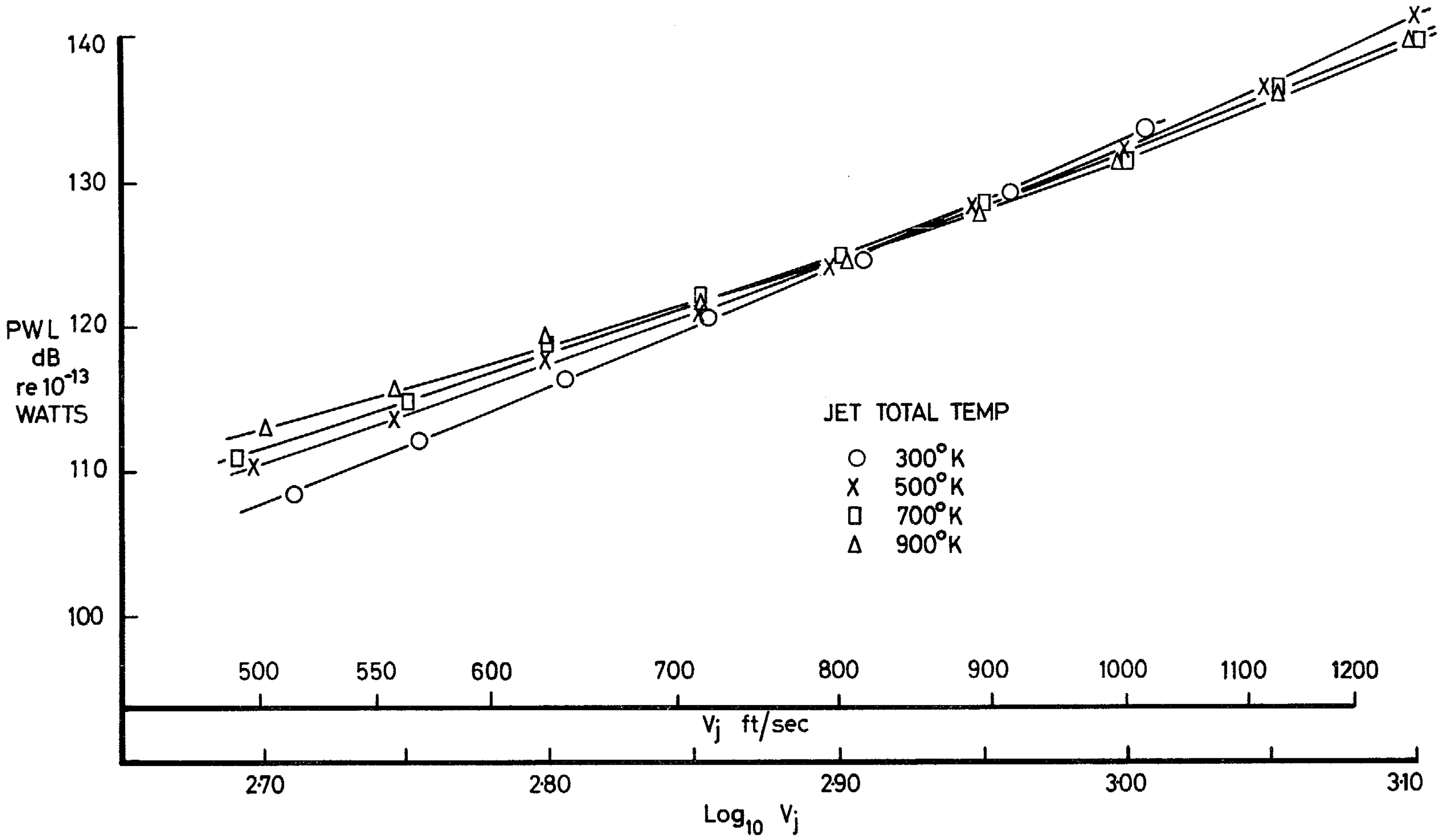

FIG. 5. PWL *v.* Jet velocity.

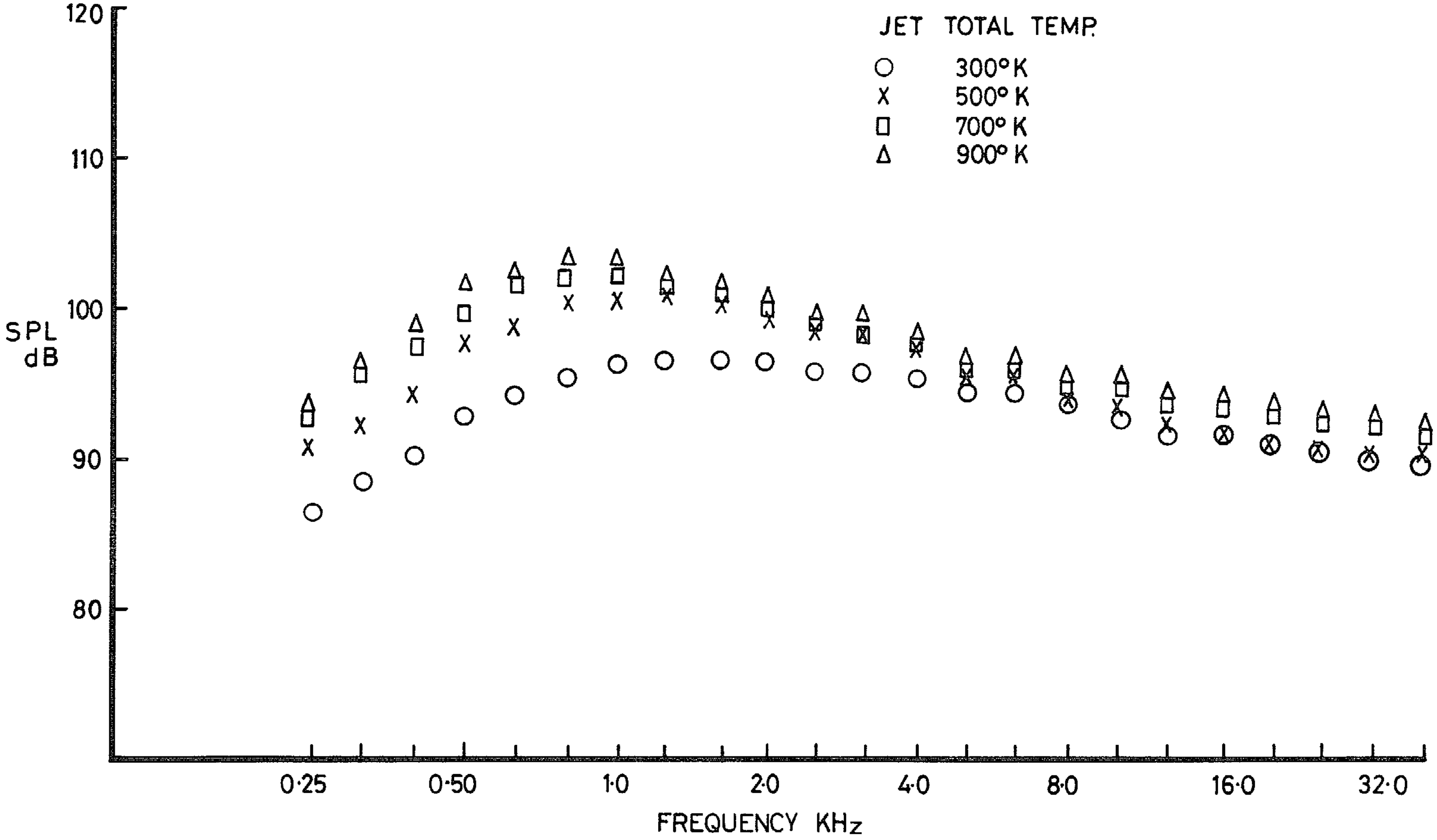

FIG. 6. 1/3 Octave power spectra ($V_j = 500$ ft/sec).

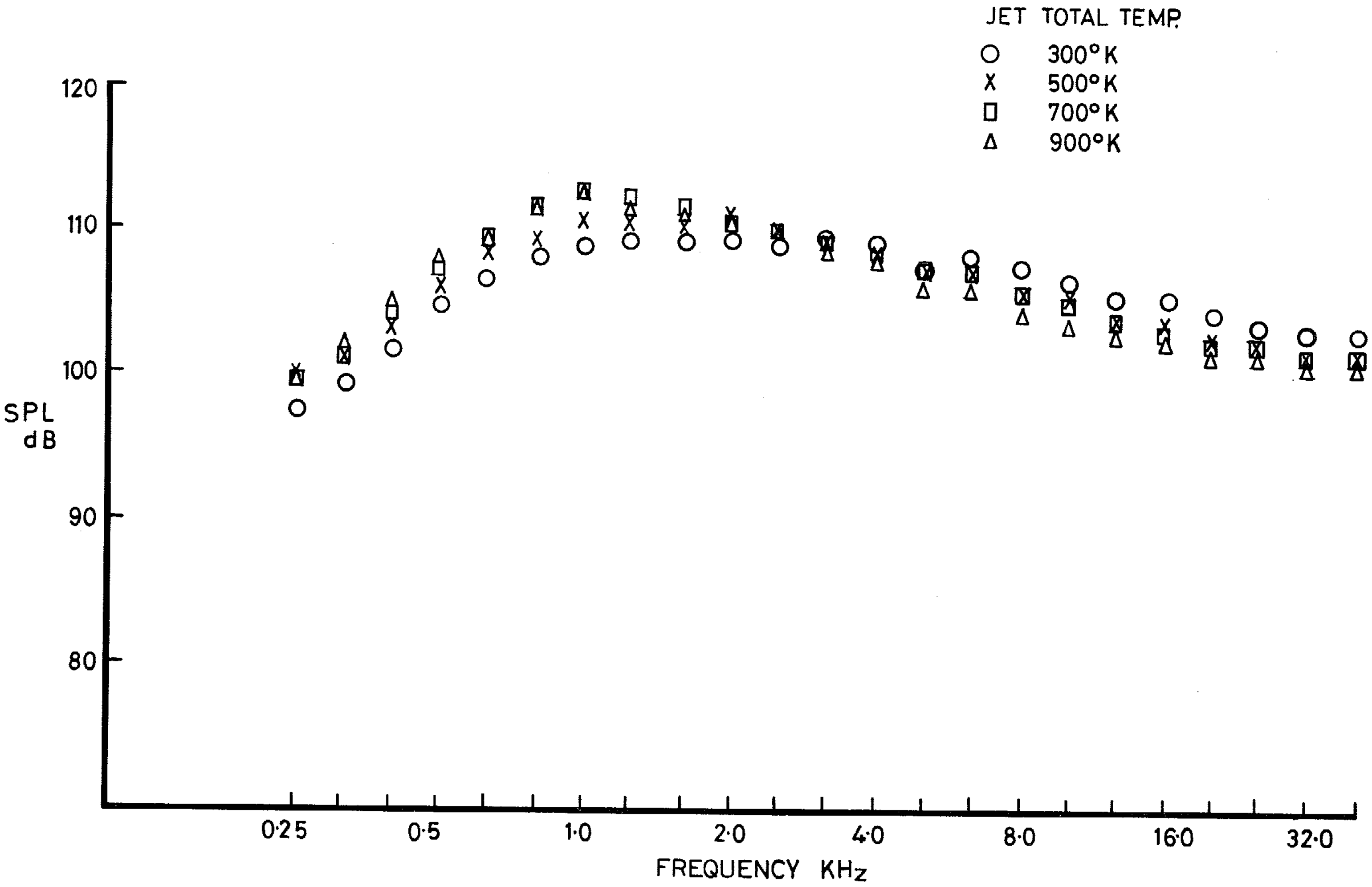

FIG. 7. 1/3 Octave power spectra ($V_j = 700$ ft/sec).

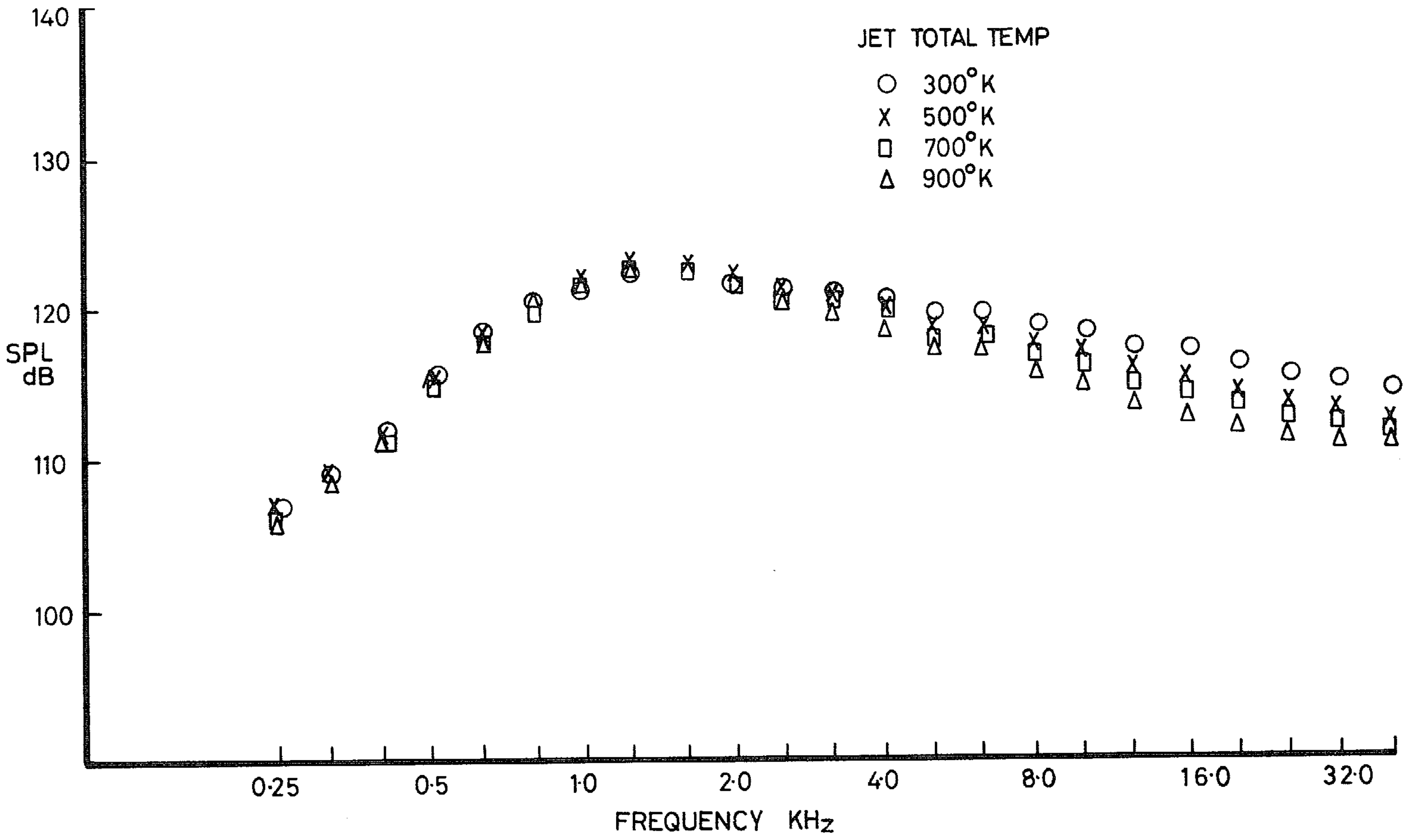

FIG. 8. 1/3 Octave power spectra ($V_j = 1000$ ft/sec).

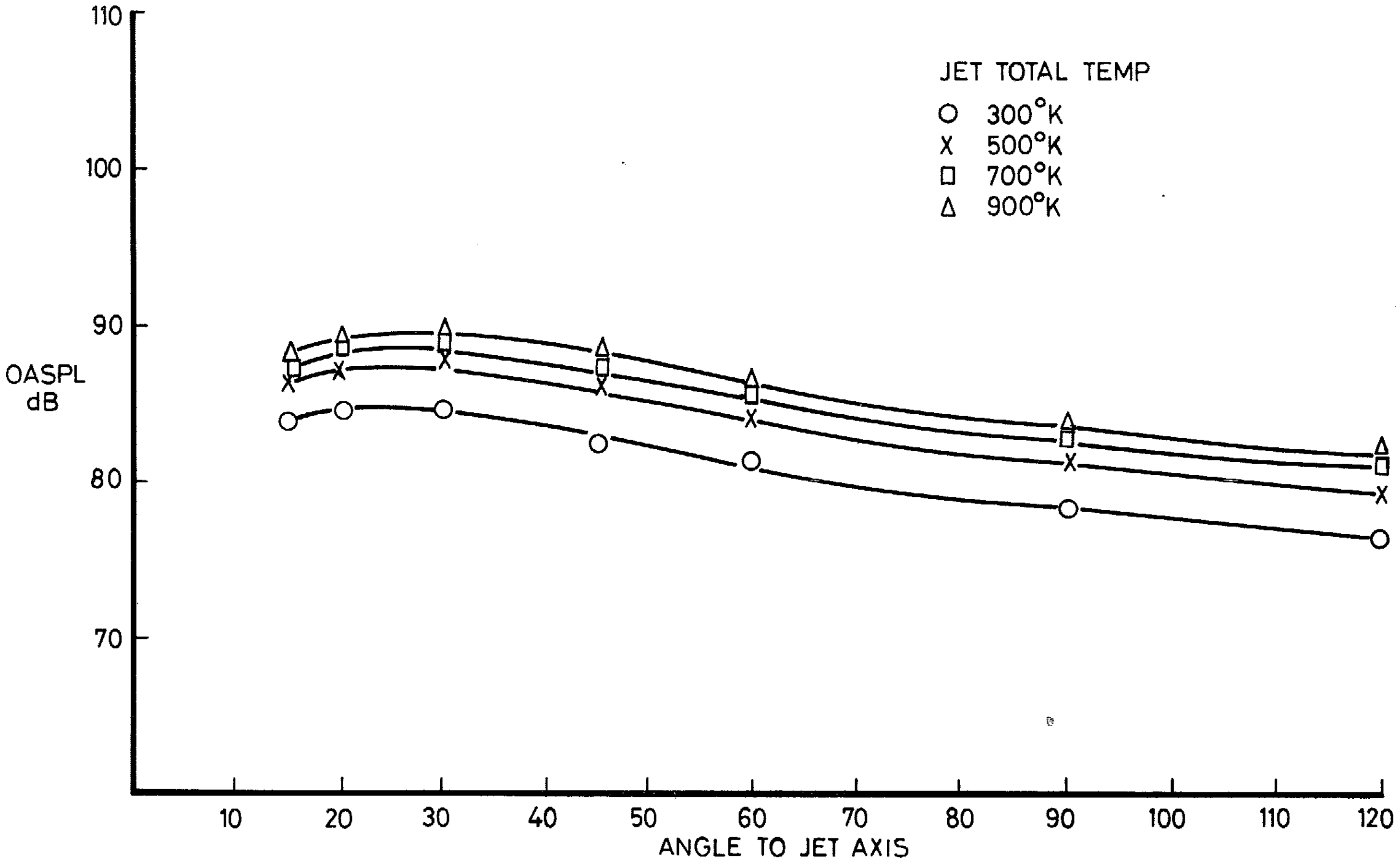

FIG. 9. Field shape ($V_j = 500$ ft/sec).

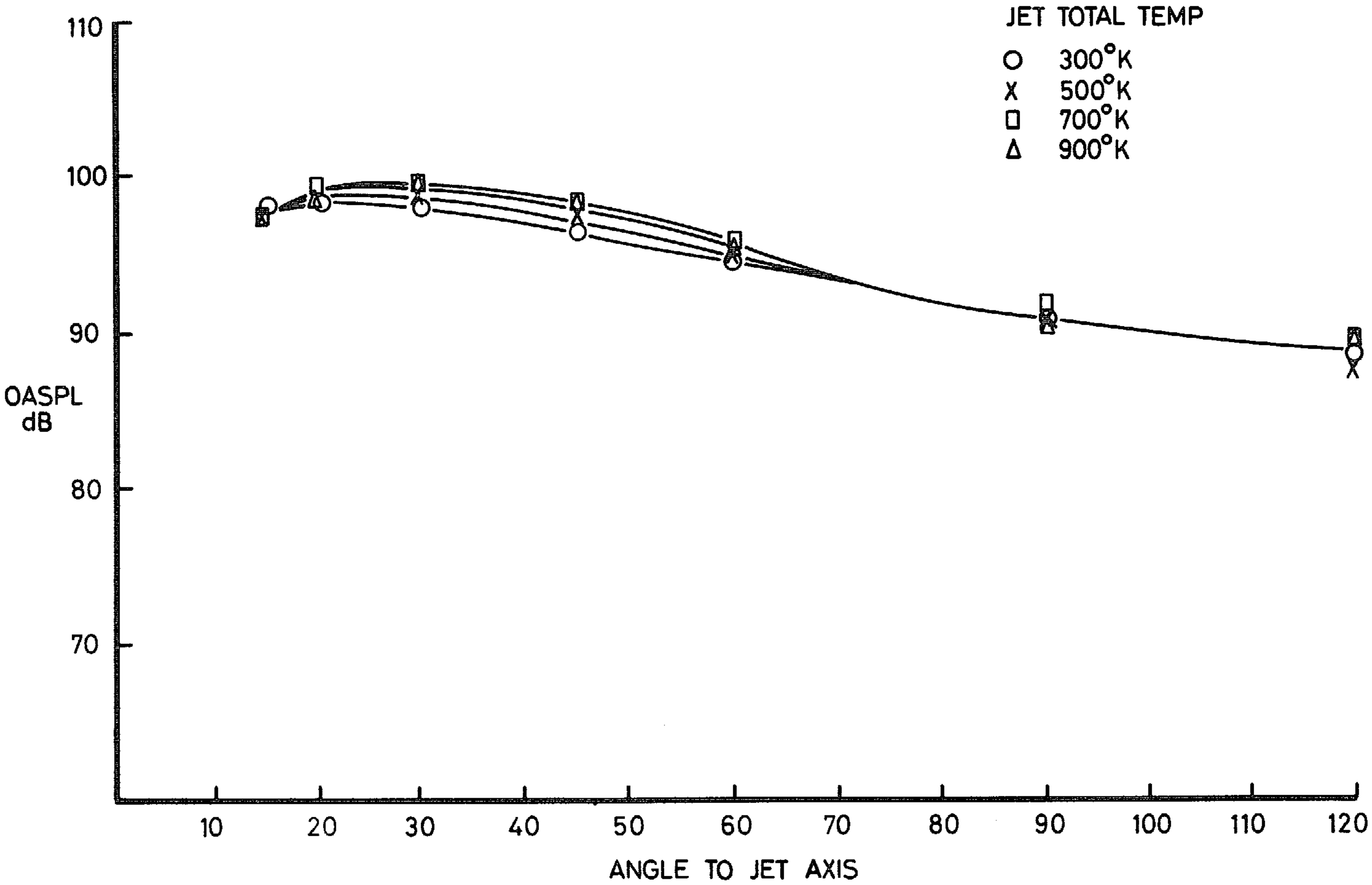

FIG. 10. Field shape ($V_j = 700$ ft/sec).

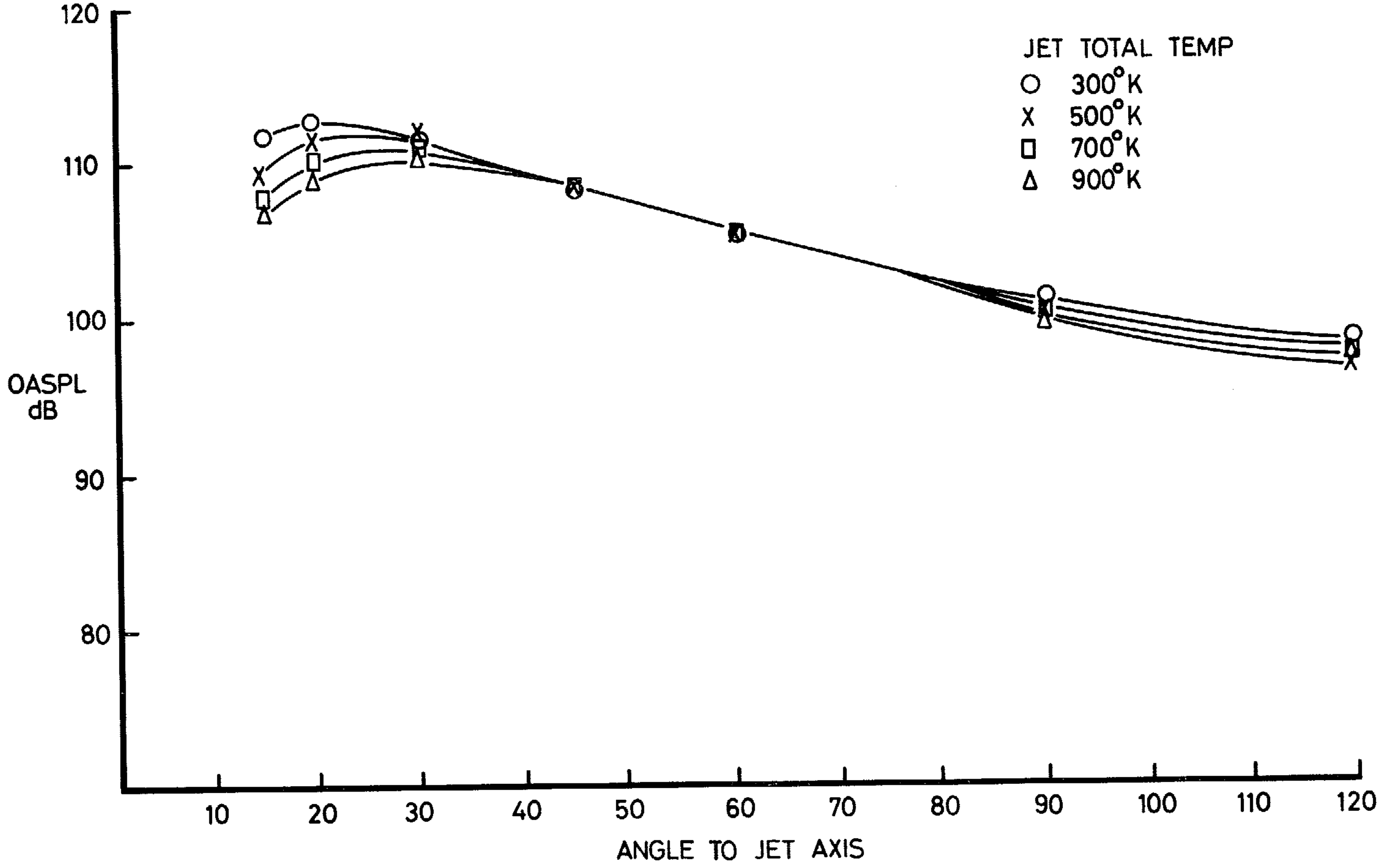

FIG. 11. Field shape (V_j = 100t ft/sec).

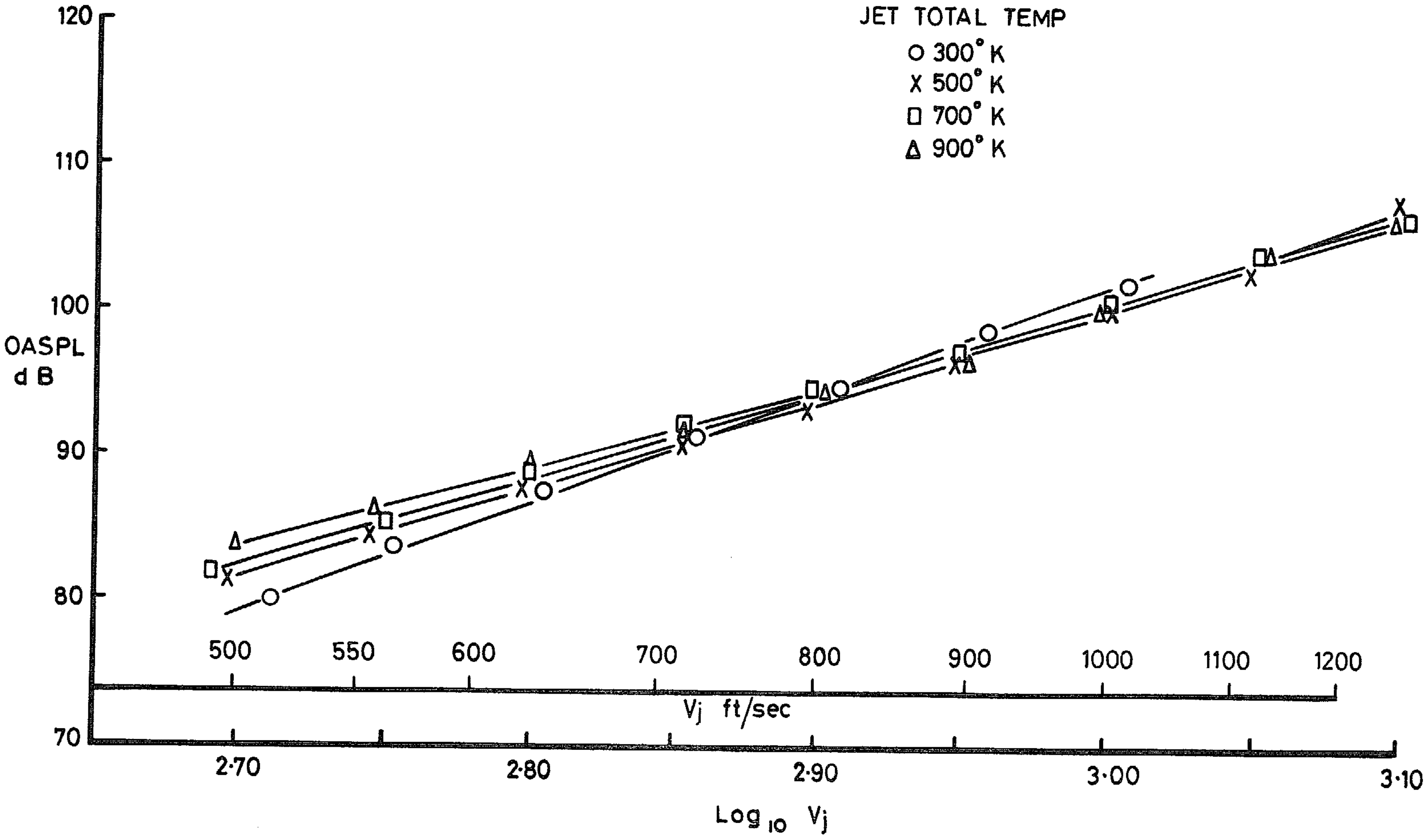

FIG. 12. OASPL *vs.* Jet Velocity (90° to jet axis).

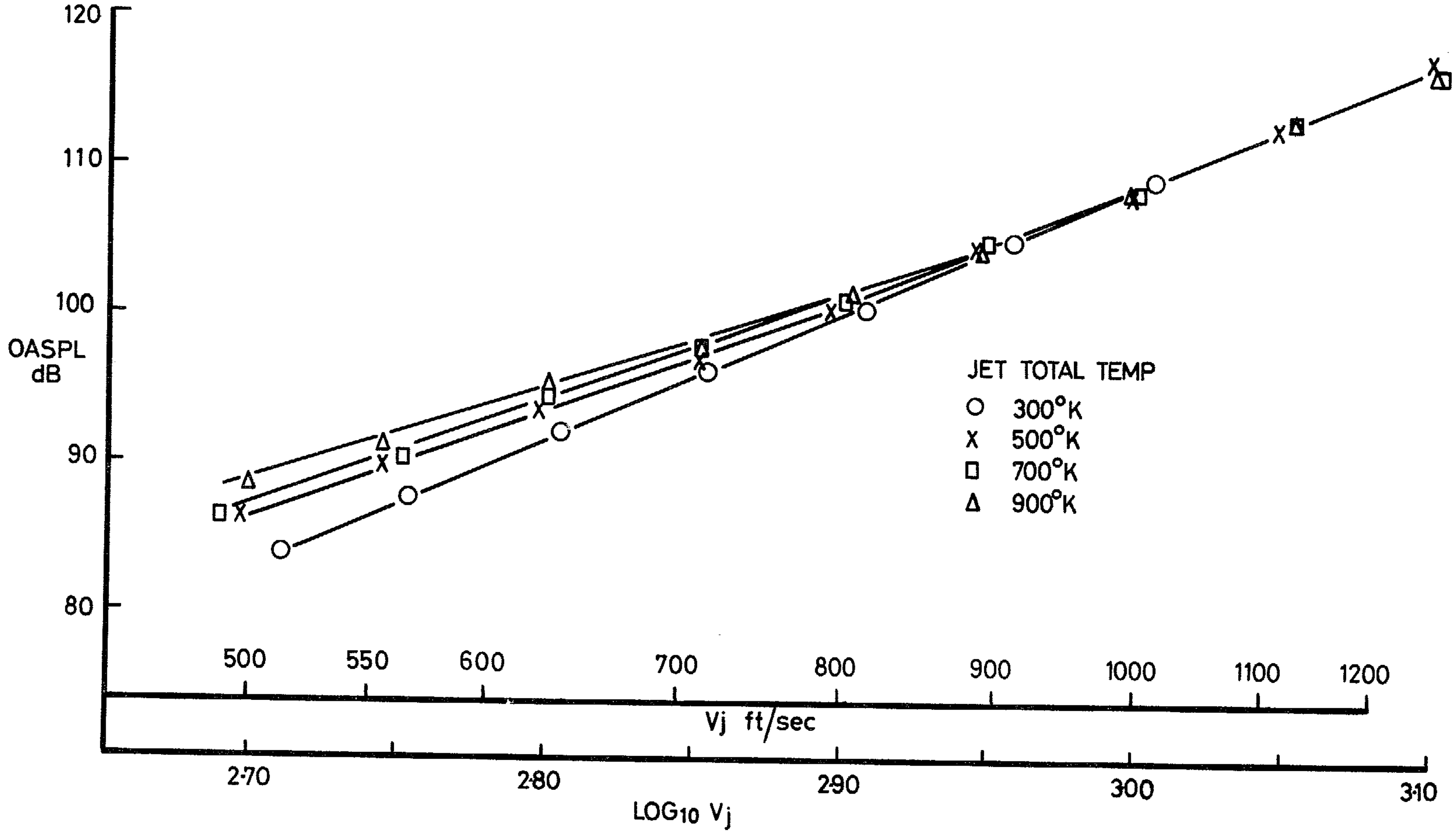

FIG. 13. OASPL *vs* Jet velocity (45° to jet axis).

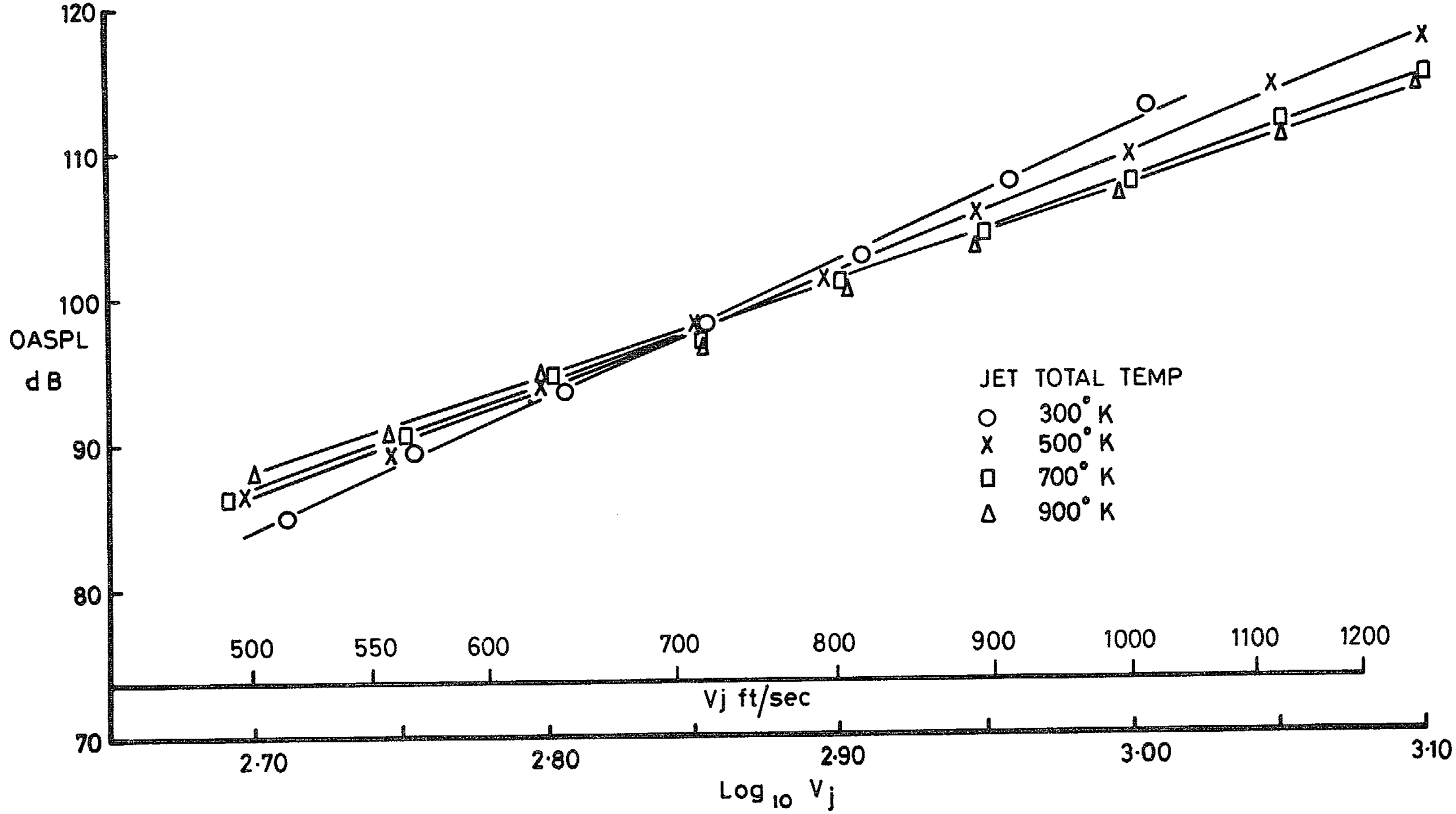

FIG. 14. OASPL *vs.* Jet velocity (15° to jet axis).

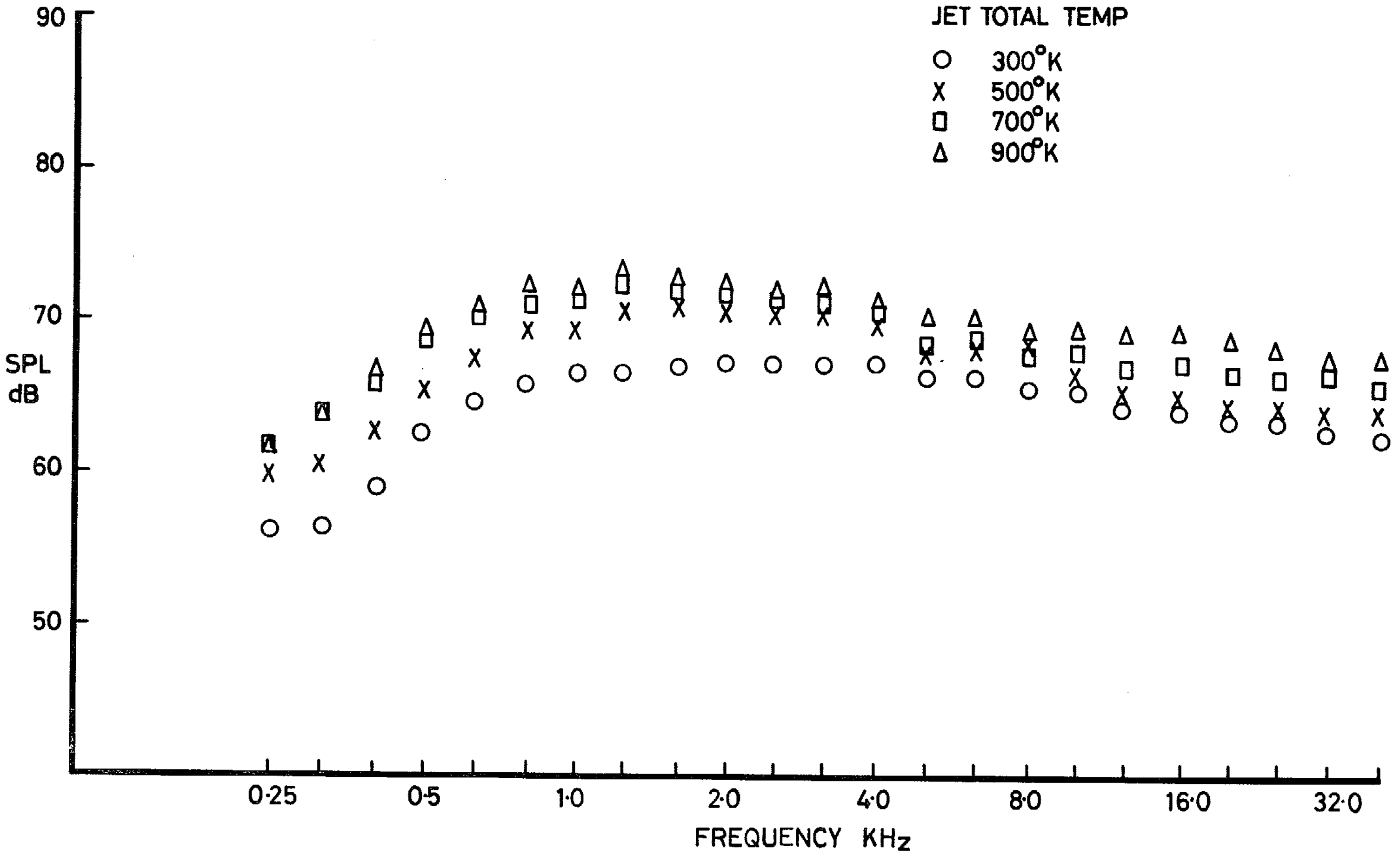

FIG. 15. 1/3 Octave spectra ($V_j = 500$ ft/sec, $\theta = 90°$).

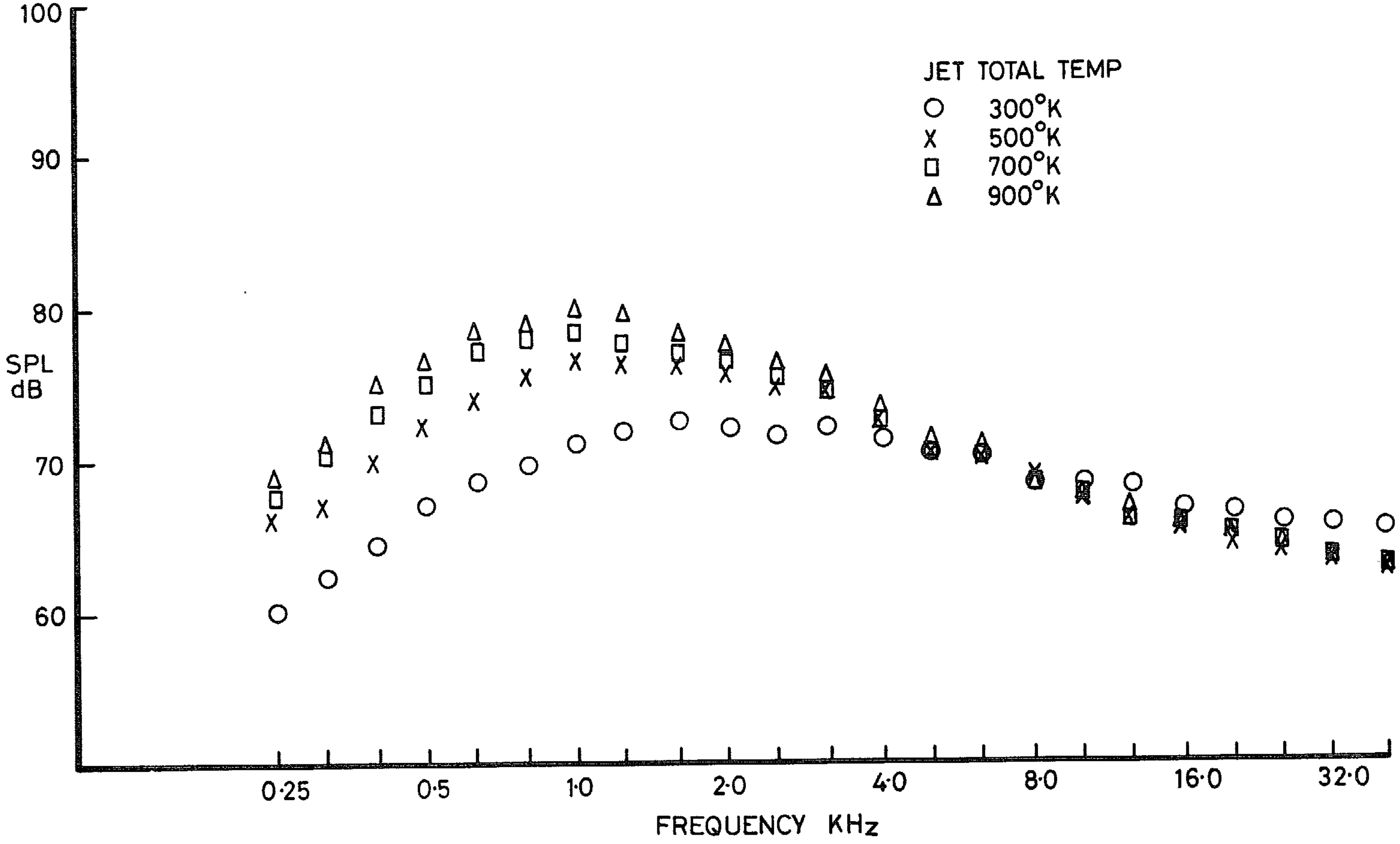

FIG. 16. 1/3 Octave spectra ($V_j = 500$ ft/sec, $\theta = 45°$). .

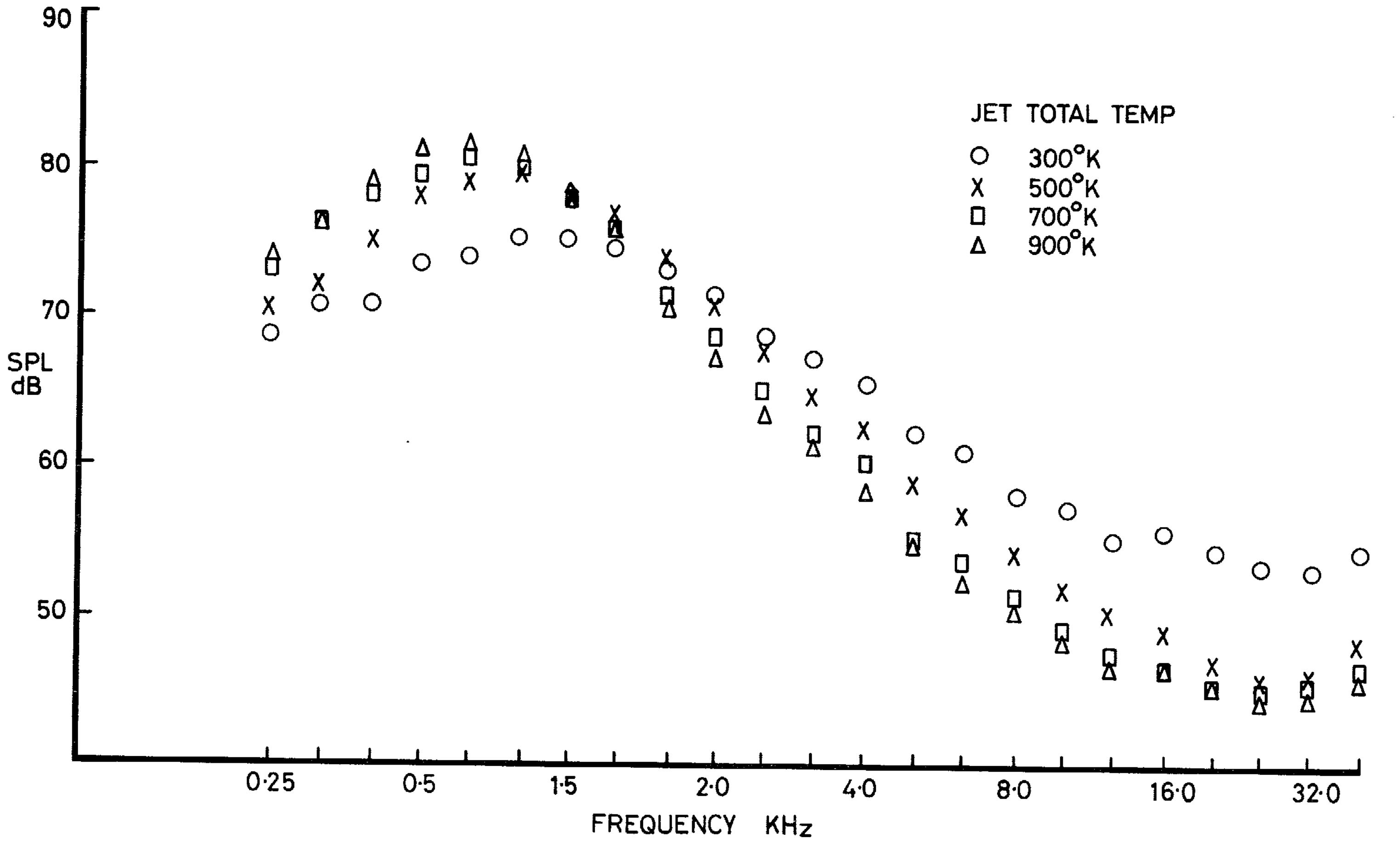

FIG. 17. 1/3 Octave spectra ($V_j = 500$ ft/sec, $\theta = 15°$).

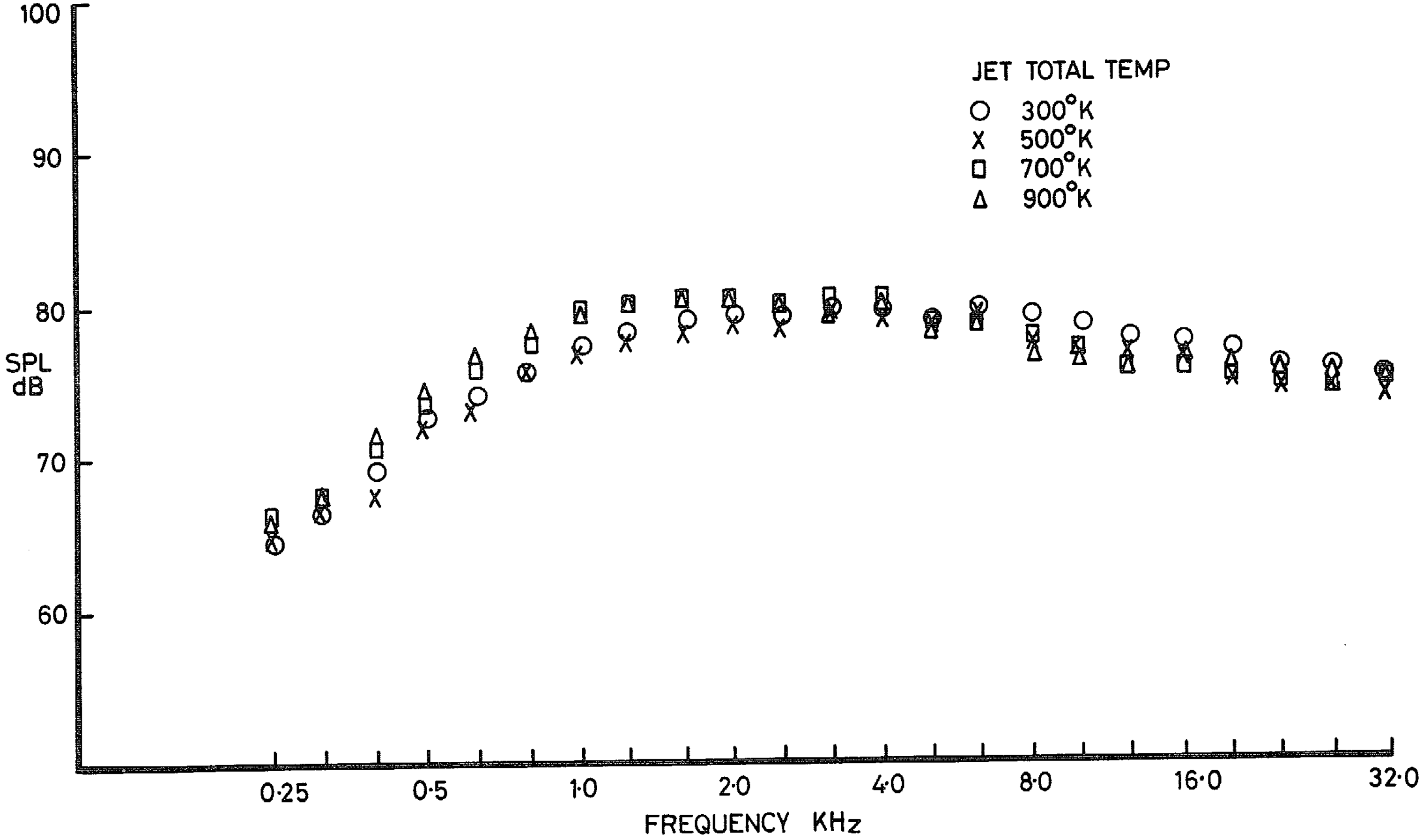

FIG. 18. 1/3 Octave spectra ($V_j = 700$ ft/sec, $\theta = 90°$).

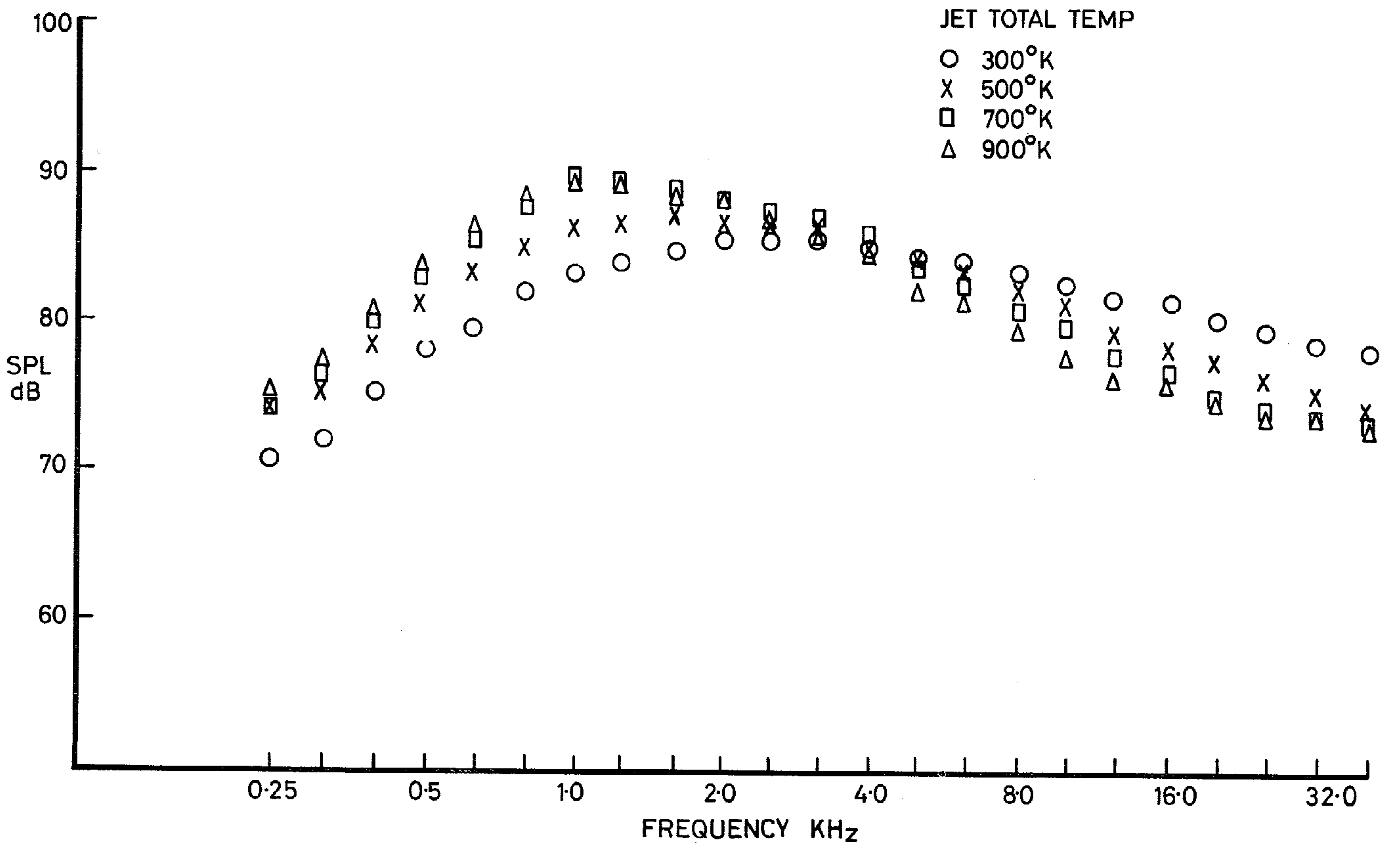

FIG. 19. 1/3 Octave spectra ($V_j = 700$ ft/sec, $\theta = 45°$).

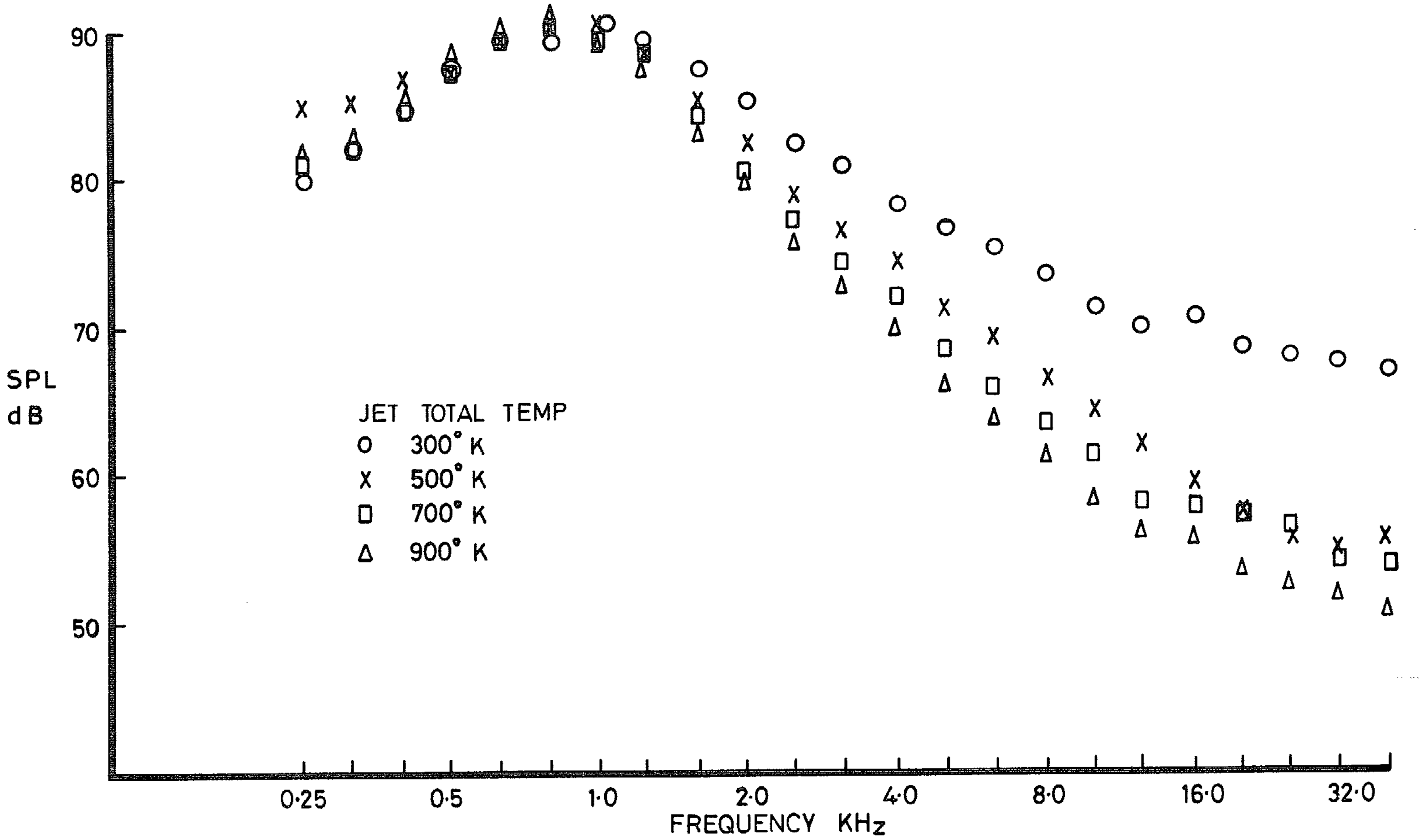

FIG. 20. 1/3 Octave spectra ($V_j = 700$ ft/sec, $\theta = 15°$).

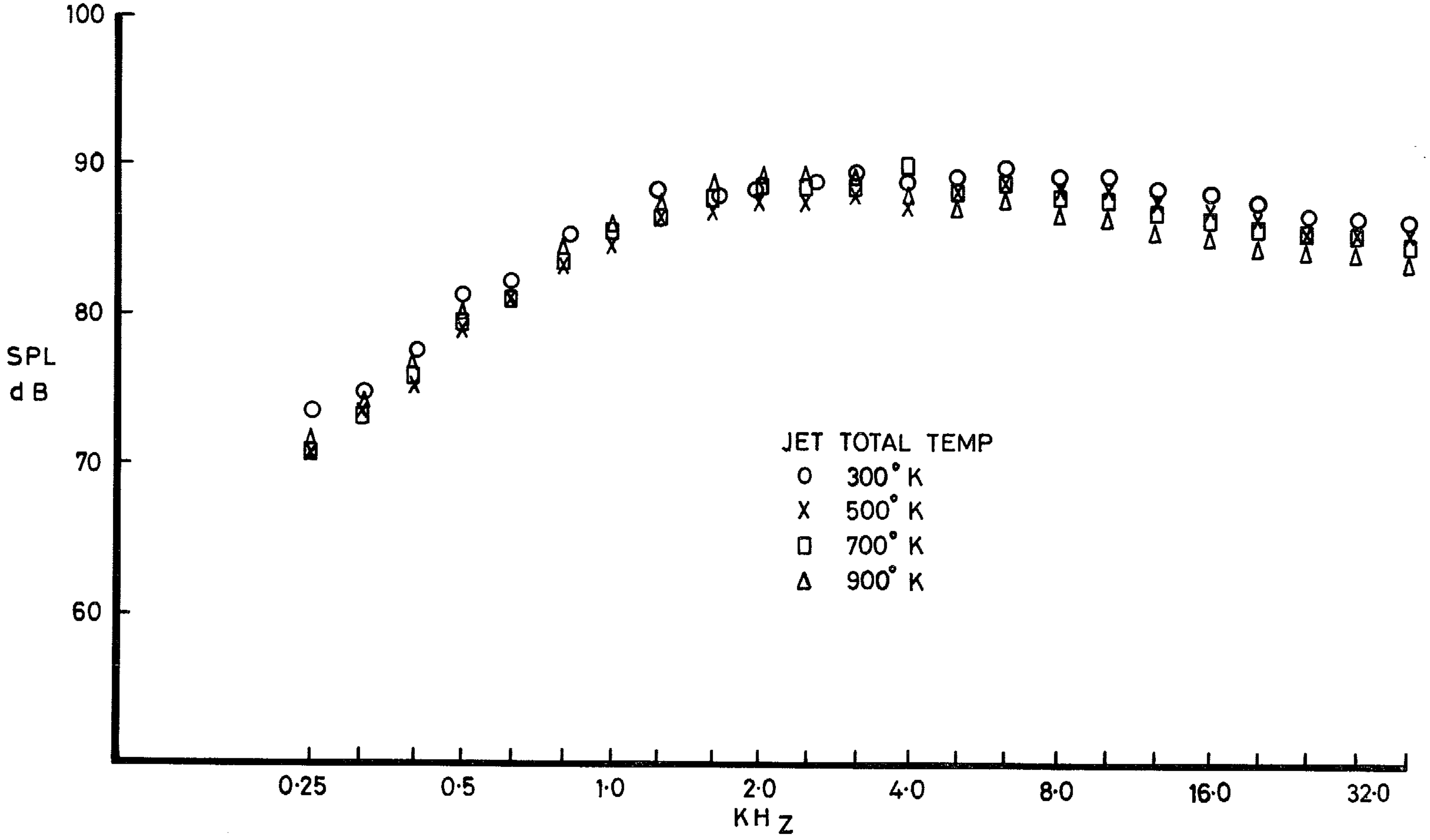

FIG. 21. 1/3 Octave spectra ($V_j = 1000$ ft/sec, $\theta = 90°$).

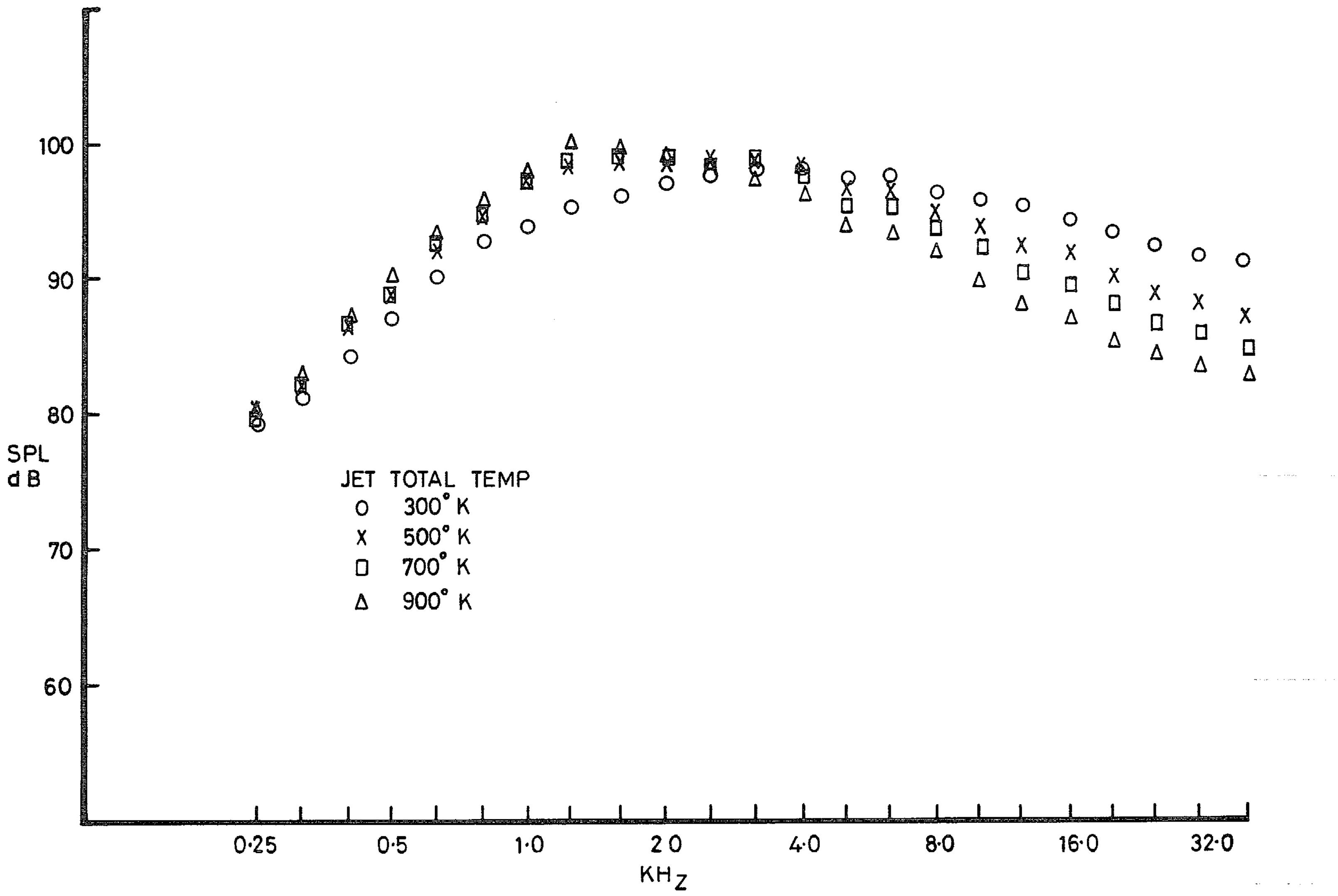

FIG. 22. 1/3 Octave spectra ($V_j = 1000$ ft/sec, $\theta = 45°$).

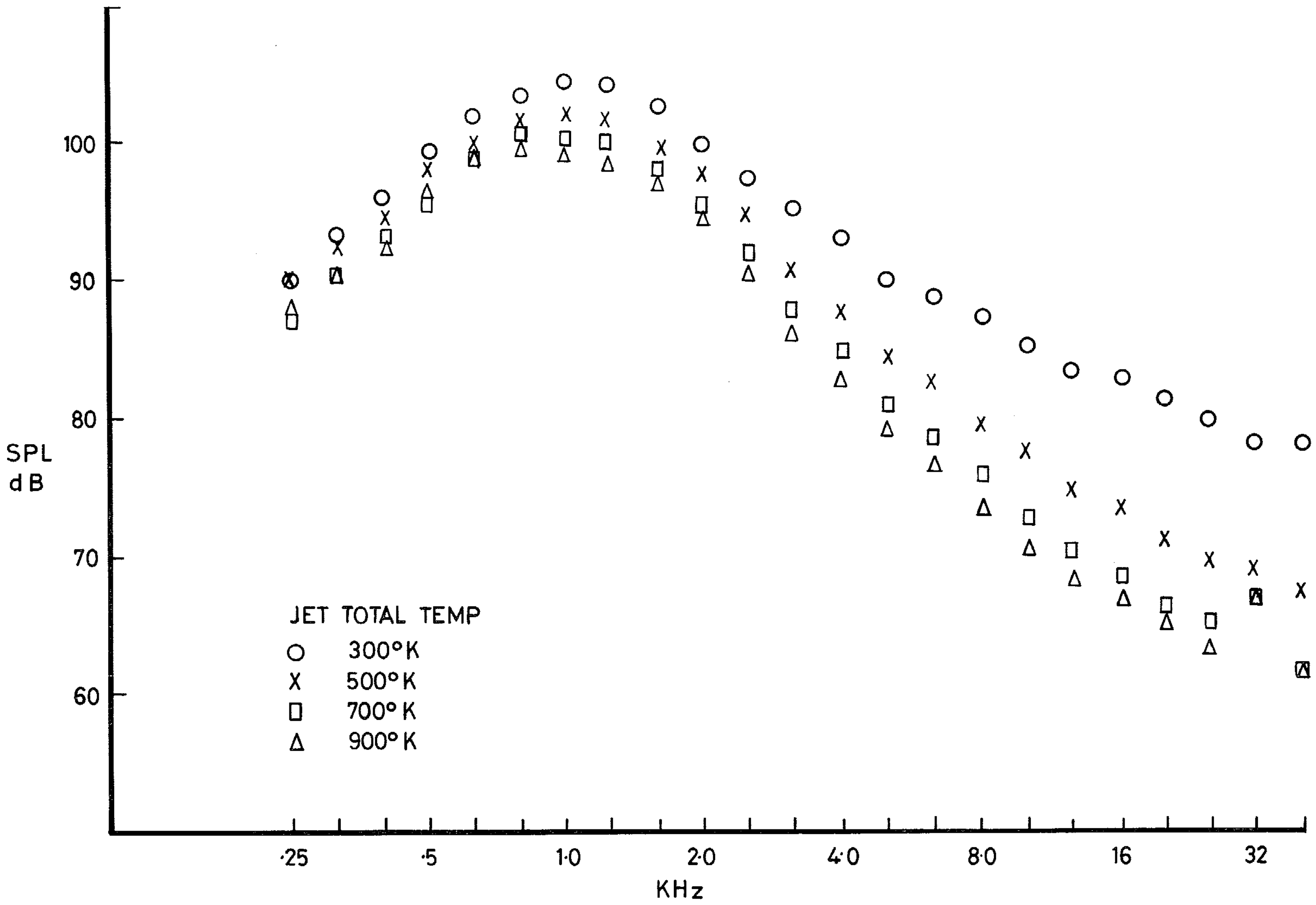

FIG. 23. 1/3 Octave spectra ($V_j = 1000$ ft/sec, $\theta = 15°$).

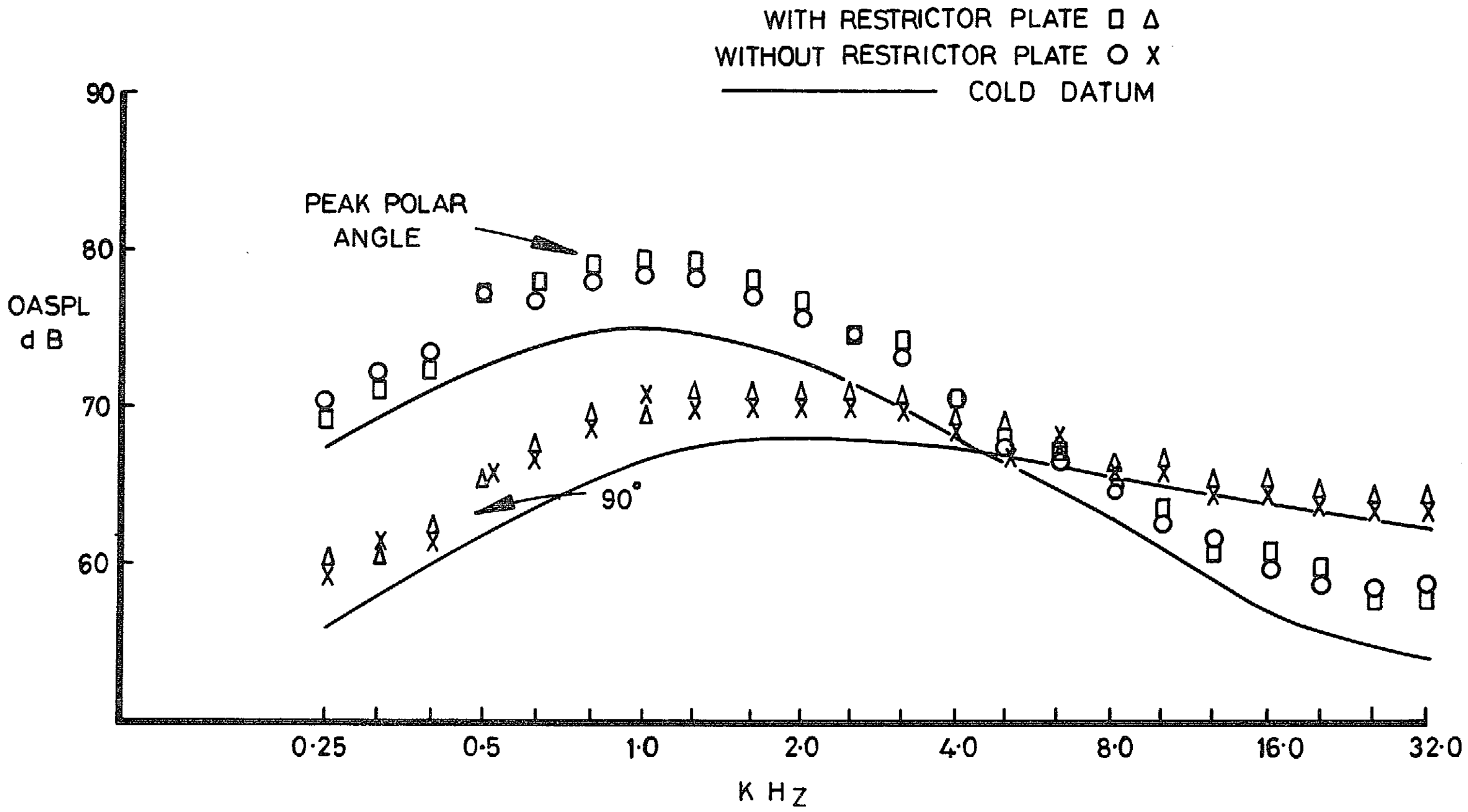

FIG. 24. Effect of restrictor plate ($V_j = 500$ ft/sec, $T_j = 500$°K).

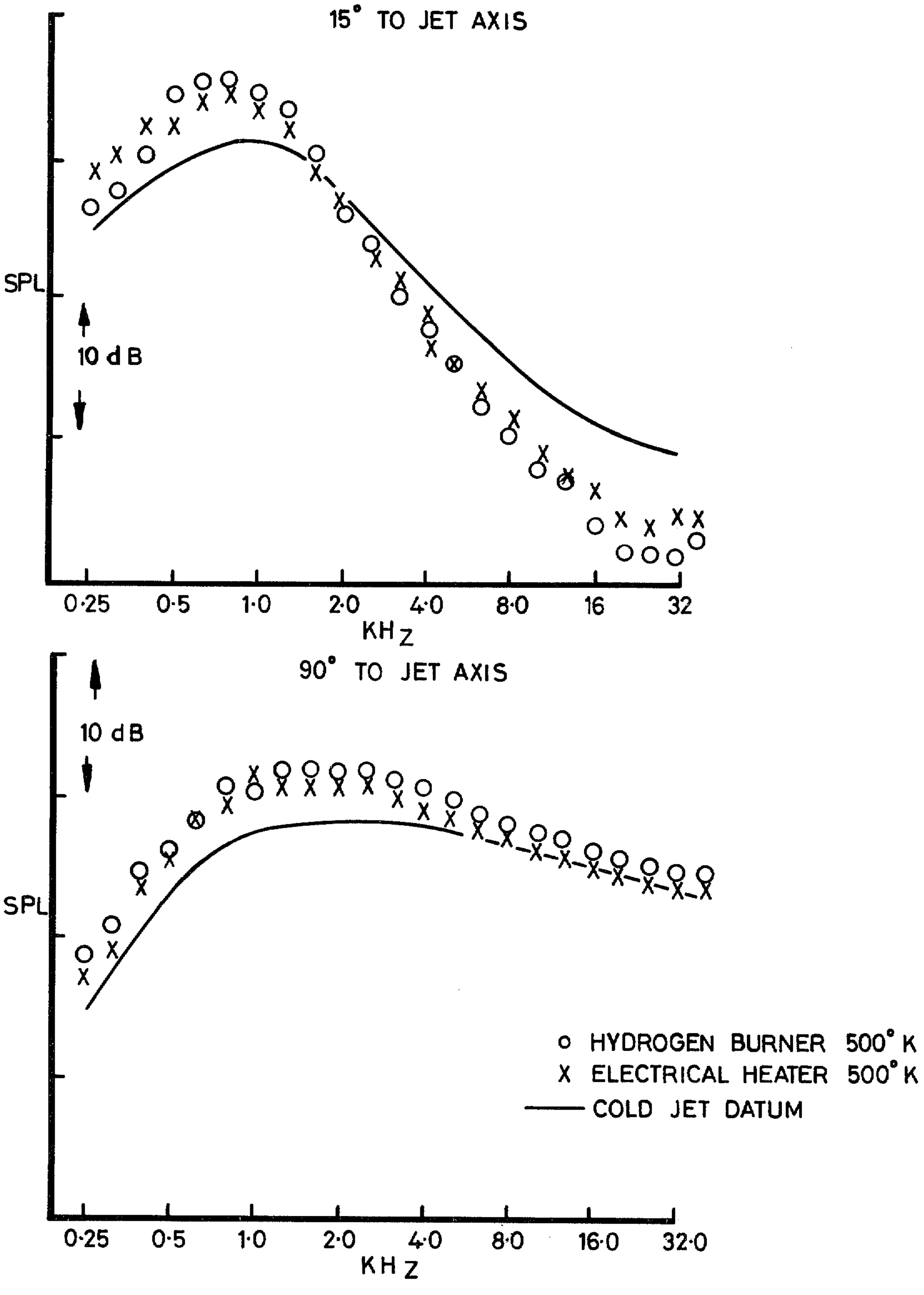

FIG. 25. Effect of electric heater ($V_j = 500$ ft/sec).

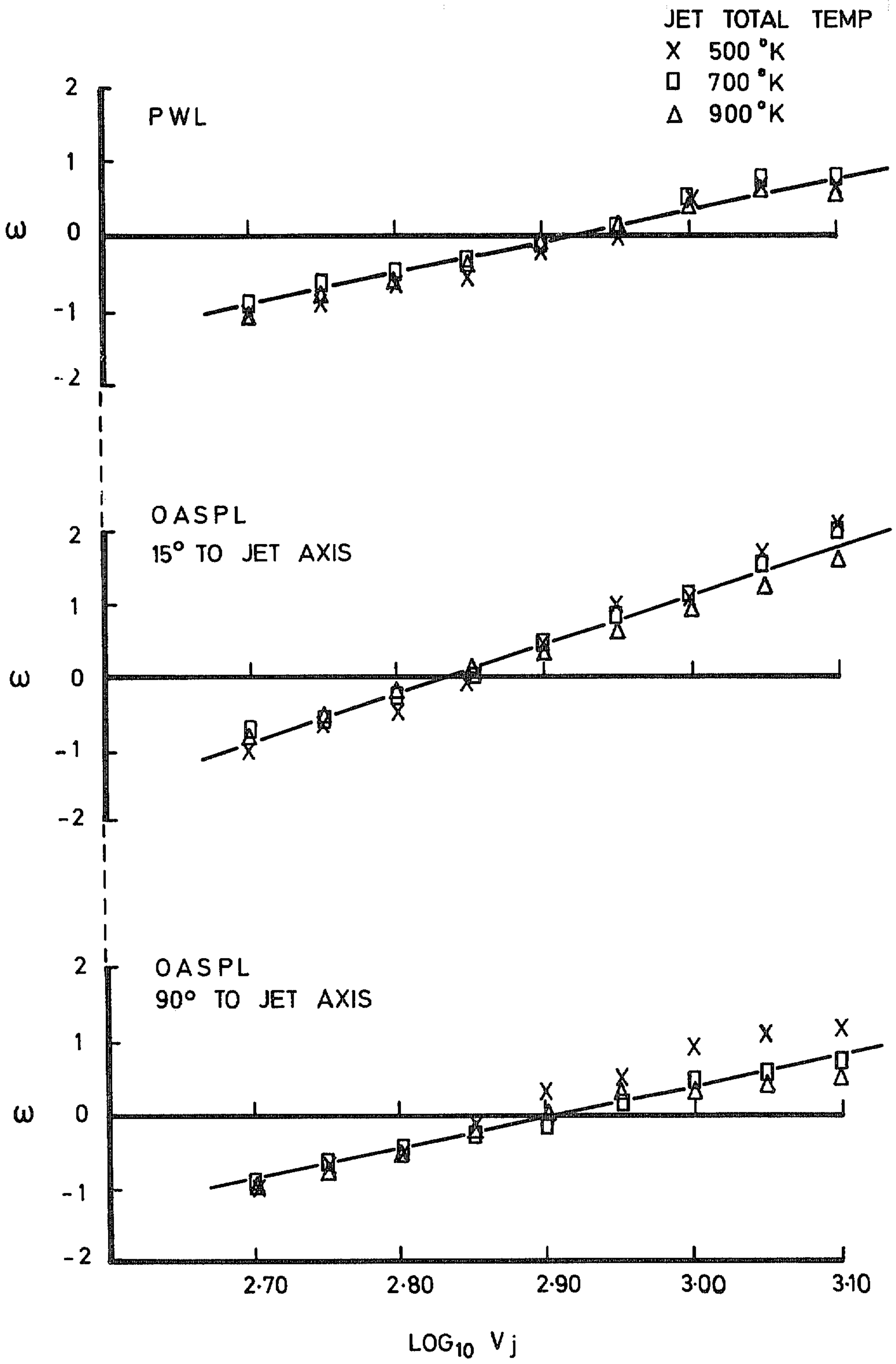

FIG. 26. Variation of jet density exponent with jet velocity.

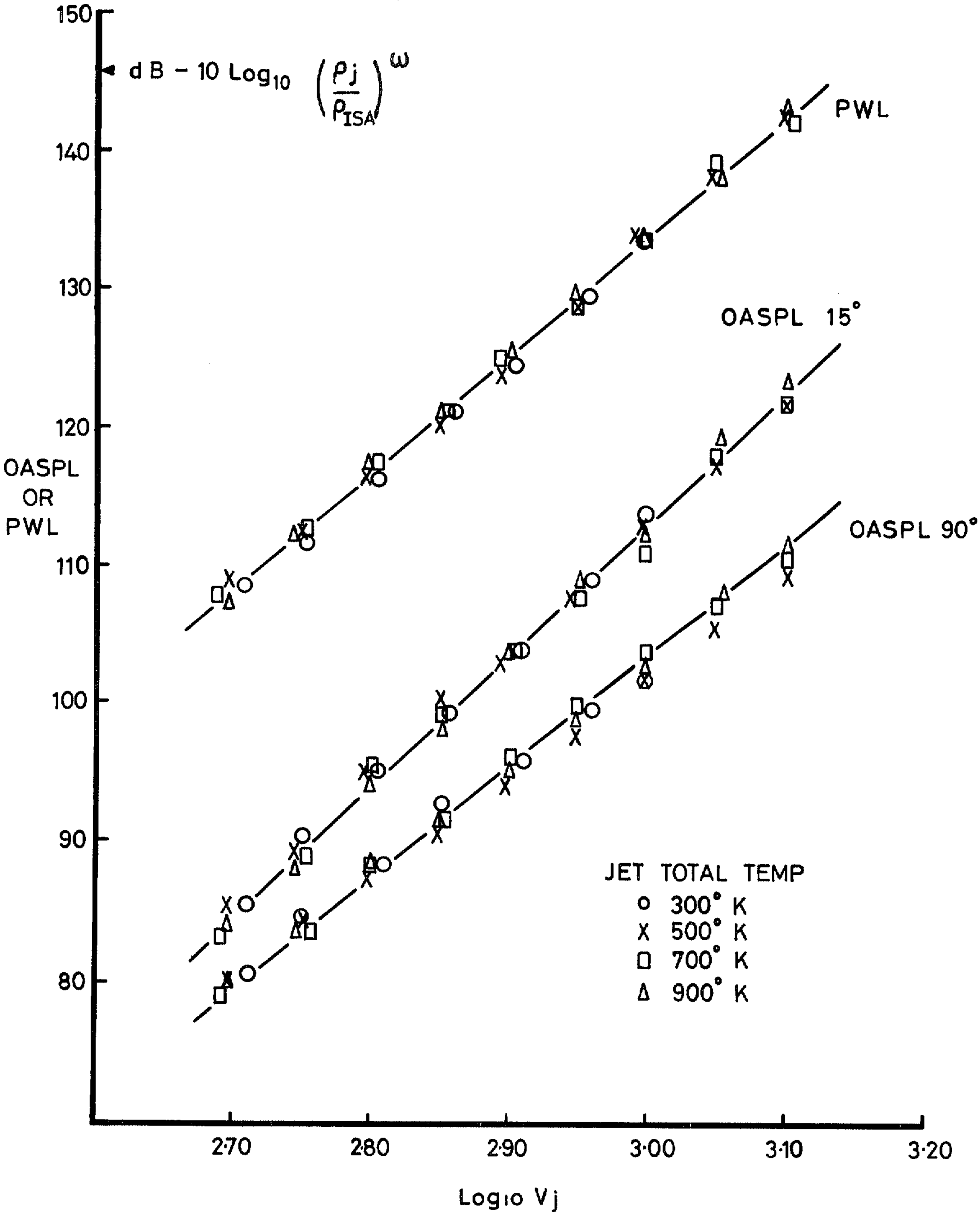

FIG. 27. Normalised noise levels.

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