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The Noise of Ejectors

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Summary.

An extensive model-test programme has been carried out on the noise properties of a series of fifteen axi-symmetric ejectors, using a two-inch diameter cold jet as the primary discharge and inducing the secondary flow from atmosphere. These ejectors had $(D/d)^2$ ratios of 2, 3 and 4, and (L/d) ratios which lay between 3 and 32, (D and L are the diameter and length of a particular ejector and d the diameter of the cylindrical primary nozzle). Parallel experiments at the Royal Aircraft Establishment, Farnborough, have investigated the static aerodynamic properties of these ejectors.

This report concentrates on the features of the broad-band discharge, after making a full survey of the types of noise present. No noise came from the ejector casing, and radiation of noise from the ejector intake was prevented by the use of an absorber box. Radiation from the exhaust for certain choked conditions was found to contain shock noise similar in nature to the unshrouded case and some unstable high-frequency broad-band noise was detected. Further discrete noise could emanate when the flow was entirely subsonic, and though the walls of the ejector were excited by the internal airflow this was not the source of this noise which had the properties of a non-linear oscillation within the shroud. The acoustic efficiency of this type of noise depended on the modes of excitation and was greatest for the shorter shrouds operating at pressure ratios of less than about 1·4. In many cases this noise was of sufficient strength to dominate the broad-band efflux noise. In certain cases the contribution due to the discrete noise could be removed by analytic means to leave an estimate of the broad-band discharge. It is shown that this latter noise appeared to be more related to the mixing conditions of the primary jet than to the conditions of the mixed stream at discharge. Defining the attenuation of an ejector as the difference between the peak (broad-band) noise levels measured along a line parallel to the jet axis with and without the ejector in position, such attenuation increased with increase in ejector length to a maximum of about 7 db but was independent of diameter.

A survey and assessment of other published noise work on ejectors is included.

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1. *Introduction.*

Although for the air traveller the introduction of the jet engine into civil aviation has brought appreciable benefits, people on the ground have discovered that another consequence has been the noisiness of the airliner exhaust during and shortly after take-off. Any method to make the reduction of such noise commercially feasible is therefore to be welcomed, and in recent years much theoretical and practical research has gone into the manner of generation, transmission and suppression of jet noise.

The classical papers of Lighthill[1, 2] which set down the fundamental relationships governing the production of noise by aerodynamic means, show by dimensional analysis that for jets of moderate Mach number the sound output can be expected to be proportional to some high power, usually near the eighth, of the jet velocity. This relationship has been substantiated by many experimenters working on a large number of circular jets operating under a wide range of conditions[3].

In an ejector system, the basic form of which is shown in Fig. 1, the discharge from the primary nozzle mixes with the entrained airflow within the sleeve. As the discharge consists of an augmented jet presenting a lower efflux velocity to the surrounding air, such a scheme seems attractive from the noise-reduction point of view, and as thrust may actually be augmented by the pumping action an application to commercial power plants may exist.

In an arrangement such as this there are clearly many parameters which affect the flow and therefore the noise. Even restricting the problem to a consideration of the mixing of cold flows within cylindrical sleeves for a given design of primary nozzle, there remain such variables as the ejector length and diameter, longitudinal position relative to the primary discharge, and inlet design.

To investigate the noise properties of such a set of ejectors, a series of experiments has been in progress in the Department of Aeronautics and Astronautics in the University of Southampton. Coupled with these tests aerodynamic experiments have been carried out at the Royal Aircraft Establishment, Farnborough, with primary nozzle and ejectors identical in construction to those used at Southampton. These measurements of inflow velocities, static-pressure distributions along the ejector, and outlet velocity profiles, are reported by Reid[4], and provide the 'steady' aerodynamic data for study in conjunction with the pressure fluctuations of the corresponding noise field.

Before describing the present tests a survey of other published noise work on ejectors is made. The assessment and comparison of results from different research groups is never easy due to differences in the techniques of measuring and analysing the noise. This is especially true in ejector work because of the large number of variables and the fact that the ejector length can be significant compared with the radius of the arc around which noise levels are customarily taken.

Most measurements of ejector noise have been made on basic designs which would not require much redevelopment to form practical units in conjunction with the turbo-jet power plants of modern airliners. Because of drag and weight problems this usually implied a rather short ejector, and reports often mentioned the desirability of a form which could retract during cruise conditions. Table 9 gives the experimental details as far as deducible from the available unclassified reports.

The earliest report on ejector noise is that of North and Coles[5]. Due to the shortness of the sixteen ejectors they tested in association with a conical nozzle little mixing occurred within the shrouds and the noise levels were practically unaltered. A single exception will be referred to later in this section.

Because of this lack of success most of the other ejector reports issued by the N.A.C.A., and latterly the N.A.S.A., dealt only with ejectors used in conjunction with nozzles which themselves possessed noise-reducing characteristics. Ciepluch, North, Coles and Antl[6] dealt with tests on an ejector with a 'mixing nozzle' but no acoustic data for this nozzle alone were presented and it was not possible therefore to assess the effect of the ejector. Coles, Mihaloew and Callaghan[7] showed that the ejectors generally produced noise levels lower at all angles than the twelve lobe nozzle with which they were tested, and which by itself gave about 3 db attenuation. The ejectors were also tested with an eight-lobe nozzle which alone gave some 7 db reduction in noise. Increasing the ejector length increased the attenuation in each case and an increase in ejector diameter also lowered the noise. The longitudinal location of the ejector had no significant effect on the levels. Further tests using an ejector with an eight-lobe nozzle are reported by Coles, Mihaloew and Swann[8].

Corcos[9] mentioned 'unpublished Douglas Aircraft Company and N.A.C.A. data' which showed that 'an ejector placed immediately at the exit of a plain nozzle is capable of decreasing the radiated noise energy by a factor as high as five' [7 db]. 'This occurs only when . . . secondary and primary air have been sufficiently mixed. "Sufficient" mixing requires a long ejector (the ejector length should be approximately eight times its diameter) . . . The gains obtained by ejectors and by corrugated nozzles are to a certain extent additive in that a combination of a corrugated (or multiple) nozzle and an ejector reduce the aerodynamic noise of a jet still further. In fact it has been found that even very short ejectors were effective complements of corrugated nozzles'. Powell[10] 'gratefully acknowledges unpublished data' from Douglas Aircraft Company in stating that an average reduction of 12½ db was found from a series of six ejector designs.

Further mention of tests on ejectors used with suppressor nozzles was made by Gordon[11], this review article stating that 'the suppressor, aerodynamic and acoustic testing done by N.A.C.A. provided invaluable assistance in the design optimisation of the CJ-805-3 suppressor', (the 'daisy' corrugated nozzle and ejector used for the Convair 880 airliner.) Discussing its design, Bertaux[12] stated that during tests 'as the length of the shroud was increased, the noise reduction capability of the suppressor was severely compromised'.

Results from both a full-scale engine and a small-scale hot jet have been described by Greatrex[13]. Figures given for the reduction in peak overall noise along a line 'nearly' parallel to the jet axis for a conical nozzle, showed that attenuation increased with ejector length but no dependence on area ratio was noted. When used in conjunction with a seven-tube nozzle the attenuation of an ejector again increased with length but it decreased with area-ratio increase. The reductions in noise were up to about 8 db and this was for an ejector length/nozzle diameter of about 13. The paper surmised that due to the low estimated velocity of the induced air in the flight case only a low attenuation would ensue.

The only unclassified report on air-to-ground noise tests known to the present Author is that of Coles, Mihaloew and Swann[8] and this stated that in the flight case the addition of the ejector to an eight-lobed nozzle made little difference either to the peak noise recorded in each octave during the fly-over or in the value of the attenuation. Figures of 2½ db at a relative jet velocity of 1000 ft/sec rising to 7½ db at 1500 ft/sec were achieved for the reduction of peak overall noise.

The tests so far mentioned have all been with a hot turbo-jet engine as the unit providing the primary discharge. Early model work at Southampton University by Foxwell[14] on two-dimensional choked ejectors using cold air revealed shock noise similar to that reported by Powell[15] in the unshrouded case. Although roughening the flow reduced the screech it failed to remove it and the tests were discontinued. This may explain the amelioration mentioned by North and Coles[5], i.e. 'recent unpublished ejector data obtained with a model air jet . . . which gave significant decreases in total sound power at nozzle pressure ratios in excess of 3·0' and why in view of the generally low attenuations achieved in the reported tests, Callaghan[16], in reviewing the noise work of the N.A.C.A., wrote 'of many combinations of nozzle and ejectors, best results so far indicate that as much as 15 to 16 db reduction of the overall level is possible'.

One of the sixteen ejectors reported on by North and Coles[5] gave 'an acoustic resonance', their third-octave analysis showing a clearly defined discrete frequency of about 160 c/s and its harmonics making the noise levels were everywhere higher than those of the unmodified nozzle. Coles, Mihaloew and Swann[8] stressed in their work that 'although some ejector configurations have shown resonant characteristics at certain operating conditions that resulted in noise level increases none of the present ejector configurations showed any at any engine speed'. With respect to this they cite Coles and Callaghan[17] but this latter report mentioned neither ejectors nor discrete frequencies. This phenomenon is different from shock noise as it can occur when the flow is unchoked. Indeed, both types of discrete-frequency phenomena have been observed on the tests about to be described. Prior to this present paper noise analysis using bands narrower than one-third of an octave appears never to have been made on ejector noise and it is therefore suggested that discrete*

* The precise meaning of the word 'discrete', as used in this context, is discussed in Section 5.3.

frequencies may have been present in strength insufficient to make their presence *obvious* in these earlier recordings yet adequate to affect the noise-level readings. In view of this it would appear desirable to treat these published results with a certain amount of reserve, although the general implications of this section have been included in Section 6 which is devoted to conclusions.

2. *The Experimental Facilities.*

2.1. *The Acoustics Laboratory and Control Room.*

All noise measurements were made in the Acoustics Laboratory of the Department. Fig. 3 shows a sketch of the laboratory together with adjoining Control Room. The shell of the laboratory was approximately 40 feet by 30 feet by 15 feet with a stepped inner frame covered with fibre-glass. Thus the walls and ceiling were highly sound-absorptive and their irregular shape prevented the formation of standing waves from any reflected sound. For the floor, iron gratings lay over transverse beams some two feet above the shell and the wells between each pair of beams were also lined with fibre-glass to prevent reflections. With this design conditions similar to those in a free field existed in a volume approximately 37 feet $\times$ 27 feet $\times$ 9 feet.

A compressed-air system was used to supply the primary jet. Room air, after being drawn through twin two-stage compressors which had cooler and water trap after each stage, passed through silica gel driers to be stored in twin reservoirs under pressures of up to 250 pounds per square inch. A supply system led from these storage tanks to the settling chamber in the laboratory. This chamber was some six feet long with an internal diameter of 6·25 inches and at the downstream end of this the primary nozzle was bolted. Thus the air discharged horizontally some seventy inches above the floor gratings. As the diameter of the primary nozzle was fractionally under two inches, the area contraction of over 10:1 from the chamber to the nozzle meant that negligible difference existed between the stagnation pressure at the nozzle and the static pressure in the settling chamber. The value of the stagnation pressure was therefore determined from the reading of a mercury manometer situated in the control room, and which was connected to a static tapping in the chamber wall.

Throughout this report, pressures ratios of '1·35', '1·65', etc. will be quoted. Unless the contrary is explicitly stated, such figures refer to the ratio of the total pressure, (i.e. gauge pressure plus atmospheric pressure), to atmospheric pressure. (This is, of course, the correct value when applying the usual isentropic relationships to an unshrouded subsonic jet as then the static pressure is equal to the atmospheric pressure. However, when an ejector is added, the static pressure at the point of discharge of the jet into the sleeve is lower than atmospheric pressure, and it is indeed the difference between the two which provides the driving head for the induced secondary flow). This designation was the method adopted by Reid[4], and it has been found convenient to follow this system and thereby afford a direct comparison between the two sets of results. Thus the *true* pressure ratio at the nozzle was higher than the one given. Although the difference depended on the actual ejector used, it is worth mentioning as a guide that a 'pressure ratio of 1·65' was roughly equal to the true choking pressure ratio of 1·89 given by a value of γ of 1·4 (e.g. Fig. 6a).

The humidity of the air in the laboratory was determined during each test by a whirling hygrometer, the 'dry' bulb of which was used as indication of the air temperature. For the jet itself, a ventilated psychrometer was fitted to a tapping at the downstream end of the settling chamber. The reading of the 'dry' thermometer was taken as the stagnation temperature of the jet, this proving a far more convenient method than employing a pitot-thermocouple. Since the compressed air was stored at 'room temperature', little difference was to be expected between the laboratory temperature and the stagnation temperature of the jet. It was found to never exceed $\pm 6°F$ and was generally within $\pm 2°F$. A Fortin barometer in the control room gave the value of the atmospheric pressure.

2.2. *The Experimental Models.*

The primary nozzle and the metal ejectors were duplications of those used in the parallel aerodynamic experiments conducted by the Royal Aircraft Establishment, Farnborough, (Reid[4]).

The precise details of the primary nozzle, which was axi-symmetric, are given in Fig. 2. A section of 20-gauge brass tubing of two inches external diameter formed the cylindrical part of the nozzle, and this was attached to the converging approach section which was of mild steel. The internal profile of this latter was a quadrant in the plane through the axis. Close to the exit plane of the nozzle two tappings were let into the wall to measure the static pressures in the internal and external flows just prior to mixing. The leads from these were buried in the wall of the nozzle to prevent interference with either flow and went to water or mercury manometers mounted on the settling-chamber support. The nozzle flange was so designed that it provided a firm seating in the end of the settling chamber. The nozzle was held in position by bolts through a retaining ring, as Fig. 2 shows.

For the ejectors three different diameters were available for each of five different lengths, making a total of fifteen. The ratios of the areas of the secondary flow annulii to the primary nozzle area were roughly 1·0, 2·0 and 3·0, and the ejector lengths were equal to 3, 6, 12, 20 and 32 primary-nozzle diameters. These fifteen therefore covered the whole range of practical constant-area axi-symmetric ejectors, although to extend some results it was found necessary to test some wooden ejectors, and these are dealt with in Section 5.3. The full details of the metal ejectors and the nomenclature adopted in this report are given in Table 1.

To provide smooth inflow conditions, brass bellmouths were fitted to each of the metal ejectors, and each had a one-inch radius in the meridian plane. The ejectors themselves were of 14-gauge mild sheet steel, rolled and welded, except for ejectors B1, B2, B4 and B5 which were of 16-gauge seamless brass. Prior to use, the metal ejectors were scoured internally in the Department of Chemistry in the University. The wooden ejectors were of teak, with bellmouths made of mahogany.

An ejector was supported at two positions. The upstream end was held between bifurcated arms extending from two horizontal rods mounted out from lugs on the flange of the settling chamber. The downstream end was supported by a stand resting on two I-beams bolted to the floor to give a rigid base. The longitudinal distance of the ejector inlet from the nozzle efflux plane was controlled by interlocking templates and these were also used to make the flow axis of the primary nozzle and the upstream end of the longitudinal axis of the ejector coincide. At the downstream end the axes were brought into coincidence using a sighting arrangement, and the ejector was then locked in position.

2.3. *Noise-Measuring Equipment.*

As subsequent sections of this report confirm, it was found necessary to make very assiduous investigations of the noise field produced by the ejectors. Such an approach required the use of a considerable amount of equipment as analyses were carried out according to the most suitable way of studying the particular noise pattern under consideration. The main pieces of equipment and their capabilities are therefore discussed in this section and the Appendix lists the full range of noise equipment used.

The pressure transducer was a Bruel and Kjaer half-inch condenser microphone. This has a linear free-field frequency response covering the range 20 c/s to 40 kc/s, using normal incidence, and its upper sound pressure level limit was considerably in excess of any noise level measured in these experiments. The variation of microphone sensitivity with temperature was negligible and the slight variation with ambient pressure could be allowed for. This cartridge was immediately succeeded by a cathode follower as pre-amplifier, and the signal was taken from the Acoustics Laboratory to the Audio-Frequency Spectrometer in the Control Room using twenty metres of cable (two ten-metre lengths connected in series).

This spectrometer consisted of input circuit and amplifier, filter circuit and output amplifier, and a meter circuit. The upper frequency limit of the spectrometer was higher than that of the microphone so that the total noise recorded by the microphone at given location could be determined by selection of the 'overall' position on the scanning dial. Also incorporated were thirty contiguous one-third octave filters, covering the range 35·5 c/s to 35,500 c/s, and these could be selected either singly or in ten consecutive groups of three to give octave levels. Designed for subjective work in full-scale tests, the three weighted networks, 'A', 'B' and 'C' of this instrument were not used in these experiments. The use of a hand-switch enabled the output from any filter, or the overall noise, to be observed for any desired length of time.

Rather than read the third-octave, octave or overall noise level on the spectrometer dial, it was sometimes more convenient to use the Bruel and Kjaer Level Recorder. The signal from the spectrometer when fed to this recorder actuated a stylus which marked the surface of calibrated waxed paper as the latter unwound, so that a permanent visual record of the noise signal was obtained. In general an electrical switchdrive connector was used with the motor of the level recorder to drive the selector switch of the spectrometer through the filter bands.

It was frequently necessary to make magnetic-tape recordings for subsequent analysis, and for this the 'overall' output from the spectrometer was fed into a Vortexion Tape Recorder. At its maximum speed this was linear up to about 14 kc/s. For broad-band analysis the tape could be replayed back into the spectrometer, whilst for narrow-band analysis to investigate discrete frequency phenomena, either the Hewlett-Packard Wave Analyser (with sweep drive to the Moseley Autograf Recorder), or the Muirhead-Pametrada Wave Analyser could be used. The former, which had a constant bandwidth of about 7 c/s was used when an indication of the frequencies of discrete signals was required, and the latter, with a constant percentage bandwidth of about 4%, (for 3 db down), when actual noise levels were wanted.

Two further instruments tried for narrow-band analysis were the Bruel and Kjaer Frequency Analyser, (which had its own associated level recorder and recording paper), and the Kay Sona-Graph Sound Spectrograph. The advantage of the former was that as it was an automatic frequency scanner it eliminated any failure to detect a peak through chance omission resulting from hand selection of frequencies on the Pametrada Analyser. However as its maximum selectivity was 6% the resolution was not as good as that of the Pametrada instrument.

Examples of the outputs from the Hewlett-Packard Wave Analyser, the Bruel and Kjaer Frequency Analyser and the Kay Sona-Graph Sound Spectrograph are shown in Fig. 4. The output from the last is an analysis of 2·4 seconds of magnetic tape with time as the horizontal scale and a linear vertical scale covering the frequency range from 85 c/s to 6000 c/s. The strength of the signal is proportional to the degree of charring produced on the surface of the specially prepared paper so that discrete frequencies occur as darker bands. This type of analysis was advantageous if a signal changed with time, as for example when the pressure ratio of the jet was steadily increased. (In the particular example shown in Fig. 4, the Hewlett-Packard Analyser, as set, went slightly non-linear after 4000 c/s. A d.c. signal and a deflection corresponding to the 50 c/s mains hum explain the initial steep descent on the left-hand side of this trace.)

The final instrument to use the spectrometer as amplifier was the E.M.I. Panoramic Waveform Analyser, in which the input actuated a beam traversing a six-inch cathode-ray tube. The horizontal distance moved was proportional to the frequency, and the vertical deflection was related to the amplitude of the signal. Both scales could be varied, though a tendency to 'drift' was present. This machine was a convenient means of visually monitoring the noise output, showing for example the possible presence of discrete-frequency components. A 1000 c/s signal and its harmonics calibrated the frequency scale, and polaroid photographs of the display were sometimes taken, (e.g. Figs. 10a and 10b), usually using six consecutive sweeps of the beam across the screen, to give the requisite density of image.

3. *The Reliability of Measurements.*

In the experiments to be described it became evident that a precise knowledge of the capability of each piece of equipment was necessary. An accurate calibration of all quantitative measuring devices was required to allow an investigation both of the consistency of noise levels and the significance of any differences.

3.1. *The Calibration of Noise-Measuring Equipment.*

All readings were related to the spectrometer dial, which was specified as indicating true root-mean-square pressures within a general accuracy of 0·2 db. Except in positions affected by the jet stream the needle of the dial was usually steady to within $\pm 0 \cdot 1$ db.

Although it was not possible to use the same microphone and cathode follower, or the same 10-metre cables, throughout the tests, all other pieces of equipment remained unchanged. For absolute sensitivity, the microphone cartridges were calibrated in sets of three at a frequency of 400 c/s using the reciprocity technique reported by Rayleigh[18]. For day-to-day work, it was found more convenient to check the whole system using the Bruel and Kjaer pistonphone. This generated a fixed-frequency noise of known level, and the difference between the indicated level on the spectrometer and the standard level was the correction factor for the particular microphone. This factor was always within about 0·2 db of the figure quoted by the makers, equal to the guaranteed accuracy of the pistonphone. The pressure response of a microphone, as determined by a Bruel and Kjaer electrostatic actuator, agreed precisely with the curve supplied by the makers. Attempts to calibrate the microphone using a Bruel and Kjaer Noise Source were not pursued as this broad-band noise generator was only accurate to within about $\pm$ 1 db.

The Vortexion Tape Recorder was used exclusively at its maximum tape speed of 15 in./sec. A record-replay response curve was obtained using an oscillator as input signal generator, and then replaying from the recorder to the spectrometer. Checks using signal height on a cathode-ray oscilloscope gave very satisfactory agreement.

The Pametrada Wave Analyser was the only narrow-band analyser used for quantitative work, and this had a frequency range from 20 c/s to 20,800 c/s. The 'in tune' filter was the narrowest one available but reading the dial was not easy because of the relatively large fluctuations in signal strength. As a consequence the 'narrow-band' filter series were used for the analysis of tape loops, but even then analysis was not easy below about 300 c/s. Using a sine-wave input the average bandwidth was found to be 4·1% (3 db down points). All narrow-band analyses in this report are presented, after correction, as spectrum levels. Checks also showed that no erasure of the high-frequency end of the spectrum occurred during the time taken to analyse a tape loop.

As the averaging meter in the level recorder had a different specification from the more accurate one of the spectrometer, a comparison was made. It was found possible to get differences in level quite consistent ones, between the temporal averaging of the fluctuations of the spectrometer dial needle and the spatial averaging of the fluctuations of the stylus trace of the recorder, and these are given in Table 2. The slight difference existing between automatic and hand switching through the octaves was due to initial stylus 'overswing' in the automatic case.

For a typical traverse, the overall noise was read on the spectrometer dial, and the octave levels were related to this by obtaining a level recorder trace using automatic switching. A typical example of such a trace is shown in Fig. 5, the vertical deflection of the stylus being 1 db/mm. Even with large damping it was possible to encounter large fluctuations in the lowest octaves, but repeated analyses gave very consistent levels. The noise levels of the main energy-bearing frequencies were certainly well-defined, and when the scale shift from this model to a full-scale ejector system is taken into account, the lowest octaves become even less important. A paper speed of 1 cm/sec and an octave sampling time of 1·44 sec was used. This enabled a constant pressure to be maintained throughout the complete spectrum sweep time of 16·2 sec and it was also possible to complete a given run, as described in Sections 3.2 and 5.4, with one quantity of stored air. This would not have been possible had slower sweep speeds been used or had all readings been taken visually from the spectrometer dial. This method also ensured that a permanent record was obtained. Third-octave analysis was only rarely employed, for as it was generally easy to make reasonably accurate spectrum level estimates from the octave levels, the additional information provided by the use of the third-octave filters was only marginal. A comparison of summed third-octave levels with measured octave levels showed that they agreed well.

Examples of the recorder output obtained whilst conditions in the jet were changing with time are also shown in Fig. 5, these particular ones being replays from tape recordings. The traces are of overall noise as the pressure was steadily increased, for the three cases of primary nozzle alone, with an ejector, and with the same ejector modified. (The flatness of the right-hand portion on the first of these indicates that in this particular case the tape recorder became overloaded.) Results such as these will be dealt with in Section 5.

3.2. *The Accuracy and Repeatability of Noise Measurements.*

To measure the noise a rectangular Cartesian system of position was adopted with intercepts of 24 inches between stations. This meant that the whole noise field could be covered with easy interpolation of values at intermediate locations and without the assumption implicit in measurements made on a single locus that the microphone is in the acoustic far field. In this report lines a, b, c and d were parallel to the discharge at 2, 4, 6 and 8 feet from the jet axis. Locations downstream were numbered from 0, square with the primary-nozzle exit plane, and upstream positions had an asterisk added. The co-ordinate system is shown in Fig. 3, including the corresponding positions on the other side of the jet, the lines there being designated with a dash. It was not possible to take measurements at all the indicated points due to encountering the jet itself, the presence of other rigs and the 'pancaking effect' of the jet on the far wall of the laboratory to produce reverse flow in outer areas. An intake box, whose use is described later, also produced a screening effect over a small area. These effects are all sketched in Fig. 3.

The microphone was mounted at the height of the centre-line of the jet and all measurements were taken in this horizontal plane. Initial measurements showed an interference effect in the noise spectrum. Checks with the self-supporting 'goose-neck' type of cathode follower proved that this was due to reflections from the mounting surface behind the microphone. By using an extension piece to this mounting the effect was removed and no other trouble with standing waves or reflections was experienced. Accurate siting of the microphone was obtained using a plumb-line over markers on the grating floor. A test showed that octave levels were only slightly affected and overall levels negligibly by any likely error in the angle which the microphone diaphragm subtended to the noise source.

A survey of the ambient noise in the laboratory was made. The overall level was about 55 to 60 db, depending on the precise microphone position and with third-octave levels appreciably lower, this meant that the background noise levels were quite acceptable. It was also found that sudden noises from external sources were never of sufficient intrusiveness to affect recordings when the jet was in action. Lagging the outside of the settling chamber, the largest untreated surface in the laboratory, made no difference to the jet-noise results obtained.

Before each series of measurements, readings of the atmospheric pressure, the temperature and humidity in the laboratory and the stagnation temperature and humidity of the jet were taken. A pistonphone check of the microphone sensitivity and a reading of the ambient noise level in the laboratory were also made.

A 'run', as considered in Section 5.4, usually meant the measurement of exhaust noise in a single traverse along a line a, b, c or d. As the edge of the jet was approached, a greater unsteadiness appeared in the signal, with sudden 'one-sided' fluctuations appearing in the trace of the lower octaves as the intermittent edge of the jet was entered. As this occurred before the overall noise level began to fluctuate greatly and these lowest octaves were significantly below the overall levels and other octave levels of interest, these results have not been excluded from the results in the appropriate tables. Inspection of the tabulation generally reveals which levels have been 'wind-influenced'. A Bruel and Kjaer Nose Cone was tested on the microphone to discover whether the range of measuring stations could be increased by protection of the diaphragm but as only a very limited improvement was noted the idea was abandoned.

The accuracy of a traverse was assessed by repeating a run. The overall noise levels measured together with those taken in the corresponding positions on the other side of the rig are compared in Table 3a. This part of the table also lists the spread of the octave levels measured amongst these three runs. Agreement was good, and a further investigation with measurements at all positions unaffected by the presence of other rigs confirmed to a high degree the symmetry of the noise field.

Consideration was also given to the sensitivity of the noise field to the precise position of ejector, and runs on ejector A3 were made in quick succession at a pressure ratio of 1·65 as follows:

To test the effect of skewness of the ejector, (i.e. the ejector axis was no longer parallel with the axis of the unshrouded primary jet), the ejector efflux end was displaced upwards, downwards, towards the measurement line and away from the measurement line. In each of these four cases the displacement was by half an inch.

To test the effect of lateral location of the ejector (i.e. the ejector axis was parallel to, but no longer coincident with, the axis of the unshrouded primary jet), the ejector was moved away from the measurement line and also towards it, in each case the shift being a quarter of an inch.

To test the effect of the longitudinal location of the ejector, the ejector was moved towards and away from the primary nozzle by a fifth of an inch, effectively altering (l/d_1) to 0·6 and 0·4 instead of 0·5.

The results of these tests are compared with the 'normal' tests in Table 3b by showing the spread produced. Although the displacements were somewhat greater than any mis-positioning which could be anticipated in normal practice, the alterations in noise levels were trifling. These tests show that the noise emitted was essentially a stable quantity and that reliance could be placed on the recorded sound pressure levels. A slight rider to this conclusion exists and this is considered in Section 5.3.

3.3. *The Accuracy of Measurements of Quantities other than Noise.*

Due to the flexibility of the floor gratings the Acoustics Laboratory was not well-suited to the taking of measurements which involved heavy pieces of equipment or rigid mountings. As a consequence the tests were almost exclusively limited to noise investigations though checks were in fact made of the inflow velocity at the mouths of several ejectors. The agreement with the results of Reid[4] were generally excellent as shown in Fig. 6a, and it was possible to reproduce the irregularity in the Mach number curve shown in his Fig.8b for ejector B1. The only noteworthy difference found on any occasion was with ejector C1 which had a slight but definite irregularity in the inflow curve at a pressure ratio of about 1·25. This is shown in Fig. 6b.

4. *The Identification of Noise Sources.*

As Section 3.2 has shown, the extraneous noise was sufficiently small to leave unaffected the noise levels measured when the ejector system was operating, and any emission must have been confined to

radiation from the ejector casing, ('noise from the sides')

radiation from the ejector intake, ('noise from the entrance')

radiation from the ejector efflux ('noise from the exit')

The investigation of these sources was the next requirement.

4.1. *Noise Radiated through Ejector Walls.*

In order to investigate the quantity of noise coming from the walls, a long ejector was selected to provide a large radiating surface. The noise levels measured during a traverse along line b when ejector B5 was mounted within an iron tube the annulus being packed with sand were no different from those taken when this ejector was mounted normally. The tube was as large as the mounting system would allow, some 54 inches long and $6\frac{1}{2}$ inches in diameter. Fig. 7 compares both their overall noise along line b and the spectra at a typical position. Had the noise been coming through the side, the addition of the weighty sand would have affected the transmission according to the 'Mass Law' with a fall-off in level approximating to 6 db per octave rise, as has been measured before in this laboratory when noise was being radiated through the walls of a structure carrying internal airflow (Middleton[19]). It was therefore clear that in the present experiments no noise was coming from the ejector walls.

4.2. *Noise Radiated from Ejector Intakes.*

In the curve of overall noise shown in Fig. 7, the bulge occurring square with the ejector intake suggested that some noise was being emitted from the intake. To investigate this effect an 'intake box' was constructed, and it is partially shown in Figs. 2 and 3. In two interlocking parts it was made of half-inch thick ply with a one-and-a-half-inches thick lining of the poly-urethane foam 'Volag' to act as sound absorber. It was mounted from the upper bar supporting the ejector clamping arrangement, and the ejector passed through a hole in the square face with the gap sealed by the soft collar of Volag nestling around the ejector. With such a design it was possible to use the same box for all three diameters of ejector. The face was 19 inches square, and the side walls stretched back $6\frac{1}{2}$ inches so that with these dimensions screening of the ejector exit only occurred for the few measuring positions indicated in Fig. 3.

Use of the intake box made it necessary to ensure that no restriction of the secondary airflow was introduced, and checks showed that the same static depressions at the ejector inlet occurred for the same value of total head as had been obtained previously. Thus the aerodynamic performance of the ejector was unimpaired. The resulting trace of overall noise for line b is shown in Fig. 8 together with third-octave spectra at positions b0 and b9. These results show that the 'bulge' around the intake location had been eradicated, whilst further downstream the noise was unaffected. This latter must therefore be solely due to radiation from the efflux.

As a result of this test it was decided to do all investigations of the efflux noise with this suppressor in position, for if this were not done the contribution from the intake noise would confuse the results. On the other hand an investigation of the intake noise in its own right was not possible since the radiation from the efflux end produced too great a masking effect. From Fig. 8 it can be seen that for this particular ejector 3 db was the most by which the overall noise was increased by the intake noise, so that the intake noise could only equal the remaining noise and was in general exceeded by it.

5. *The Types of Noise Emitted.*

The previous sections have shown that broad-band noise radiated through the ejector casing was not a significant factor, and that the effect of noise from the intake could be eliminated. The problem thus remained of identifying the types of noise emitted from the efflux.

5.1. *Shock Noise.*

It was soon evident that at sufficiently high operating condition, strong 'shrieks' were present. For the unshrouded primary nozzle, they were manifest at pressure ratios of about 2·1 and above and their onset was accompanied by a sharp change in the rate of increase of noise as indicated by the trace of overall noise *versus* pressure in Fig. 5. The display on the panoramic analyser at a given pressure ratio was similar to the photograph shown in Fig. 10a and narrow-band analyses of the noise at the b0 position are given in Fig. 11 for pressure ratios of 1·8 and 2·6. It is clear that the screech heard and the increase in noise output of the order of 10 db were due to the strong discrete-frequency components which the narrow-band analysis indicated.

This screech phenomenon was first reported by Powell[6] working on axi-symmetric jets and he subsequently extended this to two-dimensional jets[20] which were easier to study experimentally. Such shrieking can only occur when the jet is operating at a pressure ratio above the choking value of 1·89 and the mechanism can be considered as follows:

When air discharges from a convergent nozzle, the speed of flow at the mouth cannot be greater than the local speed of sound. When the total pressure upstream of the nozzle is raised above the value sufficient to produce choking at the nozzle exit, the static pressure at the mouth must increase to give a flow which is just sonic there, an effect shown in Fig. 6a. Downstream of the efflux plane the static pressure decreases towards ambient and the flow velocity increases, passing a maximum and then decreasing to a position where a standing shock is located. The conditions there are essentially a repeat of those existing at the nozzle exit, and the flow cycle would repeat itself indefinitely were it not for the dissipative effects of turbulence and viscosity. The jet stream therefore has in it a series of standing shock waves which divides the flow into 'cells'. When a disturbance in the flow from the orifice is amplified under convection downstream, the interaction between this eddy and such a shock produces an acoustic wave from the cell end. This wave propagates into the surrounding free medium and the wave on passing the nozzle lip initiates a new disturbance in the stream to complete the cycle.

Clearly the frequency of this phenomenon depends upon the cell structure in the jet as well as the convection velocity of the eddy. The frequency of the note has been shown (Merle[21]) to be inversely proportional to the diameter of the nozzle, and Powell[22] has shown that not only are there certain supercritical conditions at which no discrete noise was present, but that for axi-symmetric jets certain 'stages' existed. In each of these stages the frequency fell monatonically with increase in pressure ratio, but at particular conditions sudden changes in the value of the fundamental frequency occurred. Some hysteresis could be present in the value of the change-over position, and Merle separately[23] and together with Canac[24] has mentioned the change in cell structure which accompanied such a change in frequency. This matter has been considered more deeply in the work of Davies and Oldfield[25].

Scaling the results given by Merle[21], Powell[22], Davies and Oldfield[25] to a common reference nozzle diameter of one inch, the graph of frequency of fundamental note *versus* pressure ratio are shown in Fig. 12, together with the results for the present nozzle similarly scaled. Lassiter and Hubbard[26] also made a few measurements but much of their value is lost in that they were apparently unaware of the existence of 'stages' and the figures given were not adequate to determine just where any frequency discontinuities occurred.

Bearing in mind the differences in the methods of frequency measurement (optical and electrical) and different experimental set-ups (nozzles or orifices), together with the differences which presumably existed in the humidities, temperatures and pressure ratio, (the true value of atmospheric pressure was not recorded in some reported work), Fig. 12 indicates that essentially the results appear to agree well over large ranges but that also some differences exist. The conclusion seems to be that whilst the frequency of emission corresponding to a given stage at a given pressure ratio appears fixed, there is some latitude between one nozzle and another concerning the stage actually selected. Merle[27] has commented on the stability of stages. In the present tests it was not possible to investigate the relationship at pressure ratios above 3·5. Reflectors may have an effect on cell pattern and point of frequency change, as discussed in Part II of the work of Davies and Oldfield[25], and in the two-dimensional case by Hammitt[28]. Merle[29] has investigated the effect of baffles for a rectangular jet. It would appear, therefore, that the most plausible factor affecting the cell pattern (and hence the frequency of emission) is the precise design of discharge unit and the form of any nearby surfaces.

Some experiments were then conducted to investigate what modifying effects the presence of ejector tubes had. In the majority of the tests to be described although the primary nozzle was choked the mixed jet discharging from the ejector was subsonic, ensuring that any screech could not be due to feedback from a cell pattern downstream of the ejector's efflux lip.

That the phenomenon was again present with ejector tubes is shown by the photograph in Fig. 10a which is for ejector B1. Its existence in the present series of tests was first reported by Middleton and Richards[30]. As with the unshrouded case, a well-defined fundamental together with its simple harmonics were present. In general the higher harmonics were of weaker strength but could often be detected up to the upper frequency limit of the analysing equipment. Powell's work[31] indicated that for an unshrouded jet the ratios of their strengths were a function of measuring position. In the shrouded case such directivity effects must have been somewhat modified by the fact that the acoustic wave had to be propagated back to the orifice not through quiescent atmosphere but through the secondary flow, the subsonic annulus surrounding the supersonic primary flow. As mixing between the streams was taking place this must have further blurred the picture. Fig. 13 contains the plot of frequency of the fundamental note against pressure ratio both for the unshrouded jet and for a typical ejector. Other ejectors gave different curves, and it is clear that the cell pattern must have undergone considerable quantitative modification from the unshrouded case.

Evidence is exceedingly scanty supporting the existence of shock noise when full-scale axial-flow turbo-jet engines are operating at suitable pressure ratios. This is not simply due to temperature effects as Lassiter and Hubbard[26] reported discrete frequencies on a hot model jet, although they were relatively much weaker. This suggests that the strength of the mechanism is dependent on the amount of roughness or initial turbulence in the system. Powell[31] discussed the possibility of eliminating the discrete components by roughening the flow and so steps were taken to investigate this approach.

Using the primary nozzle without any ejector, it was found that by glueing a thin coat of sand to the convergent approach section of the nozzle some amelioration was produced. A particular result was a reduction of 5 db in the overall noise thereby bringing it to within 2 db of the broad-band contribution. The new spectrum is shown in Fig. 11. A similar coating to the external face of the primary nozzle made no difference nor did a lining of emery paper within the internal cylindrical section save for a rise in frequency consistent with the decrease in effective nozzle diameter. When used with an ejector this modified nozzle still produced discrete frequencies. Roughening made no detectable difference to the broad-band noise. It is clear from these results and from the earlier Southampton tests of Foxwell[14] which have been already mentioned, that complete elimination of such frequencies might only be possible with a system which had undergone appreciable modification. As a consequence it was decided to restrict work to the unmodified arrangement with narrow-band analysis as necessary.

5.2. *Excess Broad-Band High-Frequency Emission.*

Under certain conditions a further type of noise was found superimposed on the spectrum. Unlike the discrete-frequency phenomenon already discussed, it was broad band in character with a lower bound usually between about 5 and 10 kc/s. The level of the noise sometimes varied with time. Although this noise was first discovered when an ejector was being used, its existence was confirmed on the unshrouded primary nozzle and also on the machined nozzle previously used for other jet work in the laboratory. The phenomenon was also detected with an independent recording system of crystal microphone, transistorised cathode follower and separate recorder. Thus it was not peculiar to the particular configuration under investigation, nor was it due to a fault in the manner of recording.

Typical examples of this additional high-frequency noise are shown in Fig. 14a which illustrate that the 'excess noise' appeared to have a lower frequency limit dependent on pressure ratio. Any upper limit was above the range of the analysing equipment. Coupled with this difficulty was the fact that the magnitude was not constant with time. This point is shown in Fig. 14b, where the four narrow-band analyses are for runs carried out in quick succession in the order 1·9, 2·35, 2·35, 1·9 where these figures represent the *true* pressure ratio. The results for the two analyses made for the runs at the just-choking condition are identical, but for the higher frequencies there exists a fall-off in level between the two 'well-choked' runs. Variations in noise levels were always attributable to the change in level of the 'high-frequency bulge'. Generally this level decreased during a test but increases were also observed and at other times the noise level appeared fairly stable.

In this series of tests the excess high-frequency noise levels were never detected from flows which were entirely subsonic, and this suggested that the phenomenon was associated with choked flow. Its manifestation appeared completely independent of that other product of choked flow, the discrete-frequency emission covered by Section 5.1, as both, neither or just one of these phenomena might be present in any particular test. It seems probable that this is identical with the high-frequency radiation reported by Powell[15] but since no quantitative details were included in his report strict comparison cannot be made.

As it was not possible to study the upper frequency end of this emission, and as the radiation itself appeared to be of somewhat arbitrary magnitude, it was not considered suitable for further consideration in the present investigation. This factor and the general presence of discrete frequencies meant that all measurements made above choking conditions would require extremely assiduous analysis to determine the quantitative structure of their various noise components. Consequently, for this report no further tests were made on ejectors operating at supercritical conditions.

5.3. *Discrete-frequency Emission from Subsonic Flow.**

Attention was now directed to the subsonic region and it was confirmed that the 'intense discrete-frequency noise' mentioned by Reid[4] in Section 7 of his report for the three short ejectors was also present here. It was further found that the effect was not confined to these ejectors though the shorter the shroud, the more severe were the discrete frequencies. (No discrete frequencies were ever detected when the discharge from the unshrouded primary nozzle was subsonic). It was desirable to ascertain the nature and origin of these notes for if their method of generation were known, a possible means of suppressing them might be indicated. Some initial results are contained in a earlier paper[30].

In an otherwise 'flattish' spectrum from a narrow-band analysis a 'hump' may represent a discrete frequency, that is, a sinusoidal signal. Alternatively, it may be the result of passing random noise through a narrow (acoustic) filter. If the bandwidth of this latter is less than the width of acceptance of the narrow-band analyser, two notes fundamentally different, will yield 'identical' analyses. However the ear is far more responsive to a noise which is truly discrete, so that the aural effect may be quite different. To investigate the present phenomena, some tape recordings were analysed using an Elliott Reflecting Wattmeter as a phase-sensitive detector. An attempt was made to 'beat' the suspected 'discrete' frequency with the output from an oscillator, and it was found that definite beating, confirming the truly discrete nature of the notes, existed in some cases but not all. To give examples from narrow-band analyses presented in this report to illustrate later points, the 1640 c/s

* Although this title is a convenient one, both the words 'discrete' and 'subsonic' strictly need some qualification, as the text subsequently shows.

signal and its harmonics in Fig. 15 were found to be discrete but none of the others and none of the ones for ejector C4 in Fig. 17. On the other hand, 'discreteness' was not necessarily restricted to one 'mode' as another spectrum gave two frequencies, quite close together, as being each discrete. This pair in fact occurred in a spectrum which also contained shock noise. All the tests carried out on 'shock' frequencies showed them to be discrete phenomena. Thus the word 'discrete' in the title of this section needs to be treated with reserve. Its repeated use in the text which follows, is not therefore intended to signify precisely the nature of a given note. Correct at least in some cases, it is certainly a convenient term to describe any 'extrusions' in a spectrum.

To ensure that the discrete frequencies measured were not due to interference effects in propagation, (for example, standing waves produced by interaction between noise emitted from the ejector intake and efflux ends), measurements were taken of the noise spectrum at more than one position in the laboratory. It was found that the discrete notes had exactly the same frequency although their amplitude and that of the broad-band noise on which they were superimposed varied according to position. Significant discrete-frequency radiation was found to come from both the upstream and downstream ends of the ejector. It was also shown that, within the response capabilities of a probe microphone which was inserted into the wall of an ejector, the discrete frequencies within the tube were the same as those recorded externally. No further attempt to establish the directionality of the discrete-frequency noise was made, and measurements of this phenomenon were now restricted to the noise output recorded at position b0. A typical photograph of the resultant display on the panoramic analyser is shown in Fig. 10b.

A trace of the overall noise measured as the stagnation pressure was steadily increased is shown for ejector A2 in Fig. 5. The difference between the noise output of an ejector and that of the primary nozzle which is also shown in Fig. 5 is most marked. As the driving pressure was steadily increased, the low note dominating the jet roar, and which appeared to be present from the moment the discharge commenced, rose in frequency. Harmonics were also present, and at certain stages in the increase in operating condition, frequencies seemed to 'cut in' or die away, producing quite sudden changes in the aural quality and in the level of the noise. Thus quite complicated spectra could result. The quick changes in level are clear in the appropriate trace in Fig. 5, and the frequency changes which occurred are demonstrated in the Sona-Graph trace of Fig. 4. This latter is, in fact, an analysis of a 2·4 seconds period in the tape recording of which this level recorder trace is a replay, and it was possible in the analysis to correlate the frequency changes with alterations in the overall level.

Further increase in pressure was accompanied by a steady increase in the broad-band discharge noise, and the discrete components tended to become engulfed by this noise. However, in some cases the components were sufficiently intrusive to be still detectable when the primary nozzle had choked so that a 'mixed spectrum' resulted, i.e. a spectrum which contained discrete frequencies associated with shock noise as well as discrete frequencies which were an extension from the subsonic range. No confusion ever arose as to which type was which. Although not entirely correct it is therefore convenient to refer to this type of frequency as a 'subsonic flow discrete frequency' in contrast to the 'supersonic flow discrete frequencies' of Section 5.1.

The plot of overall noise against pressure ratio obtained from step-by-step increase in operating condition for this ejector A2 is contained in Fig. 9. When the pressure was decreased, slight hysteresis was sometimes revealed. Even allowing for the fact that the equivalent trace in Fig. 5 lacks a precise pressure scale, differences are seen to exist between these two results taken at position b0. This is due to the fact that since the pressure was being increased continuously the conditions within the shroud never achieved the 'steady' states corresponding to stepwise increases, and one could therefore anticipate differences between these two acoustic outputs. The response time of the recorder stylus might also have some effect on the trace in Fig. 5. A plot of the overall noise from the unshrouded primary nozzle, as measured at position b2, is also included in Fig. 9. It is evident that this discrete noise could be of sufficient magnitude to more than off-set any reduction in the broad-band noise which the ejector system might achieve over the unmodified jet.

Two mechanisms might be envisaged as possibly responsible for the production of such tones. The first was that turbulence in the internal flow caused pressure fluctuations on the inner face of the ejector and the recorded sound was due to this excitation of the tube. Weyers[32] has in fact reported this effect in measurements on tubes made of Mylar. A second mechanism was that some type of 'organ-piping' was occurring, the word here meaning any periodic motion associated with the airflows inside the ejector. Clearly these methods are not mutually exclusive and it might be that each contributed to the production of these notes.

To determine the type of oscillation, some simple tests were carried out, using ejector A2. A crystal strain gauge to measure any bending or twisting strain in the plane of the surface and an accelerometer to measure vibrations perpendicular to the surface were mounted on the ejector. The usual supports for the ejector were adapted for use on an antivibration block in the Structures and Vibration Laboratory of the Department. The stud from a Goodman's Vibration Generator was mounted through a hole 0·4 inch from the unflanged end of the ejector and a Muirhead-Wigan Decade Oscillator used to excite the vibrator. The strain-gauge output was taken both to the Solartron Resolved Component Indicator and to the Tektronix Dual-Beam Oscilloscope, this latter also monitoring the input frequency. Although it can only be used with a sine-wave input and thus not with jet noise, the advantage of the Resolved Component Indicator was that by measuring phase change as well as signal magnitude it was possible to locate a resonant peak even if the transducer were on a node. This analysis became rather lengthy due to the very large frequency range to be covered and was replaced by noting the magnitude of the deflection of the output signal on the oscilloscope. In this way the frequencies of the tube up to 5000 c/s were located. A similar check was made using the accelerometer. The ejector was next excited using the output from a Dawes White Noise Generator, and the output on a tape was then narrow-band-analysed by the Pametrada Wave Analyser. This procedure was repeated after moving one of the supports for the ejector. The results showed that due to the change in constraint small alterations had occurred in the values of the frequencies, especially the lower ones. The ejector was then remounted in its usual manner relative to the primary nozzle and the noise, accelerometer and strain-gauge outputs were measured for a pressure ratio of 1·35. With the ejector re-erected with only one support, these outputs were re-taken for the same pressure ratio. The results from these strain-gauge and noise tests are shown in Fig. 15 but no allowance has been made for the non-linearity of the strain-gauge response. The accelerometer results, being similar to those of the straingauge have been omitted*. It is clear from this figure that whilst the modes of vibration of the tubes were dependent on the constraints of the mounting the noise output was not thus dependent. Therefore although the walls of the tube were excited by the internal airflow, the frequencies of their vibration were not identical with the acoustic discrete frequencies and the phenomenon was not due to mechanical vibration.

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* 'Similar' here means that many of the frequencies shown by one were also shown by the other. However, each possessed spectrum peaks not apparent in the second.

To investigate whether the amplitude of the shell vibration had any effect on the radiated noise, a half-inch thick layer of 'Aquaplas', which has high natural damping properties, was placed around the ejector A2. Previously the freely suspended tube when struck had given quite a 'metallic ring' but it now sounded completely 'dead'. However, at given operating condition of the jet the noise level and the spectrum were identical with the unmodified ejector results.

The noise level and the spectrum shape were also completely unaffected when the system was mass-controlled by encasing the ejector within a two-inch thick annulus of sand. A check on ejector B5 showed that its discrete frequencies were so weak as to be virtually undetectable, and so the earlier tests covered by Section 4.1 had in fact dealt with the sole question of transmission of broad-band noise through the ejector shell. These earlier tests and the present ones together show that neither broad-band nor discrete-frequency noise was radiated from the ejector walls.

The differences between the two noise spectra shown in Fig. 15 are only slight but serve as a good example of the difficulties which sometimes appeared in attempts to locate and identify discrete frequencies. For example, in one of the cases the peak at about 6500 c/s was not discernible above the background noise. A second hazard was that a weak frequency could be obscured by the skirts of a strong frequency as happened in the case of the 1350 c/s signal in the left-hand spectrum. Thirdly, two frequencies of similar amplitude could be so close together that the analysis suggested a single peak of intermediate frequency as tended to happen to the 2800 c/s and 2990 c/s signals shown. Also present in some analyses were what may be termed extra 'broad-band peaks' occurring below about 1000 c/s. An example of this, covering the range from about 200 c/s to 600 c/s, is shown in Fig. 15.

Since some of the frequencies could be up to 30 db above the immediate surrounds and up to 50 db above the frequencies further away, it was necessary to check that the 'noise' measured at some distance away from a strong frequency was not simply the filter contribution of the skirt of the main frequency. A Cawkell Band Pass Filter was used to remove the dominant frequency, and since exactly the same noise levels resulted for the remainder of the spectrum, the indicated levels were in fact genuine.

An alternative method of obtaining narrow-band frequency distributions was attempted using the Southampton University Correlator. The procedure was to obtain the autocorrelation function of the signal using this machine and then determine the spectrum levels from the Fourier transform of the function. This method was not successful as a strong note could so dominate the signal that a longer time delay than the machine possessed, (140 milli-seconds), was required to fully evaluate the autocorrelation.

In a test on ejector C2, when the operating conditions appeared to be quite steady, a fluctuating output was heard with a change in aural quality about once in every two seconds. Analysis of the tape showed that a 3 db variation in the overall noise existed and that this was produced by fluctuations in the strengths of the dominant discrete frequencies. The main frequency of 1780 c/s would stay at a certain level before dropping about 15 db and this would be accompanied by a rise of some 12 db in the second frequency of 2080 c/s. After about 2 seconds these frequencies would revert to their former strengths and so the cycle continued. Other discrete frequencies present were also modulated but to a lesser degree. Apart from this single illustration the transfer of energy from one mode to another appeared to be a gradual process with redistribution occurring over a pressure change of about 0·1 p.s.i. or more. Thus for a given condition a spectrum was generally quite reproducible, both in the values of the discrete frequencies and their levels.

Tests were then undertaken to determine what other factors might have some effect on them, and teak ejectors were constructed with internal dimensions similar to those of the metal ones. Mahogany bellmouths were also prepared and the same mounting arrangement used as for the metal ejectors. It was found that a wooden ejector had the same inflow characteristics as the corresponding metal one and that for a given pressure ratio the discrete frequencies detected were the same. There were certain differences in the relative strengths of these frequencies but the general picture was quite similar and the broad-band noise levels were identical. The construction of the ejector walls was therefore relatively unimportant.

Different longitudinal locations of an ejector could produce severe changes in the noise output according to the relative strengths of the particular discrete modes excited. Normally, their frequencies lowered and their intensities lessened as the ejector was moved downstream. It was still possible to get discrete notes even when the entrance face of the bellmouth was downstream of the exit plane of the nozzle. A check on ejector A3 showed that in its normal location the discrete frequencies were very weak and hence it was unlikely that their contribution had significantly changed in the displacement tests reported in Section 3.2.

Even when the primary nozzle was allowed to discharge into a large pipe, the one described in Section 4.1, a very undulatory spectrum resulted, the peaks being 10 db or more above the surrounding levels. As might be anticipated from a presumably rougher flow, the peaks tended to be broader than with a proper ejector, but otherwise they exhibited the same characteristics.

It was further discovered that any alteration of the inflow conditions in the secondary annulus could have a profound affect on the noise output. Complete blockage of the inlet resulted in a smooth spectrum modified only by a few weak peaks. These did not bear any obvious relationship to the ones of the unobstructed flow, and may have been associated with cavity resonances or other separated flow phenomena.

It was clear from the complicated relationship of these discrete frequencies that the phenomenon was not a linear one. Inspection has shown that the frequencies present were those associated with combination tones, i.e. 'sum' and 'difference' frequencies of the primary notes were present due to non-linear interaction. The discrete frequencies appearing in various figures in this report have been broken down into these sum and difference relationships in Table 4. In this table each frequency has been expressed as a linear combination of x and y where x denotes the principal frequency and y the difference frequency. The results could of course be rewritten in terms of linear combinations of any two other non-harmonically related frequencies thereby giving the table a slightly different appearance. When fewer notes were present the relationship was not so obvious and in many cases it was not at all clear just what was the underlying pattern.

In Section 5.1 an outline was given of the methods used in attempts to eliminate, or failing this, to reduce the discrete frequencies due to supersonic flow. Similar approaches were adopted in the subsonic case.

Lining the ejector internally with sandpaper was found to be efficient for lowering the discrete components at some conditions but such roughening produced little or no change at others. This is demonstrated by an inspection of the traces of overall noise shown in Fig. 5 for ejector A2 unmodified and then lined with sand. As the rates of pressure increase were not the same and a small shift in datum level existed between the two traces, strict comparison is not possible.

The use of splitters of various lengths inside tubes which were otherwise unmodified produced spectra in which the frequencies were blurred and weakened though unchanged in value. Splitters were also tested in conjunction with an ejector known to be almost free from discrete notes and a considerable change in the directivity and strength of the noise field ensued, presumably due to the introduction of dipole radiation as well as changes in the basic aerodynamic parameters.

The final method was an attempt to absorb these frequencies using a foam plastic as the internal lining for the ejectors. A half-inch thick coat for ejector C1 reduced its dimensions to approximately those of ejector A1, and the discrete output was much less than that from either of these ejectors when unmodified. In contrast, when the foam linings were tested in conjunction with tubes whose discrete frequencies were weak, the noise level increased.

The conclusion from this work was that no physical method existed of removing these discrete frequencies which did not entail a most drastic modification of the whole system.

5.4. *Broad-Band Discharge Noise.*

The foregoing sections have shown that the study of the broad-band noise from the efflux of ejectors was severely complicated by the presence of other types of noise, the only one to be successfully eliminated being the noise from the inlet by the use of an intake box. All tests on ejectors were therefore carried out using the intake muffler as the only significant modification to the corresponding ejector set-up of Reid[4]. In view of Sections 5.1 and 5.2 the jet had generally to be subsonic, although in certain cases operation slightly above the choking pressure ratios was found to be permissible. Even in the subsonic cases the discrete-frequency phenomena described in Section 5.3 could be so severe that it was impossible to estimate the level of the broad-band spectrum on which these discrete frequencies were superimposed. These frequencies were strongest for the shorter shrouds but, as this section will show, extrapolation from the longer shrouds indicated that the anticipated broad-band attenuation from these short ejectors would be very small and less than the likely error involved in such estimation. Noise tests on ejectors were therefore restricted to those conditions where it was possible to make a reasonable assessment of the contribution of the discrete frequencies to the overall noise.

The procedure adopted for noise measurement has been described in Sections 3.1 and 3.2. Complete surveys over lines a, b, c and d were made for the primary nozzle operating at pressure ratios of 1·2, 1·35 and 1·65, and as there was no evidence of shock noise or 'high-frequency bulge', measurements were also taken at a pressure ratio of 2·0. This range covered the greater proportion of the efflux velocities encountered in ejector tests. Inspection of the results showed that interpolation of levels at any point within the area of measurement presented no difficulty, and more comprehensive tests at a particular point showed that over the velocity range encountered the value of n was constant in the assumed relationship:

Sound pressure in octave bandwidth is proportional to the nth power of the jet velocity.

For the position selected, approximately that of peak noise on line b, this value of n lay between about 6·5 and 10 (depending on the particular octave) and the overall noise had a velocity index of about 8·5, which is similar to Lighthill's value of 8 for the integrated sound power output.

The contours of overall noise obtained from the spectrometer dial readings are shown in Fig. 16a for a pressure ratio of 1·65, and the corrected octave levels for all four operating conditions are given for line b in Table 5. These results illustrate that the noise field from the primary nozzle is in qualitative agreement with the profuse literature now available on the noise from simple jets, e.g. von Gierke[3], together with the work of Gerrard[33] for cold subsonic jets and Pietrasanta's results[34] for full-scale hot turbo-jets.

A full noise survey was also made on an ejector for which the discrete frequencies were known to be weak, and the resulting contours for ejector A3 are shown in Fig. 16b. The general features are the same as those of the primary nozzle suggesting that in such a case the discrete frequencies did not greatly modify the overall picture.

In order to investigate more precisely the effect that the discrete frequencies were having, measurements were restricted to line b after checks on the decrease of noise level with distance had demonstrated that this line lay in the acoustic far field. These tests also showed that the attenuation of an ejector, conveniently defined as the difference between the peak noise level of the primary nozzle and that of the ejector as measured along some line parallel to the efflux, was independent of the line selected. It therefore seemed reasonable to restrict measurements to a single line and line b was especially suitable having neither the flat noise characteristic of lines c and d nor the excessive shortness and peakedness of line a.

The method adopted was to make a tape recording of the noise at the co-ordinate nearest to the peak noise position (as interpolated from the traverse along line b). From the narrow-band analysis of the tape the magnitudes of the intrusive discrete notes could be established and hence their contribution to the overall noise found. An autocode programme was specially devised to do this calculation, using the Pegasus Digital Computer of the University.

In order to test whether this method would give reliable results a check was made by adding to the broad-band spectrum from the primary jet operating subsonically 'artificial' discrete notes from an oscillator driving a loudspeaker suspended below the jet. Fig. 17a shows the resultant spectrum when a 1000 c/s note was superimposed on the jet noise. The octave levels, as measured directly on the spectrometer dial and as calculated from narrow-band analysis, (making these latter sum to the direct overall noise), were as follows:

Octave Number	1	2	3	4	5	6	7	8	9	10	O.A.
Direct Reading	64·3	66·8	73·3	79·8	87·0	88·0	88·1	87·7	86·0	85·6	95·2
As Computed	60·7	66·9	73·5	79·4	86·5	87·1	88·4	88·5	86·7	85·3	datum
	db re 0·0002 dyne/sq. cm										

Without the 1000 c/s note the measured level in the fifth octave fell to 84·5 db and the overall level to 94·9 db. The computed levels were 84·4 db and 94·9 db respectively, which is certainly good agreement.

For noises which had well-defined broad-band spectra the method could therefore be used to indicate with reasonable accuracy the octave levels of this broad-band noise. Fig. 17b shows the spectrum from an ejector for which this method was used. It will be noted that extrapolation of the narrow-band analysis up to 35,500 c/s was necessary, but such extrapolation was believed to be not too prone to error.

The ejectors for which this method was feasible were found to be the —3, —4 and —5 length ejectors of all diameters at pressure ratios of both 1·35 and 1·65, and ejector A2 at the 1·65 pressure-ratio condition. Table 6 gives the spectrometer readings for the overall noise for these conditions and also the amounts by which the discrete frequencies were calculated to increase the overall levels at the positions indicated. Showing the corrected octave values taken from the level recorder, the parameter in Table 7 is ejector length whilst in Table 8 it is ejector diameter. In the right-hand column in these two tables some octave levels are shown, these being the levels after the discrete contribution had been filtered out at the specified position. In this column a value identical with the corresponding position in the main table indicates the strength was insufficient to alter it by as much as half a decibel whilst the absence of any figure means that no discrete note was detected in that octave.

The results immediately demonstrate that the *longer* the ejector the smaller the quantity of noise radiated. To assess the effect of tube *diameter*, Fig. 18 has been plotted. It shows that ejectors of similar length tend to produce similar amounts of noise, and this is emphasised when the influence of the discrete notes is removed by altering the level by the indicated amounts. The comparison of the broad-band spectra for ejectors of equal length is made in Fig. 19 and their similarity is most marked. It is unfortunate that it was not a practical proposition to attempt to filter out the discrete frequencies at all positions, (checks having shown that their contribution could be different at different locations), and so strict comparison was limited to this study at the co-ordinate near the peak noise position. However, Table 8 shows that the unfiltered spectra at any other positions are similar for all three diameters.

The work of Reid[4] demonstrated that at given operating pressure ratio, the difference between static depression at the mouth of one ejector and another of the same length was not sufficiently large to produce any big difference in the true Mach number of their primary discharges. The variation for the —3, —4 and —5 tubes, to which the discussion is now limited, was quite small. Thus for a given applied pressure, the primary jet discharged into these sleeves at virtually the same velocity, although the efflux velocity at the end of the ejector was sensitive to tube diameter as well as tube length. As summarised recently by Lighthill[35, 36], when dealing with the discharge from a given shape of exit, it has usually been possible to relate the radiated noise to some velocity measure in the jet. Such factors as velocity profile, scale of turbulence and other parameters mainly govern the relationship between the noise from one *type* of nozzle and another. Therefore a plot of the filtered peak noise levels against the logarithm of the peak final efflux velocities is given in Fig. 20. It is Fig. 21, however, showing the peak-to-peak reduction in broad-band noise plotted against ejector length which gives the good collapse of the data. From this graph it may be concluded that little additional attenuation would result from employing ejector tubes of even greater length. It is also clear as mentioned earlier, that the reduction in the broad-band noise to be expected from the shorter ejectors is so small that its magnitude would be less than the likely error in the method. No dependence of attenuation characteristics on operating condition is revealed as a single curve, independent of pressure ratio, may be fitted to these results.

The similarity of the broad-band noise field from ejectors of given length and operating at a given pressure ratio, together with the fact shown in Fig. 20 that the noise levels were appreciably higher than would be anticipated from a simple jet of equivalent velocity suggests that the noise measured was essentially that of the primary jet discharging and mixing within the sleeve. The chief modifying factor would be its passage along the ejector itself, and the lined ejector tests of Section 5.3 have shown that the internal noise can be affected in this way.

6. *Conclusions.*

As was stressed in the part of Section 1 reviewing the published work on ejector noise, a correlation of the results is not easy. The early work of North and Coles[5] referred to the reduction achieved in total acoustic power but as this obscures directivity effects it has become more customary to refer to the noise-reducing ability of a suppressor in simple terms such as the difference in peak sound pressure levels measured along the same line or arc for the device and an unmodified nozzle. Sometimes it has been possible to use units more adapted to the response of the ear by transforming the spectra to get subjective units like 'PN db'. Due to the question of frequency shift from the present small-scale cold jet to a full-scale hot jet, in the present report it has been more convenient to deal only in objective units.

The following table shows how different the attenuations may appear when quoted in different ways even though the discussion is limited solely to objective units. In each case the attenuation is defined as the difference between the maximum overall sound pressure level measured for the primary nozzle and for the ejector along the indicated locus, and is quoted to the nearest $\frac{1}{2}$ db.

The conditions are:

(i) a line parallel to the jet axis

(ii) an arc, centred on the primary nozzle, and of radius 90 nozzle diameters

(iii) as (ii), except that for the ejector the arc is centred on its downstream end.

Ejector	P/p_0	'Attenuation' db		
		(i)	(ii)	(iii)
A2	1·65	1	$-\frac{1}{2}$	0
A3	1·35, 1·65	$2\frac{1}{2}$	$1\frac{1}{2}$	3
B5	1·35, 1·65	7	$6\frac{1}{2}$	10

For the three ejectors shown, the discrete-frequency components were weak and would not therefore have a large effect on the figures quoted. As Section 5.4 has stated, the attenuation obtained from (i) was independent of the line selected. The difference between the results for methods (ii) and (iii) would naturally decrease as the radius of the arc increased. The figure of ninety used above is the largest one that the confines of the measurement area would allow. The actual figures for methods (ii) and (iii) were obtained by interpolation from contours similar to those of Fig. 16.

The foregoing work may be summarised by the following conclusions.

(1) A relatively small quantity of broad-band noise was radiated from an ejector intake. It was principally high frequency, suggesting it came from the initial part of the primary jet as it discharged and mixed with the induced secondary flow. At a given position the noise from the intake was generally dominated by the contribution from the exhaust, and a separate study of its own properties was therefore not feasible. In the present tests it was effectively suppressed using the absorber box described in the text.

(2) In addition to the usual broad-band discharge some broad-band noise of high frequency appeared under certain conditions. It was detected when the primary nozzle was operating both with and without any ejector. Its magnitude appeared to vary in an arbitrary manner with time, and as a significant proportion appeared to lie above the frequency range of the available instrumentation, its study was not pursued. Its presence seemed to be confined to pressure ratios above choking, and so to exclude the effect, quantitative measurements of the broad-band noise from ejectors were restricted to subsonic conditions.

(3) Shock noise appeared in the noise from the primary nozzle when operating at supersonic conditions. The variation of frequency of the fundamental note with pressure ratio agreed well with the work of some of the earlier experimenters. Differences existing amongst these workers may be due to differences in their experimental arrangements.

(4) This shock noise was also found to be present when the primary jet was operating supersonically within an ejector. The variation of frequency with operating condition differed for different ejectors suggesting modifications to the cell pattern by the ejector. Various references[5, 16] support the view that the phenomenon may have been present in associated unpublished data.

(5) A second source of discrete-frequency noise has been shown to exist. Although, for a given ejector, these frequencies may have been detected at operating conditions which continued into the supersonic range, they were usually strongest at the lower conditions, say below a pressure ratio of about 1·4. The shorter the ejector tested, the stronger were these notes, with increases of up to about 20 db recorded over the broad-band noise. They were independent of the material of the ejector, and had the characteristics of a non-linear oscillation within the shroud. At a given condition, several frequencies were usually present, related by 'sum' and 'difference' expressions. Not all these peaks in the narrow-band analyses were found to represent truly discrete frequencies, but had more the characteristic of random noise passed through narrow filters. The frequencies changed with pressure ratio and the acoustic efficiency of the system depended on the particular dominant frequencies. On one occasion the periodic transfer of energy between modes was observed, but usually the emission was quite stable at a given condition.

This phenomenon of discrete-frequency noise from an ejector system operating subsonically has been observed previously[5] on full-scale turbo-jet engines and it may therefore have been present, though undetected, in other tests. It may be the relative contributions of this factor which accounts for some of the different conclusions reached by different workers.

(6) The walls of an ejector were excited by the passage of the internal flow, but such vibrations did not contribute to the radiated noise. No noise was found to transmit from the ejector walls.

(7) Attempts were made to remove both types of discrete frequency by roughening the flow in various ways. Although in some cases reductions of up to 7 db were achieved no method produced complete elimination. An absorptive lining inside the ejector also reduced the strengths of the discrete notes.

(8) Although in many cases the strengths of these discrete notes were sufficient to more than off-set any reduction obtained in the broad-band emission, it was sometimes possible to achieve an estimate of the broad-band spectrum. When this was done, it was found that within the limits of the experiment, the broad-band noise field was independent of the ejector diameter and it did not depend crucially on the spacing distance.

(9) The broad-band noise attenuation increased as the length of the ejector increased. The difference between the peak noise level of the unshrouded jet and those of the longest ejectors tested, measured along a line parallel to the jet axis, was about 7 db. Extrapolation of the results suggested that only marginal increases would result from even longer ejectors.

(10) Conclusions (8) and (9) together show that the initial mixing conditions and length of ejector play a more important role than the final efflux velocity. The radiated noise was greater than that expected from a simple jet with the same mean velocity as that of the augmented flow.

(11) In contrast to most suppressor nozzles, (e.g. Greatrex and Brown[37]) and other work on ejectors[8], the attenuation appeared constant rather than increasing with operating condition.

(12) Supporting the conclusions of other workers on ejector noise, this report shows that an appreciable lowering of noise output, say to 10 db or more below that of an unmodified nozzle, may only be achieved with ejectors of moderate length if they are used with primary nozzles which themselves have noise-reducing properties. Even this presupposes that the roughness and other factors in a full-scale hot turbo-jet are sufficient to inhibit the occurence of strong discrete frequencies and this has not always been the case.

7. *Acknowledgements.*

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REFERENCES

No.	Author(s)	Title, etc.
1	M. J. Lighthill	On sound generated aerodynamically. I. General theory. *Proc. Roy. Soc.* (A), Vol. 211, p. 564. 1952.
2	M. J. Lighthill	On sound generated aerodynamically. II. Turbulence as a source of sound. *Proc. Roy. Soc.* (A), Vol. 222, p. 1. 1954.
3	C. M. Harris (Editor)	*Handbook of noise control.* (Chapter 33, by H. E. von Gierke) McGraw Hill Book Co. 1957.
4	J. Reid	The effect of a cylindrical shroud on the performance of a stationary convergent nozzle. A.R.C. R. & M. 3320. January, 1962.
5	W. J. North and W. D. Coles ..	Effect of exhaust-nozzle ejectors on turbojet noise generation. N.A.C.A. Tech. Note 3573. October, 1955.
6	C. C. Ciepluch, W. J. North, W. D. Coles and R. J. Antl	Acoustic, thrust and drag characteristics of several full-scale noise suppressors for turbojet engines. N.A.C.A. Tech. Note 4261. April, 1958.
7	W. D. Coles, J. A. Mihaloew and E. E. Callaghan	Turbojet engine noise reduction with mixing nozzle-ejector combinations. N.A.C.A. Tech. Note 4317. August, 1958.
8	W. D. Coles, J. A. Mihaloew and W. H. Swann	Ground and in-flight acoustic and performance characteristics of jet-engine exhaust noise suppressors. N.A.S.A. Tech. Note D–874. August, 1961.
9	G. M. Corcos	Some measurements bearing on the principles of operation of jet silencing devices. A.R.C. 20 213. March, 1958.
10	A. Powell	Considerations concerning an upper limit to jet noise reduction. *J. Acoust. Soc. Amer.*, Vol. 31, p. 1138. 1959.
11	B. J. Gordon	A review of work in jet engine noise control at the General Electric Company. *Noise Control*, Vol. 7, No. 3, p. 14. 1961.
12	W. S. Bertaux	The design and development of the General Electric CJ 805–3 thrust reverser and noise suppressor. Society of Automotive Engineers, Preprint 162B. 1960.
13	F. B. Greatrex	By-pass engine noise. Society of Automotive Engineers, Preprint 162C. 1960.
14	J. Foxwell	Unpublished data. Department of Aeronautics and Astronautics, University of Southampton. 1958.

No.	*Author(s)*	*Title, etc.*
15	A. Powell	A 'schlieren' study of small-scale air jets and some noise measurements on two-inch diameter air jets. A.R.C. 14 726. December, 1951.
16	E. E. Callaghan	Noise suppressors for jet engines. *Noise Control*, Vol. 5, No. 1, p. 18. 1959.
17	W. D. Coles and E. E. Callaghan	Full-scale investigation of several jet-engine noise-reduction nozzles. N.A.C.A. Report 1387. 1958.
18	J. W. S. Rayleigh	*The theory of sound* (2 Vols.). MacMillan. 1894.
19	D. Middleton	The testing and development of a ground muffler for jet engine exhaust noise. A.R.C. C.P. 610. December, 1962.
20	A. Powell	On the noise emanating from a two-dimensional jet above the critical pressure. A.R.C. 15 472. June, 1952.
21	M. Merle	Ondes sonores émises par un jet d'air. *Comptes Rendus*, Vol. 240, p. 2055. 1955.
22	A. Powell	On the mechanism of choked jet noise. *Proc. Phys. Soc.*, Vol. 66B, p. 1039. 1953. (also A.R.C. 15 623. December, 1952).
23	M. Merle	Sur la structure d'un jet d'air à grande vitesse. *Comptes Rendus*. Vol, 240, p. 1972. 1955.
24	F. Canac and M. Merle	Relation dans les jets d'air à grande vitesse, entre la forme, les dimensions de la buse et la nature des émissions acoustiques. *Comptes Rendus*, Vol. 248, p. 1953. 1959.
25	M. G. Davies and D. E. S. Oldfield	Tones from a choked axisymmetric jet. I. Cell structure, eddy velocity and source locations. II. The self excited loop and mode of oscillation. *Acustica*, Vol. 12, p. 257. 1962.
26	L. W. Lassiter and H. H. Hubbard	The near noise field of static jets and some model studies of devices for noise reduction. N.A.C.A. Report 1261. 1956.
27	M. Merle	Sur la fréquence des ondes sonores émises par un jet d'air à grande vitesse. *Comptes Rendus*, Vol. 243, p. 490. 1956.
28	A. G. Hammitt	The oscillation and noise of an overpressure sonic jet. *J. Aero. Space Sci.*, Vol. 28, p. 673. 1961.

REFERENCES—*continued*

No.	*Author(s)*	*Title, etc.*
29	M. Merle	Rôle d'un baffle sur l'émission sonore d'un jet d'air sonique. Paper O48, Congress Report Vol. 1, Fourth International Congress on Acoustics, Copenhagen. 1962.
30	D. Middleton and E. J. Richards	Discrete frequency noise from ejector nozzles. Paper L21, Congress Report Vol. 1, Fourth International Congress on Acoustics, Copenhagen. 1962.
31	A. Powell	The reduction of choked jet noise. *Proc. Phys. Soc.*, Vol. 67B, p. 313. 1954.
32	P. F. R. Weyers	Vibration and near-field sound of thin-walled cylinders caused by internal turbulent flow. N.A.S.A. Tech. Note D–430. June, 1960.
33	J. H. Gerrard	An investigation of the noise produced by a subsonic air jet. *J. Ae. Sci.*, Vol. 23, p. 855. 1956.
34	A. C. Pietrasanta	Noise measurements around some jet aircraft. *J. Acoust. Soc. Amer.*, Vol. 28, p. 434. 1956.
35	M. J. Lighthill	Sound generated aerodynamically. The Bakerian Lecture, 1961. A.R.C. 23 326. November, 1961.
36	M. J. Lighthill	Jet noise. Wright Brothers Memorial Lecture, Institute of Aerospace Sciences. 1963.
37	F. B. Greatrex and D. M. Brown	Progress in jet engine noise reduction. *Advances in Aeronautical Sciences*, (2 Vols.). (Proceedings of First International Congress in the Aeronautical Sciences, Madrid. 1958.) Pergamon Press. 1960.

APPENDIX

List of Equipment used in the Measurement and Analysis of Noise and Vibration

Company	*Equipment Title*	*Designation*
Bruel and Kjaer Laboratories Ltd.	Half-inch Condenser Microphone Cartridge	Type 4133
	Cathode Follower	Type 2615
	Cathode Follower (goose-neck style)	Type 2614
	Microphone Extension Cables (2×10 metres)	Type 4142
	Audio-frequency Spectrometer	Type 2111
	Frequency Analyser*	Type 2107
	Level Recorder	Type 2304
	Level Recorder*	Type 2305
	Recording Paper	Type QP 2351
	Recording Paper*	Type QP 1130
	Automatic Frequency Scanner Drive	Type AQ 0002
	Microphone Calibration Equipment	Type 4142
	Pistonphone	Type 4220
	Noise Source	Type 4240
	Beat Frequency Oscillator	Type 1014
	Electrostatic Actuator	Type UA 0033
	Probe Microphone Kit	Type UA 0040
	Nose Cone	Type UA 0052
Cawkell Research & Electronics Ltd.	Band Pass Filter	Type FU4
Dawe Instruments Ltd.	White Noise Generator	Type 419B
Electrical and Musical Instruments Ltd.	Panoramic Waveform Analyser	Type 1950/2
	Emitape Recording Tape	—
Elliot Bros. (Electrical Measurement Division)	Portable Reflecting Wattmeter	Model 5999
General Electric Company Ltd.	Vibration Crystal Straingauge	Cat. No. SP 1100
	Accelerometer, screened	Cat. No. SP 1000
Goodmans Industries Ltd.	Vibration Generator	Model V.47
Hewlett Packard Co.	Oscilloscope Camera	Model 196A
	Wave Analyser	Model 302A
	Sweep Drive	Model 297A (spec. H03–297A)

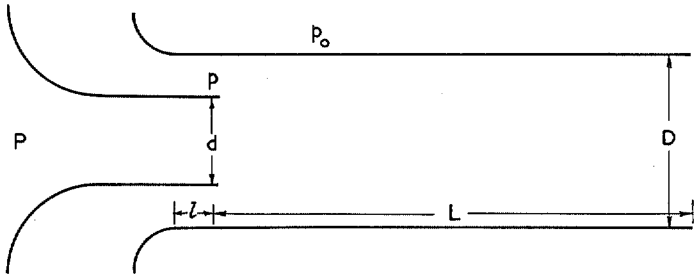
* Signifies equipment on loan.

Company	*Equipment Title*	*Designation*
Kay Electric Co.	Sona-Graph Sound Spectrograph Model Recorder* (Recorder, Amplifier Analyser, Power Supply)	Cat. No. 662A
Massa Laboratories Inc.	Crystal Microphone*	Model M-211
F. L. Moseley Co.	Autograf Recorder	Model 2D2
Muirhead & Co. Ltd.	Muirhead-Pametrada Wave Analyser Muirhead-Pametrada Supply Unit Muirhead-Wigan Decade Oscillator	D-489-EM D-489-05 D-890-A
Polaroid Corporation	Picture Roll (3000 speed)	Type 47
Solatron Laboratory Instruments Ltd.	Resolved Component Indicator	Model VP 250
Tektronix Inc.	Dual-Beam Oscilloscope	Type 502
Vortexion Ltd.	Tape Recorder	Type W.V.A./4
University of Southampton	Correlator Loudspeaker unit	
Ferranti Ltd.	Pegasus Digital Computer	

* Signifies equipment on loan.

TABLE 1

Primary Nozzle and Ejector Nomenclature



I. *Physical Dimensions.*

d Internal diameter of primary nozzle, 1·928 in.

l Approach length of an ejector, 0·964 in.

(Except for the specific cases mentioned in this report, the value of $l/d = 0\cdot5$ was maintained throughout.)

L Length of cylindrical part of an ejector minus the approach length

—1 ejectors are defined as those with $L = 5\cdot78$ in.

—2 ejectors are defined as those with $L = 11\cdot56$ in.

—3 ejectors are defined as those with $L = 23\cdot11$ in.

—4 ejectors are defined as those with $L = 38\cdot52$ in.

—5 ejectors are defined as those with $L = 61\cdot63$ in.

D Internal diameter of cylindrical part of an ejector

A ejectors are defined as those with $D = 2\cdot840$ in.

B ejectors are defined as those with $D = 3\cdot340$ in.

C ejectors are defined as those with $D = 3\cdot840$ in.

The full table is therefore:

Area Ratio $\left(\frac{D}{d}\right)^2$	Length ratio L/d				
	3·0	6·0	12·0	20·0	32·0
2·17	A1	A2	A3	A4	A5
3·01	B1	B2	B3	B4	B5
3·98	C1	C2	C3	C4	C5

II. *Aerodynamic Parameters.*

P Stagnation pressure in jet

p Static pressure at primary-nozzle exit plane

p_0 Atmospheric pressure

γ Ratio of specific heats of air

TABLE 2

List of Corrections for Noise Results

All noise results in this report have been corrected by the amounts indicated below.

Absolute noise levels are all quoted in db relative to 0·0002 dyne/sq. cm.

Levels from the spectrometer dial are quoted to 0·1 db, and from the level recorder to ½ db.

(1) Microphone cartridge frequency response:
—taken as linear in view of the calibration curve.

(2) Correction to tape recorder record-replay signal to obtain linear response:
—taken from calibration curve obtained as described in the text.

(3) Corrections from level-recorder spectrum to true spectrometer levels when employing manual selection of octaves:

Octave mid-frequency c/s	50	100	200	400	800	1600	3150	6300	12500	25000	O.A.
db correction	+5	+3	+2	+1	+½	0	0	0	0	0	Datum

(4) Corrections from level-recorder spectrum to true spectrometer levels when employing automatic switching through the octaves.

Octave mid-frequency c/s	50	100	200	400	800	1600	3150	6300	12500	25000	O.A.
db correction	+3½	+3	+2	+1	+½	0	0	0	0	0	Datum

(5) Correction of microphone-spectrometer dial readings to obtain absolute noise level:
—obtained from reciprocity technique and also checks with pistonphone. Overall levels on the recorder were always adjusted to the corrected overall level shown by the spectrometer dial and the octave levels shifted by this amount together with correction (3) or (4) as appropriate.

Note. The corrections from level-recorder spectrum to true spectrometer levels for one-third octave bands were not obtained. The only results to quote third-octave levels, (Figs. 7 and 8) were merely for comparing relative levels.

TABLE 3

The Reliability of Noise Results

(a) *The Repeatability of Noise Levels and the Symmetry of the Noise Field*

Results of traverses along line b, line b repeated, and line b′ on the other side of the rig

(Ejector A3, $P/p_0 = 1 \cdot 35$)

Position		2*	1*	0	1	2	3	4	5	6	7	8	9
I. Comparison of Overall Noise Levels; db re 0·0002 dyne/sq. cm.													
Line b		89·0	91·0	93·5	95·9	96·9	95·8	94·8	93·2	92·0	90·4	89·3	
b repeat		88·7	90·8	93·6	95·5	96·4	95·4	94·4	92·9	91·4	89·9	88·4	
Line b′		88·5	90·8	93·6	95·7	96·4	95·3	94·4	93·2	91·9	89·9	89·0	
II. The Scatter of the Octave Levels; db.													
Octave mid-frequency cycles per second	50	4	1	3	2	1	2	1	5½	4½	4	4½	
	100	2	½	2½	½	½	1	½	1	1	½	½	
	200	1	2½	1	0	1	1	2	2	1½	1	½	
	400	½	0	1½	1	½	1½	1½	1	1½	1	0	
	800	1½	1	1	½	½	1½	1	½	½	1	1	
	1600	½	½	½	1	1	1	1	1	½	1	½	
	3150	2	0	0	1	1	1½	1	1	1	1	0	
	6300	3	1½	2½	2½	3	2½	2½	1½	1	1	2	
	12500	4	2½	2½	3	2½	3	3	3	1½	1½	2	
	25000	3½	2	2½	2	2½	2	1½	2½	1	1½	2½	

(b) *The Effect of Mis-positioning the Ejector.*

Ejector A3 placed in 8 non-standard locations, ($P/p_0 = 1 \cdot 65$) (described in Section 3.2)

Position : b		5	6	7	8
I. Scatter in the Overall Levels, relative to the 'Standard Position' Noise Results; db.					
From		−0·4	−0·4	−0·1	0·0
to		+0·2	+0·6	+0·9	+1·0
II. The Scatter of the Octave Levels; db.					
Octave mid-frequency cycles per second	50	5½	4½	2	1½
	100	3½	4	1	2½
	200	2	2	3	2
	400	2½	2	1½	3
	800	3	1½	2	3
	1600	2½	2	1	2
	3150	1½	1½	½	2½
	6300	2	2	1½	3½
	12500	1	1½	1	3½
	25000	1	2	1½	3½

TABLE 4

Examples of Sum and Difference Relationships existing between Discrete Frequencies, (Subsonic Flow)

(1) Fig. 4. (Hewlett-Packard Wave Analyser results for wooden 'A' ejector, with $L = 9\cdot7$ in., $P/p_0 = 1\cdot22$).

Frequencies detected	325,	560,	885,	1210,	1535,	1770,	1860,	2095,	2420,	2745,	2980,	3070,	3305,	3630,	3955
May be rewritten	y	$x-2y$	$x-y$	x	$x+y$	$2x-2y$	$x+2y$	$2x-y$	$2x$	$2x+y$	$3x-2y$	$2x+2y$	$3x-y$	$3x$	$3x+y$

i.e.

			y	
$x-2y$	$x-y$	x	$x+y$	$x+2y$
$2x-2y$	$2x-y$	$2x$	$2x+y$	$2x+2y$
$3x-2y$	$3x-y$	$3x$	$3x+y$	

where $x = 1210$ c/s, $y = 325$ c/s.

(2) Fig. 4. (Bruel and Kjaer Frequency Analyser results for Ejector A1, $P/p_0 = 1\cdot21$).

Frequencies detected	380,	460,	840,	1300,	1760,	2140,	2600,	3060,	3900,	4360
may be rewritten	$x-y$	y	x	$x+y$	$x+2y$	$2x-y$	$2x+2y$	$2x+3y$	$3x+3y$	$3x+4y$

i.e.

		y			
$x-y$	x	$x+y$	$x+2y$		
$2x-y$			$2x+2y$	$2x+3y$	
				$3x+3y$	$3x+4y$

where $x = 840$ c/s, $y = 460$ c/s.

(3) Fig. 15. (Pametrada Wave Analyser noise results for Ejector A2, $P/p_0 = 1\cdot35$).

Frequencies detected	770,	1060,	1350,	1640,	1930,	2220,	2510,	2800,	2990,	3280,	3860,	4920,	6560
may be rewritten	$x-3y$	$x-2y$	$x-y$	x	$x+y$	$x+2y$	$x+3y$	$x+4y$	$2x-y$	$2x$	$2x+2y$	$3x$	$4x$

i.e.

$x-3y$	$x-2y$	$x-y$	x	$x+y$	$x+2y$	$x+3y$	$x+4y$
		$2x-y$	$2x$		$2x+2y$		
			$3x$				
			$4x$				

where $x = 1640$ c/s, $y = 290$ c/s.

(4) Fig. 17b. (Pametrada Wave Analyser results for Ejector C4, $P/p_0 = 1\cdot35$).

Frequencies detected	280,	400,	520,	640,	880,	1000,	1360,	1720
may be rewritten	x	$x+y$	$x+2y$	$x+3y$	$x+5y$	$x+6y$	$x+9y$	$x+12y$

where $x = 280$ c/s, $y = 120$ c/s.

TABLE 5

Primary-Nozzle Noise Results

Noise levels along line b expressed in db re 0·0002 dyne/sq. cm.

Position		2*	1*	0	1	2	3	4	5	6	7	8	Pressure ratio
octave mid-frequency; cycles per second	50	50½	57½	57½	59½	61½	61	58½	56½	57½	59		
	100	56	58½	61	65½	63	62½	61	61	60½	59		
	200	62	65	67	69	68½	68	70	68	67½	66½		
	400	68	70	73½	74½	74½	74½	76	74	74½	74		
	800	70	74½	78½	79½	80	80	80	79	78	78		
	1600	74	78	80½	82½	83	82	82	79½	78	77		1·2
	3150	75	78½	81	83	82½	81	79	77	75½	74½		
	6300	74½	78	81	82½	82	78½	75½	73	73½	72½		
	12500	72½	76	79½	80½	79	74	71	69	69½	68		
	25000	70	75	79	80	78½	72	68	65	64½	63		
Overall S.P.L.		81½	85	88	89½	89½	88	86½	85	84	82½		
octave mid-frequency; cycles per second	50	63	64½	67	67	69½	68½	65½	62	63	58½		
	100	68½	66½	67½	69½	70	69½	67½	67½	66	66½		
	200	70½	70	73½	75½	75½	76½	76	77	75	75		
	400	74½	75	79½	81	82	84	84	84½	83	82½		
	800	78	81	85	86½	88½	90	89½	89	87½	86½		
	1600	82½	85	88½	90½	92½	93	91	90	87	85		1·35
	3150	84	86	89	91	92½	92½	88½	87	85	83½		
	6300	84	86	89½	91	92	89½	85½	85	82½	82		
	12500	82½	86	89	91	91	86	81	80	78	76		
	25000	80½	84½	87½	89½	88	82½	78	75½	74	71		
Overall S.P.L.		89½	92½	96	98	98½	98	96	95	93½	92		
octave mid-frequency; cycles per second	50	64	65½	70	73	77½	78	73½	71	71	67½		
	100	67½	70½	72½	77	78	76½	77½	75½	76	79		
	200	75	76½	78½	81½	82	83	85	85	83½	83		
	400	80½	82	86	88	89	91½	93	93	92	91		
	800	85½	88	92	94	95½	99	100½	100	98	96½		1·65
	1600	90	92	96	98	100½	101½	102½	100	98	97		
	3150	91½	93½	97	99½	101½	101	99	95½	93	93		
	6300	92	94	98	100	101½	99½	95	93	91	90½		
	12500	92½	94½	98	100	99½	94½	91½	89½	86½	87		
	25000	90	94	96½	98	98	91½	87	85	82	80½		
Overall S.P.L.		98½	101	104	106	107½	107½	106½	105	103½	102		

TABLE 5—*continued*

Position		2*	1*	0	1	2	3	4	5	6	7	8	Pressure ratio
octave mid-frequency; cycles per second	50	68½	70½	73½	78	78½	82½	79½	75½	74	75½	77½	
	100	74	73	77	82	81	82	81	79	78	79	82	
	200	79	80	82	86½	86½	88½	89	89½	87½	88	88	
	400	85	86	89½	92	93	96½	98	98	96	97	96	
	800	90½	92½	95½	99	100½	104½	106½	106½	103½	102	102	
	1600	95½	97½	100	103½	105½	109	109½	108½	105	104	103½	2·0
	3150	97	98	101½	104½	107	107½	105½	103	99½	98½	97	
	6300	99	100	102½	105	107	105½	102	99½	96½	96	95	
	12500	103	105½	104½	105½	106	101½	99	97½	95	93	94	
	25000	100	104	104½	105½	103½	99	94½	93	89½	88	89	
Overall S.P.L.		107	109	110½	112	113	113½	113	112	109½	108½	107	

TABLE 6

Overall Noise Levels for Conditions where Discrete Frequencies were Weak (Spectrometer Results)

Position	2*	1*	0	1	2	3	4	5	6	7	8	9	10	Contribution of discrete notes at † increases O.A. noise by
P/p_0	I. Primary-nozzle results.													
1·2	81·5	85·0	87·9	89·7	89·5	88·2	86·6	85·0	84·0	82·6				
1·35	89·5	92·7	96·0	97·9	98·7	97·8	96·2	95·0	93·5	91·9				
1·65	98·5	101·0	103·9	106·2	107·5	107·5	106·5	105·1	103·5	102·0				
2·0	107·0	109·0	110·5	111·9	113·1	113·6	113·0	111·8	109·7	108·7	106·9			
Ejector	II. Ejector results, $P/p_0 = 1·35$													
A3	89·0	91·0	93·5	95·9	96·9†	95·8	94·8	93·2	92·0	90·4	89·3			0·4
A4	84·0	85·9	87·6	90·4	92·8	93·6†	92·5	91·3	90·0	88·5				0·1
A5	79·9	81·0	82·6	85·1	87·4	90·7	91·6†	90·4	89·2	87·4	86·1			—
B3	91·9	94·4	96·4	97·9	97·9†	96·4	94·8	93·5	91·9	90·6	89·4			1·0
B4	85·8	87·3	88·8	90·7	92·9	93·4†	91·9	90·2	88·6	87·0	85·7			0·0
B5	80·5	81·4	82·5	84·1	86·9	90·3	91·2†	89·5	87·5	86·0	84·8	82·8		0·1
C3	94·8	97·0	98·5	99·2	99·1†	97·4	95·3	94·1	92·6	91·4	89·6	89·1		1·5
C4	88·4	89·8	90·7	92·1	94·5	94·7†	92·9	90·3	88·7	87·2	85·4			0·8
C5	81·6	82·6	83·7	84·7	87·3	90·1	91·6†	89·6	87·2	85·5	84·7	84·4		0·1
Ejector	III. Ejector results, $P/p_0 = 1·65$													
A2	98·1	101·3	105·0	106·9†	106·7	107·1	106·7	105·6	104·5	102·7				0·6
A3	95·9	97·4	100·6	103·5	104·6†	104·4	104·2	102·9	101·4	100·0	98·0			—
A4	91·0	92·6	95·2	98·0	100·6	101·5†	100·9	99·8	98·5	96·9	95·7			0·0
A5	87·1	88·7	90·1	92·2	95·6	98·7	99·9†	98·8	97·6	96·4	95·2	94·3		—
B3	97·6	99·6	102·0	104·9	105·4†	104·0	103·6	102·3	101·0	99·4	98·4			0·6
B4	92·5	93·3	95·7	98·5	101·4	101·9†	100·5	99·2	97·4	96·2	95·3	94·4	93·4	0·0
B5	86·9	88·0	89·1	91·1	94·5	98·9	100·5†	98·0	96·7	95·0	93·8	92·3		0·0
C3	99·6	101·0	104·0	105·7	106·0†	104·1	103·1	102·0	100·8	99·6	98·6			0·7
C4	92·8	94·5	96·4	98·5	101·2	101·7†	99·5	97·8	96·5	94·9	93·5			0·2
C5	88·1	89·1	90·2	92·0	95·1	99·2	100·4†	97·9	95·9	93·9				0·1

In final column a dash signifies no detectable contribution, 0·0 db means the contribution was negligible.

TABLE 7

Effect of Ejector Length

(B Ejectors, $P/p_0 = 1 \cdot 35$)

Noise levels along line b, expressed in db re 0·0002 dyne/sq. cm.

Position		2*	1*	0	1	2	3	4	5	6	7	8	9	Broad band noise at †
Ejector B3						†								
octave mid-frequency; cycles per second	50	57½	61	63	67½	71½	73½	70	68½	65	64	69½		
	100	67½	69	71	72	74	74	72½	72	71	71½	70½		
	200	81½	85	82½	80	80	79½	81	80½	80	78½	77		78
	400	82½	85	87	85½	87	86½	86	86	85	83½	82		83½
	800	85½	89½	91	93	92	89½	90	89½	87½	86	84½		91
	1600	87	90	92	93	94½	92½	91	90	87	85½	84		93½
	3150	84½	86	87½	89½	90½	87½	86	84	83	80½	80		90
	6300	79	81	82½	85	86½	84	80½	78	76½	75	74		
	12500	73	75	78½	81½	82½	80	75	72½	70½	68½	67		
	25000	69	71	75½	79½	82½	77½	72	68	66	63½	62		
Overall S.P.L.		92	94½	96½	98	98	96½	95	93½	92	90½	89½		97
Ejector B4							†							
octave mid-frequency; cycles per second	50	54½	59	65	69½	67	70½	69½	69½	69½	64	70		
	100	67	68½	69½	69½	71	71	70½	69½	70	68½	67		
	200	76½	77	76	75½	77½	77½	77	76	77½	75	74½		76½
	400	78	78½	79½	78½	81	82	81½	80	80½	78½	77½		81
	800	78½	81½	83½	84½	86	86	84½	83½	83½	82	80		85½
	1600	79	82	83½	84½	87½	87½	86½	84½	83½	81½	79½		
	3150	77	79½	81½	83	86½	86½	85	81½	79½	77	76		
	6300	74	77	79½	81½	85½	86	83	78½	77	73½	72½		
	12500	71	73½	76	78½	83½	84	79½	74½	72½	69½	68		
	25000	66½	70	73	76	82½	83½	76½	71½	69½	66½	63½		
Overall S.P.L.		86	87½	89	90½	93	93½	92	90	88½	87	85½		93½
Ejector B5								†						
octave mid-frequency; cycles per second	50	53	57	58½	57	60	63½	66	66	68½	66½	62	62½	
	100	61½	65½	65	65½	65	68	69½	67½	69	67½	68½	67	
	200	72	72½	71½	71	72	73	74½	74	74	74	73½	73	74½
	400	73½	74½	73½	73	76	78	78½	78	78½	78	77	75½	78
	800	73	73½	74½	75½	79½	81½	82	81½	80½	79½	79	77	82
	1600	73	74	74½	77	81	83½	83½	83½	81	79½	78	76	
	3150	72½	73	74½	76½	80½	84	84½	82½	79	75½	76	74	
	6300	71½	72½	73½	76	80	84	84½	82	77½	73½	75½	72	
	12500	69½	70	69½	71½	76½	82	82	77½	72½	69	69½	67	
	25000	68	66½	64	67	74	81	81	75½	69½	65	63½	61	
Overall S.P.L.		80½	81½	82½	84	87	90½	91	89½	87½	86	85	83	91

Absence of a figure in the final column indicates that no discrete frequency was located in that octave.

TABLE 8

Effect of Ejector Diameter

(—3 Ejectors, $P/p_0 = 1 \cdot 65$)

Noise levels along line b, expressed in db re 0·0002 dyne/sq. cm.

Position	2*	1*	0	1	2	3	4	5	6	7	8	9	Broad band noise at †
Ejector A3					†								
octave mid-frequency; cycles per second: 50	59½	67	65½	69½	74	77½	75½	73	72½	69	68½		
100	70	70	71½	75	78½	79	78½	77½	75	75½	75½		
200	77½	78	79½	83	83½	85	85	85½	86	85	83		
400	81	82½	85½	87	88½	90½	92	91½	91½	92	90		
800	85½	88	91	93½	94½	96	98½	97½	96½	96	93½		
1600	90	91½	94½	97½	99	100	100½	98½	96	95½	92½		
3150	91	92	95	98	99	99½	99	95	92	91½	88		
6300	88½	90	93	96½	97	97	94	90	86	86	82		
12500	85	87½	91½	95	95	93½	89	84	81	80½	78		
25000	82	85	90	94½	92½	90	85	80	77	76½	74		
Overall S.P.L.	96	97½	100½	103½	104½	104½	104	103	101½	100	98		

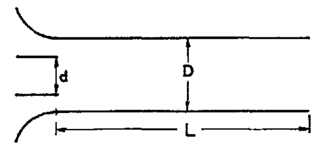
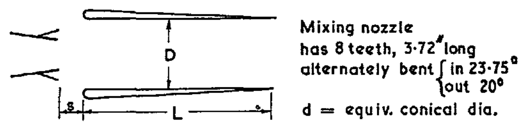
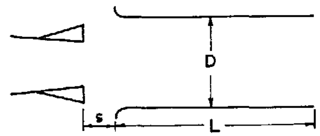
Position	2*	1*	0	1	2	3	4	5	6	7	8	9	Broad band noise at †
Ejector B3					†								
octave mid-frequency; cycles per second: 50	63½	67	70	72½	75½	80	78	77	73½	70½	74		
100	72½	73½	76	78	81	79½	79½	79	78	77	78½		
200	85½	85½	84½	84½	86	86½	87½	88	87	85½	85½		85
400	86	88	90½	91	91½	91½	93½	94½	93	91½	91½		90
800	90	92	96	97	97½	96½	98	98	96½	94½	93½		97
1600	92½	95½	97	100	101	99½	100½	99	96	94½	93		99½
3150	91½	93½	96	99	99	97	96½	93½	91½	90	89½		99
6300	86½	88½	91½	94½	96	93½	90½	87½	85	84	82½		
12500	82½	84½	89	92	93	89	84½	81½	79	77½	76½		
25000	80½	82	87	93	93	87	81½	78	75½	73½	72½		
Overall S.P.L.	97½	99½	102	105	105½	104	103½	102½	101	99½	98½		105

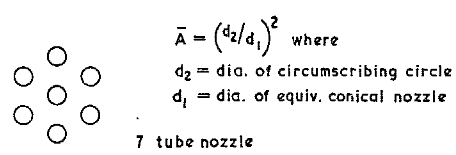
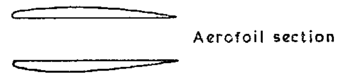
Position	2*	1*	0	1	2	3	4	5	6	7	8	9	Broad band noise at †
Ejector C3					†								
octave mid-frequency; cycles per second: 50	66½	67½	73½	74	79	80½	78	74½	80	71½	77		
100	75½	76	78	82½	82	81	79½	79	79	78½	79		
200	88½	90	89	87	88	87	88	87½	87	86	86		86
400	90½	92	94	94½	95½	94½	94	93	93	92	91½		92½
800	94	96½	99½	100	100	97½	97½	97	96	95	94½		99
1600	95	96	99½	100½	102	100	99	97½	95½	94½	94½		101½
3150	91½	91½	95	98	99	96½	94	91½	90½	90	89½		98
6300	85½	87	90½	93½	95½	93½	88	85½	84½	84	82		
12500	81½	82½	87	91½	92	89	82	80½	79	77	77		
25000	78½	79	84	90½	91	86½	79	76	75	73	71½		
Overall S.P.L.	99½	101	104	105½	106	104	103	102	101	99½	98½		105½

Absence of a figure in the final column indicates that no discrete frequency was located in that octave.

TABLE 9

Experimental Conditions, Other Reported Ejector Work

Ref.	Power Units and Primary Nozzles	Ejector Intakes	$\frac{A}{a}$	$\frac{D}{d}$	$\frac{L}{D}$	$\frac{L}{d}$	$\frac{S}{d}$	$\frac{L+S}{d}$		Conditions for noise measurements and Notes
5	5000 lb thrust jet engine; (P/p = 1·75, max.); conical nozzle	bell-mouths (length un-stated)	1·44 and 1·96	1·2 and 1·4 with each of:	0·15 0·45 0·60 0·75 0·90 1·05 1·20 1·50	0·18 to 2·1 (16 values)	0	0·18 to 2·1	200 ft radius, 15° increments	1·2 D/d at 100, 90, 80% r.p.m. 1·4 D/d at 100% r.p.m. 
6	9000 lb thrust jet engine; mixing nozzle (with centre-body)	slight fairing (part of L)	2·12	1·46	1·33	1·94	0·107	2·05		86% thrust 
7	9000 lb thrust jet engine; (P/p = 2·3 max.) 12-lobe nozzle (open centre)	flared inlet	2·0 2·89	1·42 1·70	? ?	? ?	0·07 to 0·30 −0·28 to +0·23	2·59 to 2·91 1·38 to 2·89		45, 68, 86, 96% of rated thrust Nozzle diameter 29·5 in.  Nozzle diameter 30·1 in.
	5000 lb thrust jet engine; 8-lobe nozzle (open centre)	flared inlet	2·56	1·60	0·96 to 1·46	1·54 to 2·34	0·10	1·64 to 2·44		1700 ft/sec jet velocity Maximum velocity of both engines, 1750 ft/sec.

8	Static tests: Single jet engine, approx. 7000 lb thrust, ($P/p = 2\cdot1$), of twin-engined aircraft with 8-lobed nozzles Flight tests: two engines in use or 1 engine at condition, the other throttled.	radiussed to 0·375 in. at leading edge	?	? (L = 39 in.,	1·15 D = 34 in.)	?	?	?	85, 90, 96% max. r.p.m. (approx. 1100, 1300, 1600 ft/sec velocity)  Level fly-overs at 1000 ft altitude. Take-offs and simulated take-offs. 300 ft and 635 ft altitude, relative jet velocities 1000–1600 ft/sec approx.
13	'Full-scale Avon engine and small scale jet engine, 5 in. nozzle diameter.' Tests also done with '7-tube nozzle' $\bar{A} = 3\cdot0$	not stated	'about 2' and 'about 4'	?	?	3·8 to 13·0 (9 values)	?	?	1600 ft/sec jet velocity with measurements 'nearly parallel to jet axis'. Results for the 2 engines are not separately indicated. 

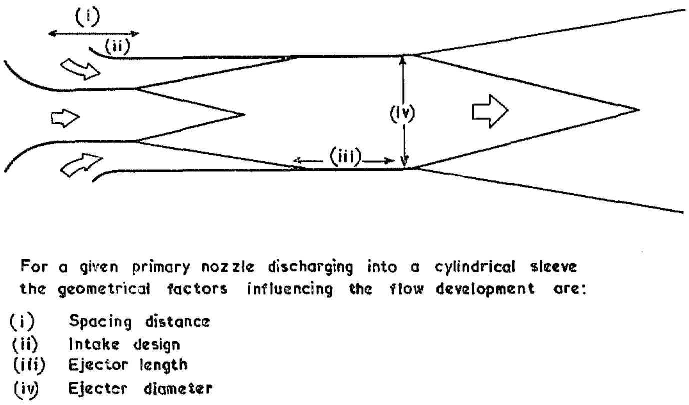


FIG. 1. Ejector mixing processes.

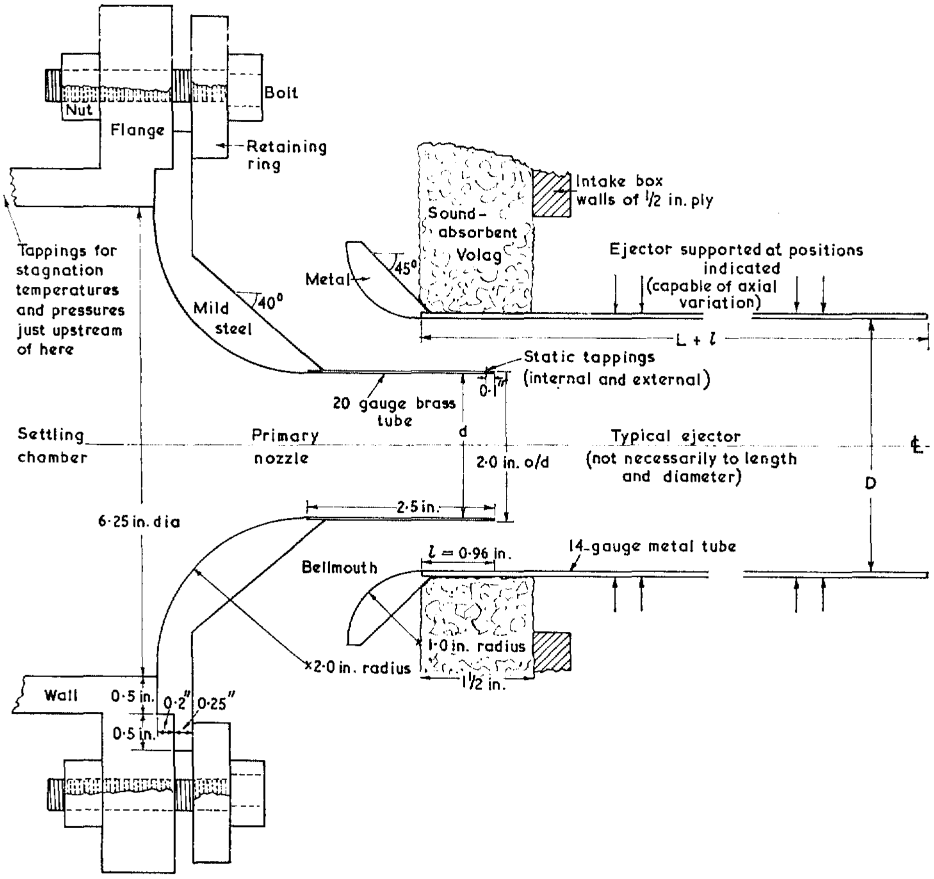


FIG. 2. Rig design—primary nozzle with generic ejector.

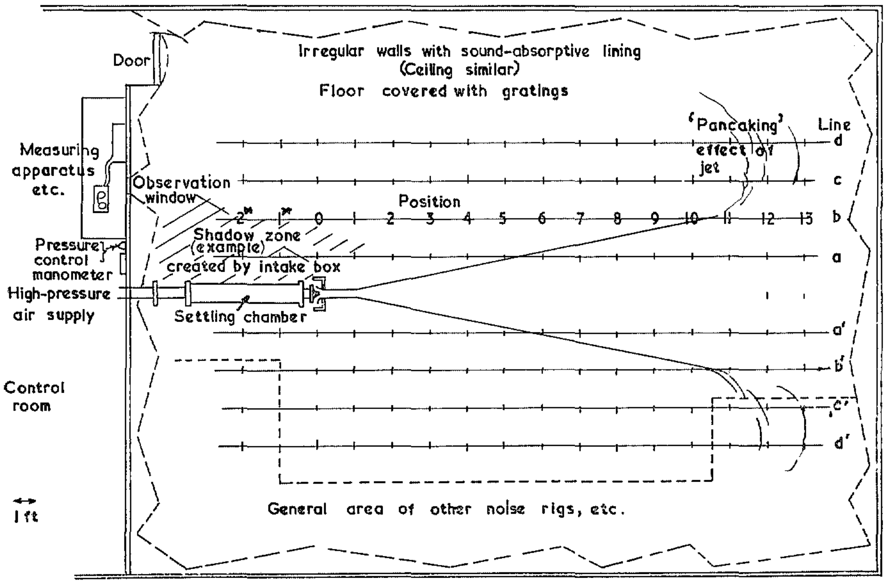


FIG. 3. Plan view, Acoustics Laboratory and Control Room.

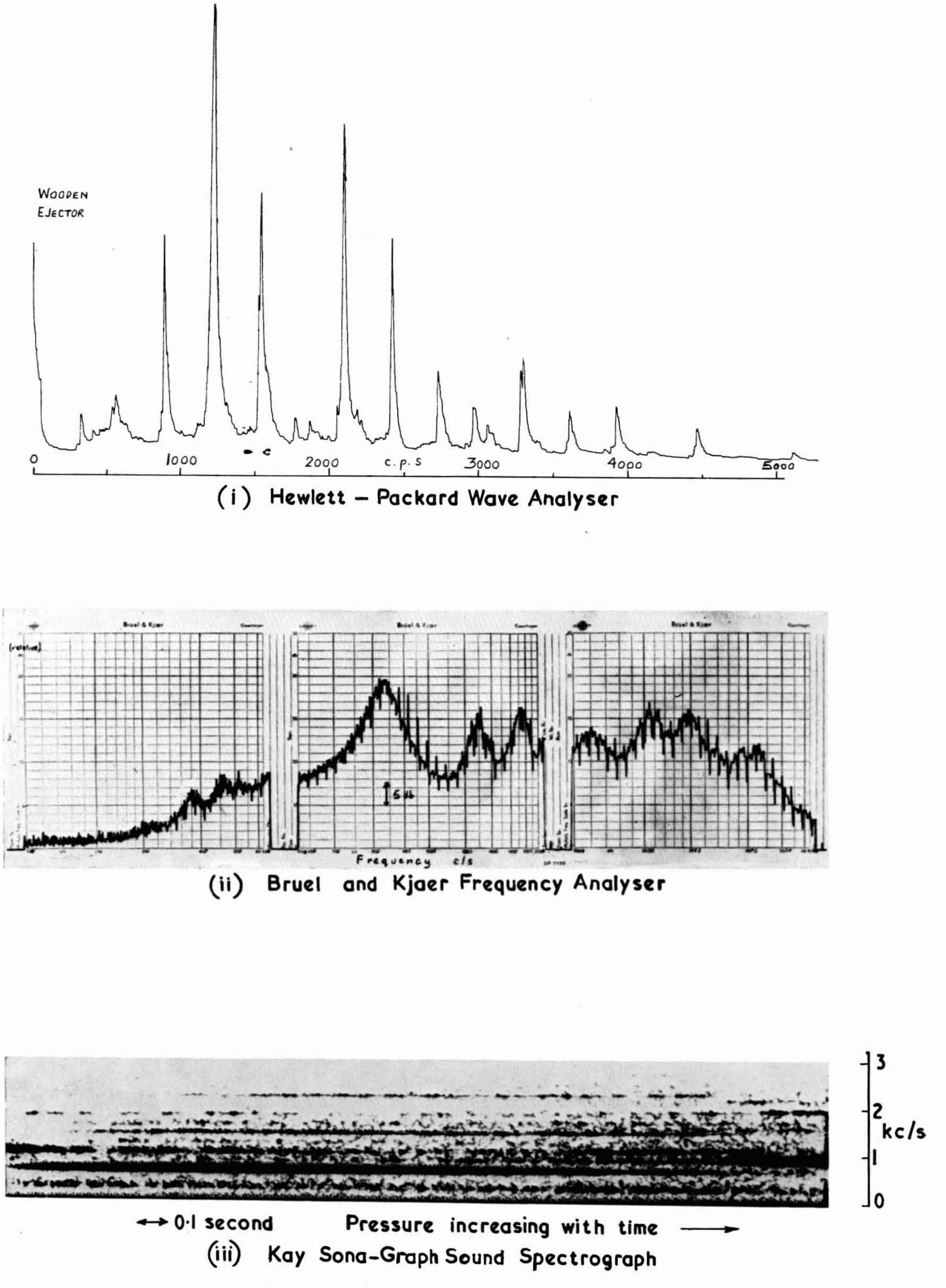


FIG. 4. Examples of narrow-band analyses, various instruments.

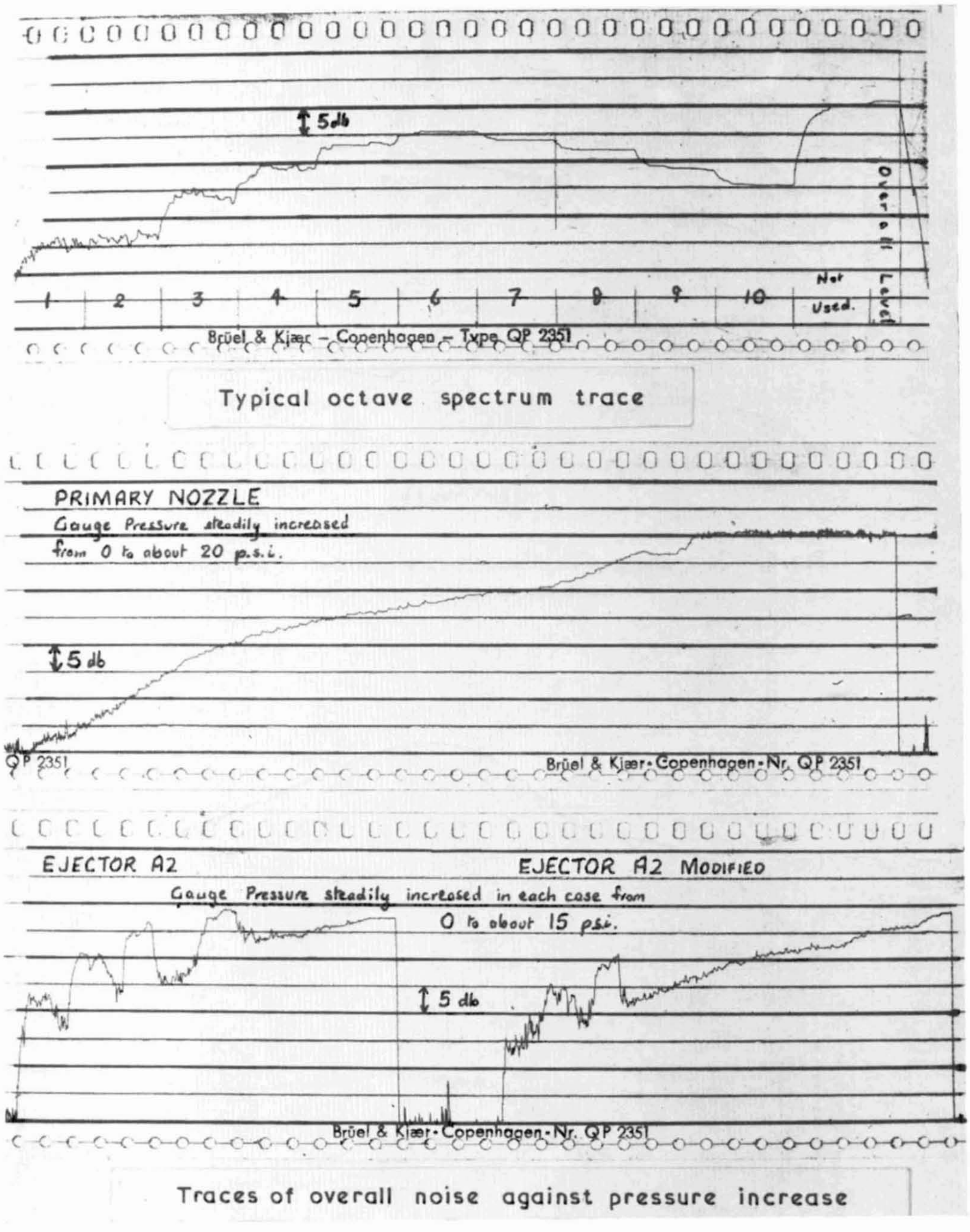


FIG. 5. Examples of outputs from level recorder.

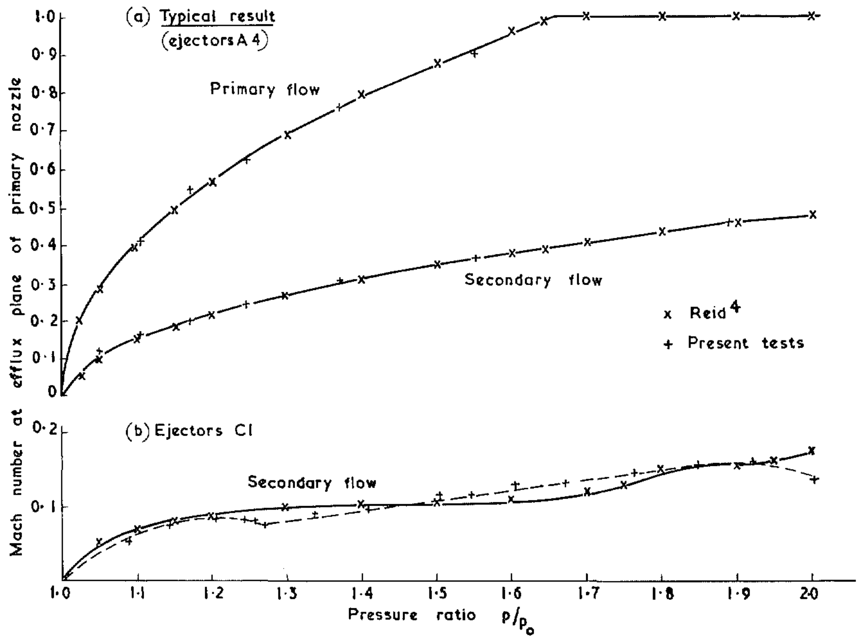


FIG. 6. Comparison of Southampton and Farnborough[4] results for Mach numbers of flow at ejector inlet.

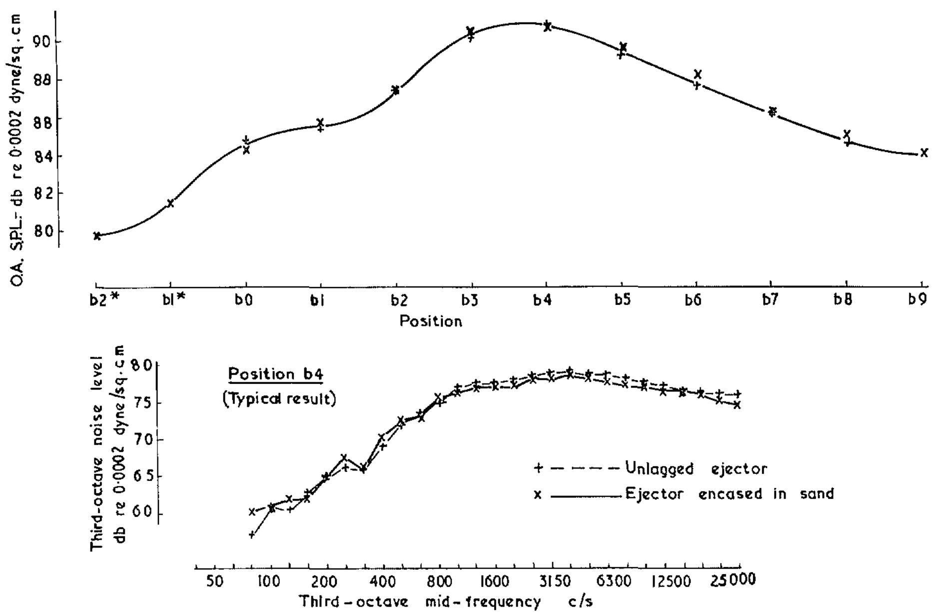


FIG. 7. Investigation of amount of noise radiated from ejector wall (Ejector B5, $P/p_0 = 1 \cdot 35$).

(91137)

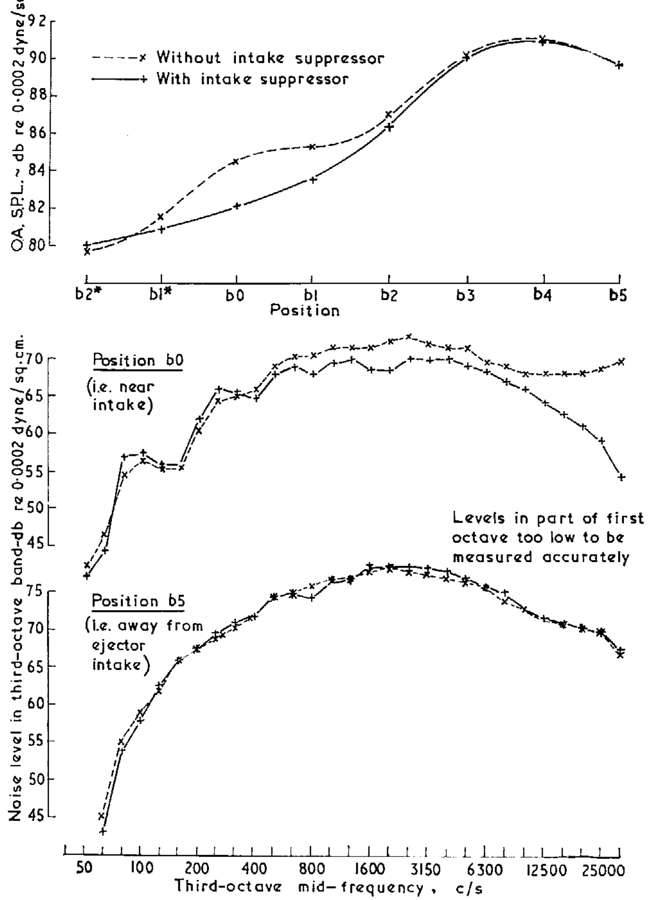


FIG. 8. Investigation of noise radiated from ejector intake (Ejector B5, $P/p_0 = 1{\cdot}35$).

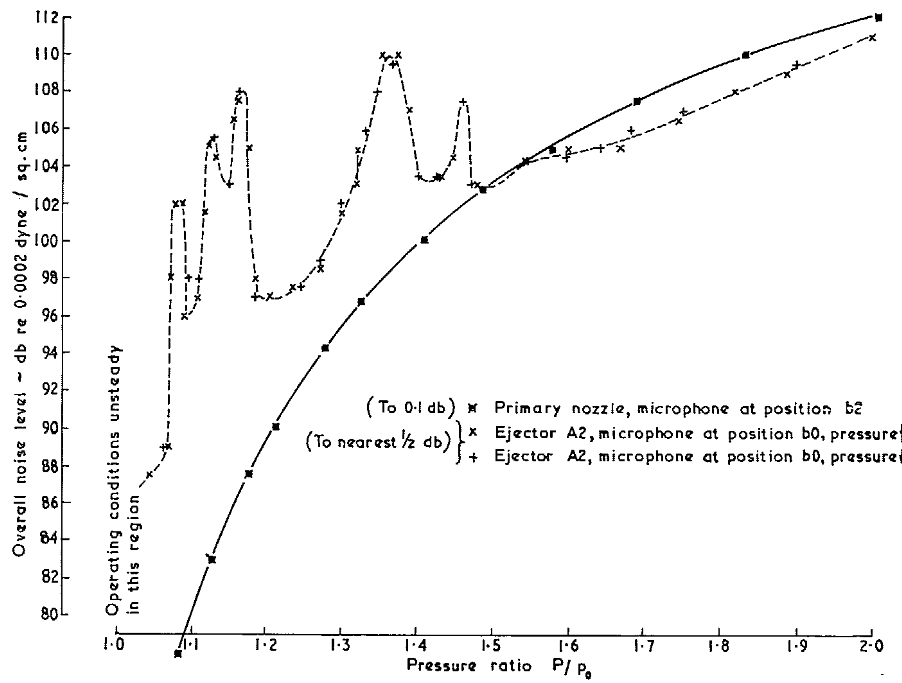
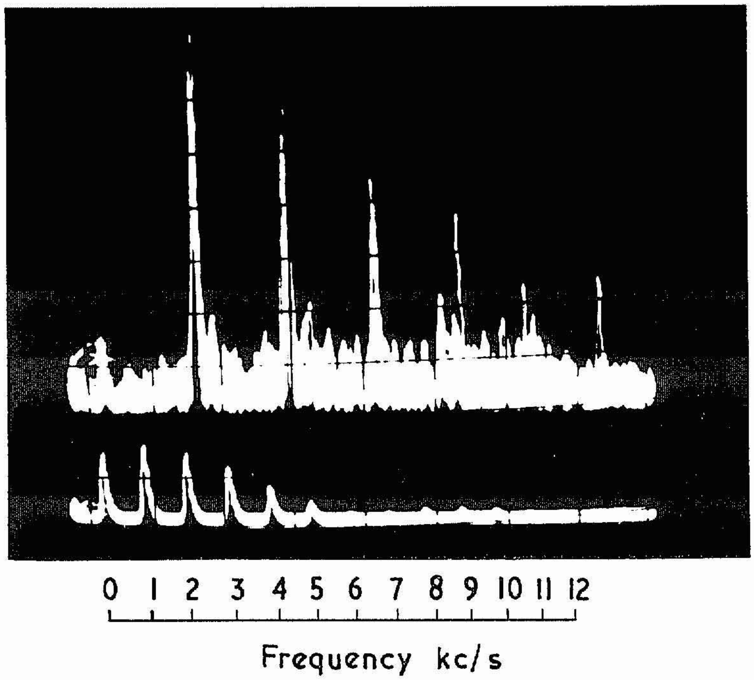
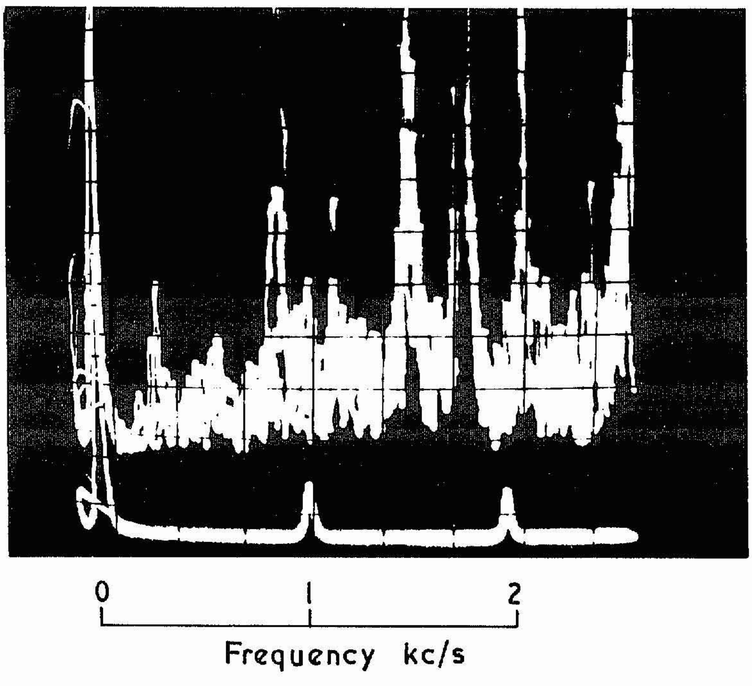


FIG. 9. Overall noise *versus* pressure ratio. Primary nozzle alone and with an ejector.

F



(a) Example of supersonic flow emission, (Ejector B1 $P/p_0 = 2 \cdot 3$)



(b) Example of subsonic flow emission, (Ejector A2 $P/p_0 = 1 \cdot 4$)

FIG. 10. Discrete-frequency display on Panoramic Analyser.

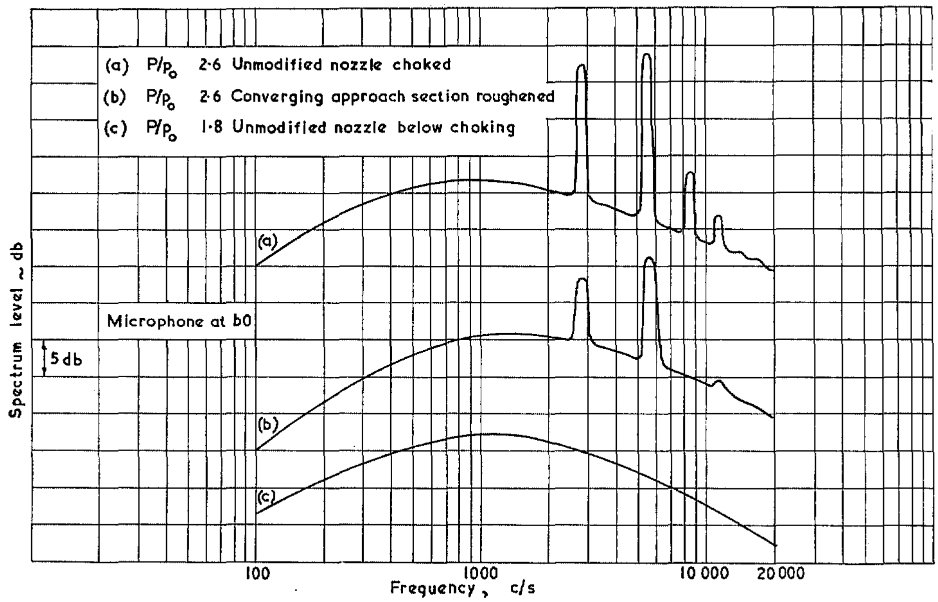


FIG. 11. Narrow-band analyses of primary-nozzle spectra.

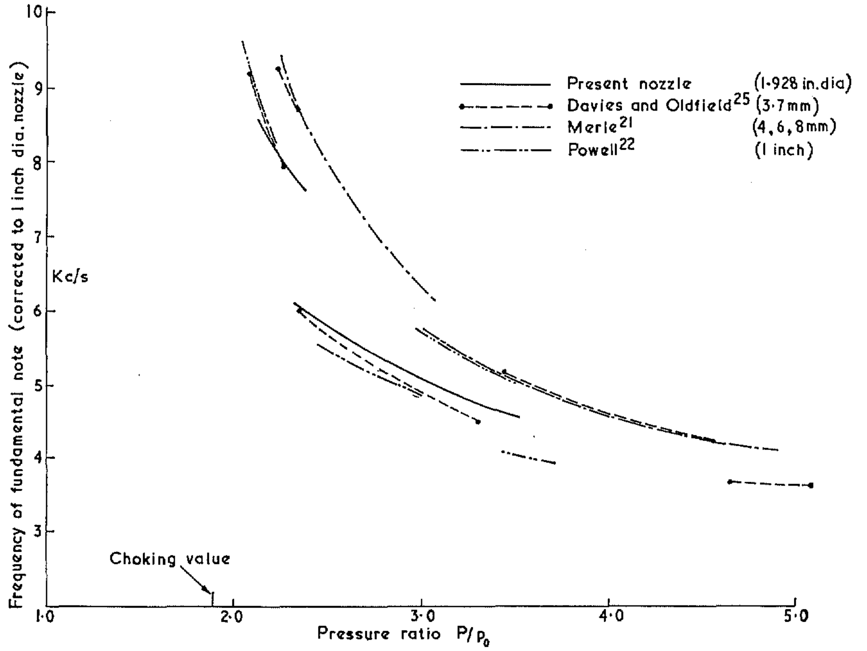


FIG. 12. Variation of frequency of shock noise with pressure ratio—results of various experimenters on circular nozzles.

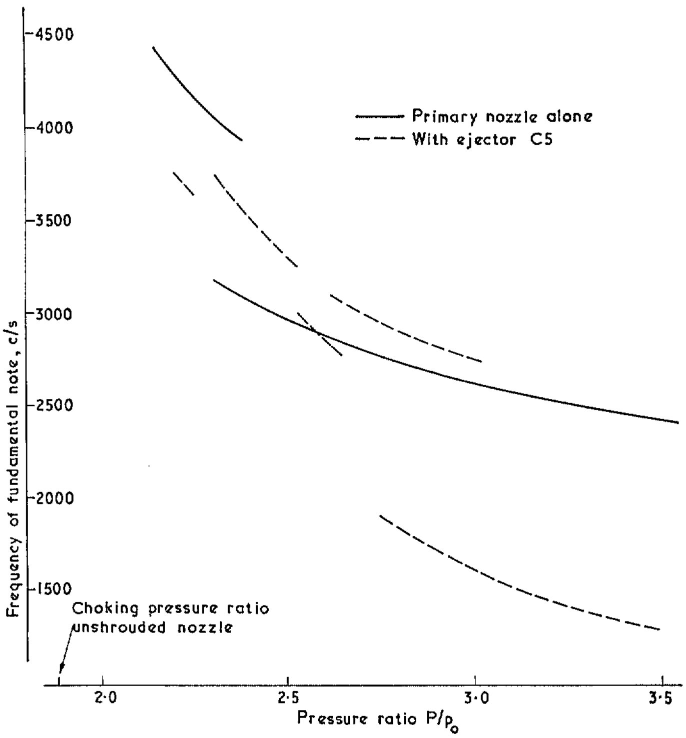


FIG. 13. Variation of frequency of shock noise with pressure ratio: primary nozzle alone and with a typical ejector.

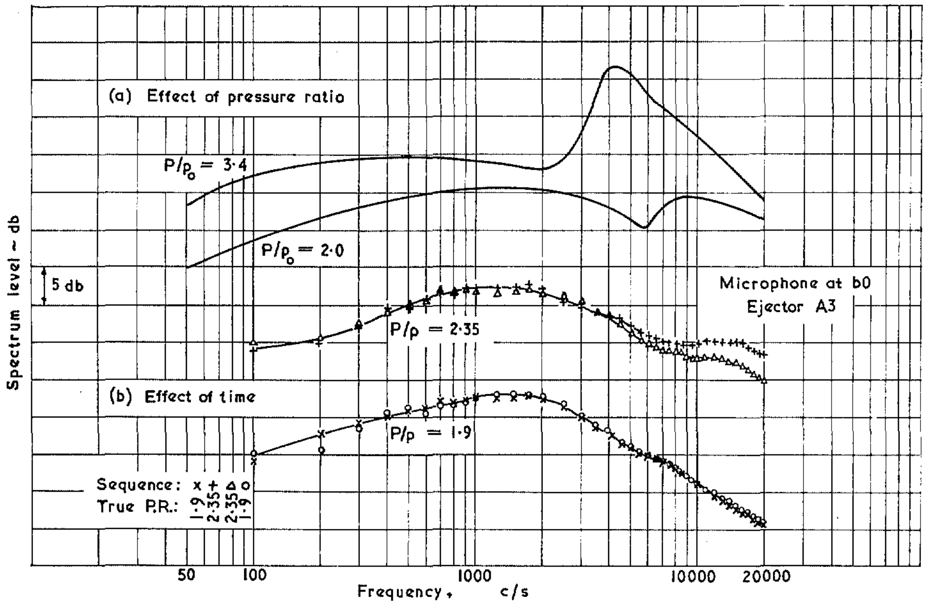


FIG. 14. Effect of pressure ratio and time on 'excess high-frequency noise'.

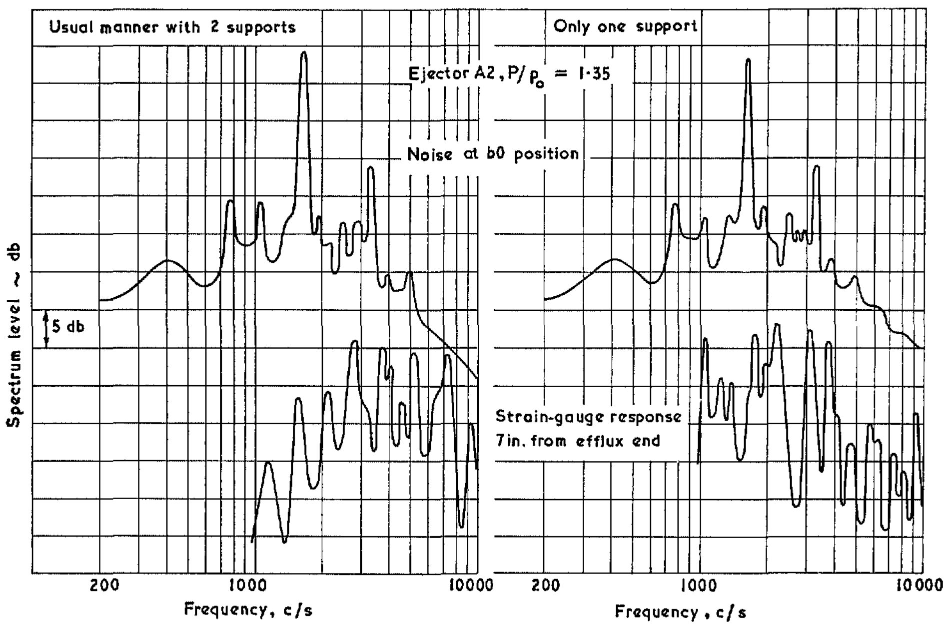


FIG. 15. Effect of mounting on the noise and vibration of an ejector.

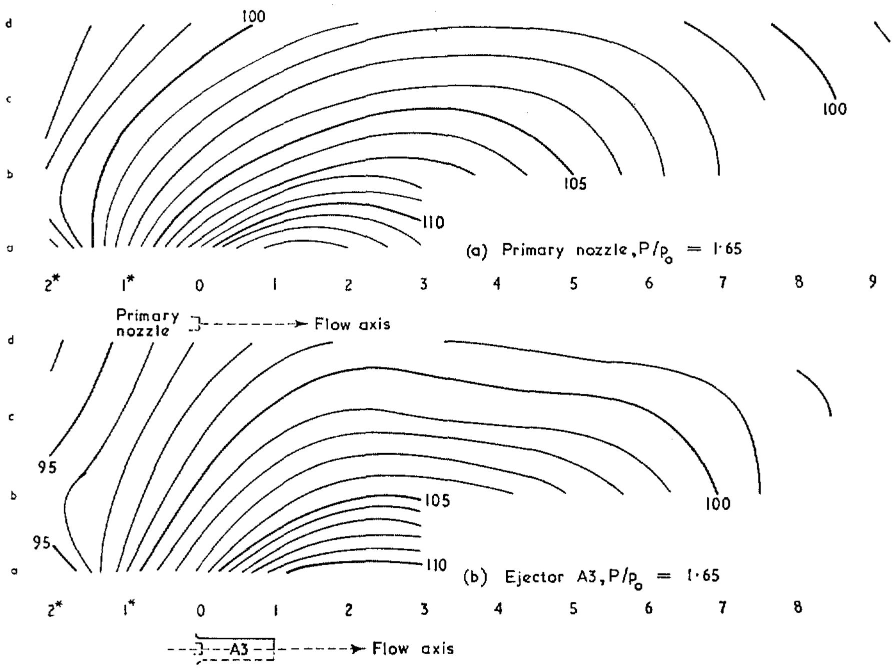


FIG. 16. Contours of overall noise (db re 0·0002 dyne/sq. cm).

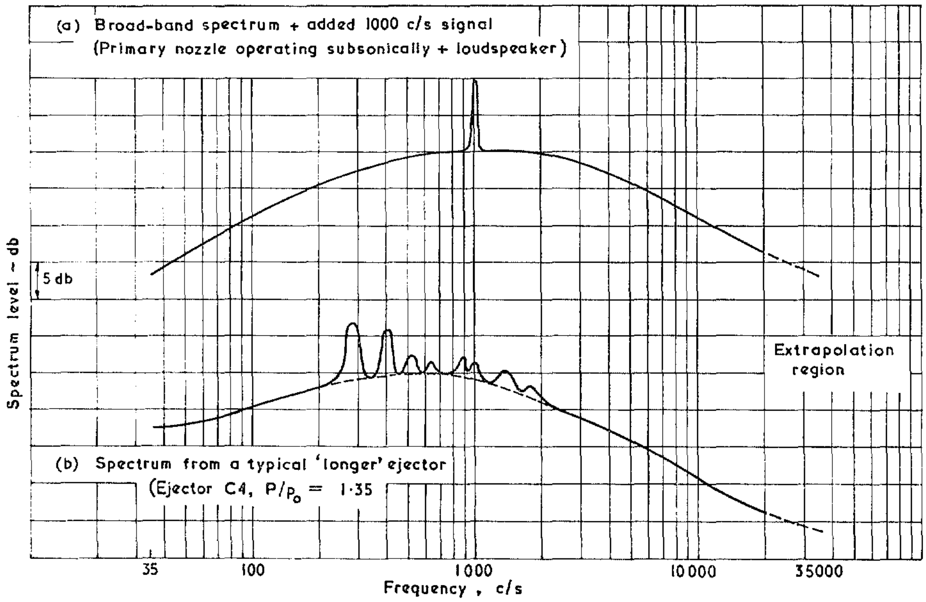


FIG. 17. Spectra with 'artificial' and 'natural' discrete frequencies for removal.

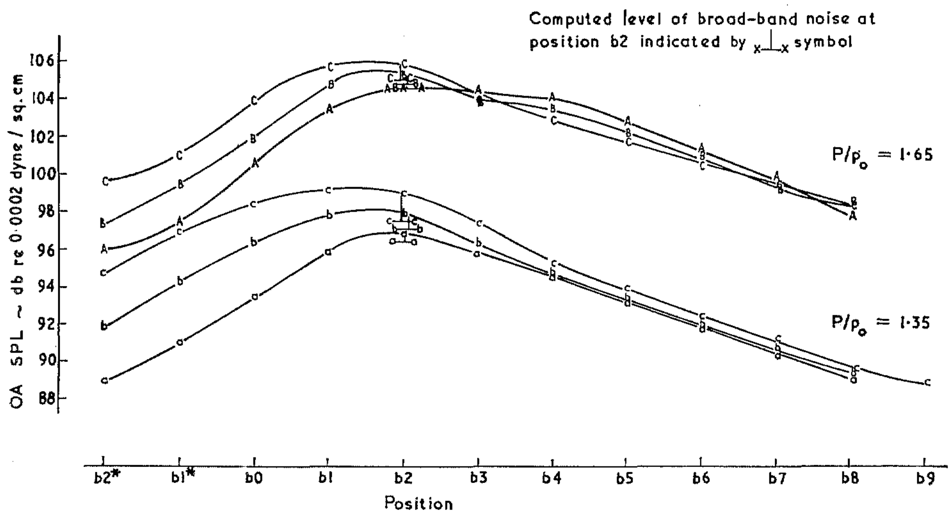


FIG. 18. Overall noise levels measured along line b, —3 length ejectors.

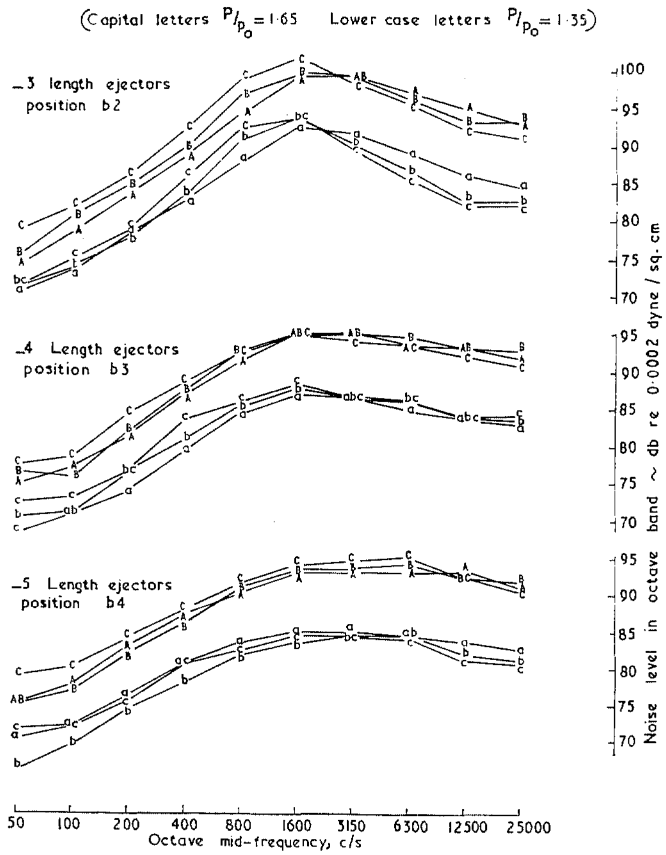


FIG. 19. Spectra at peak linear noise position, after removal of discrete-frequency components.

(91137) Wt. 66/2301 K.5 8/65 Hw.

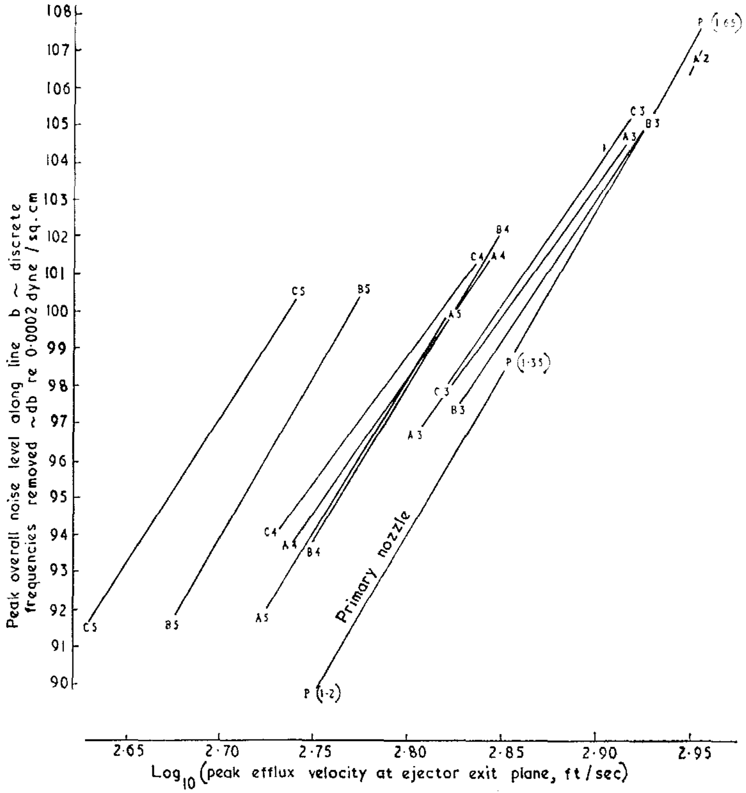


FIG. 20. Peak linear noise level (filtered) *versus* $\log_{10}$ (peak efflux velocity).

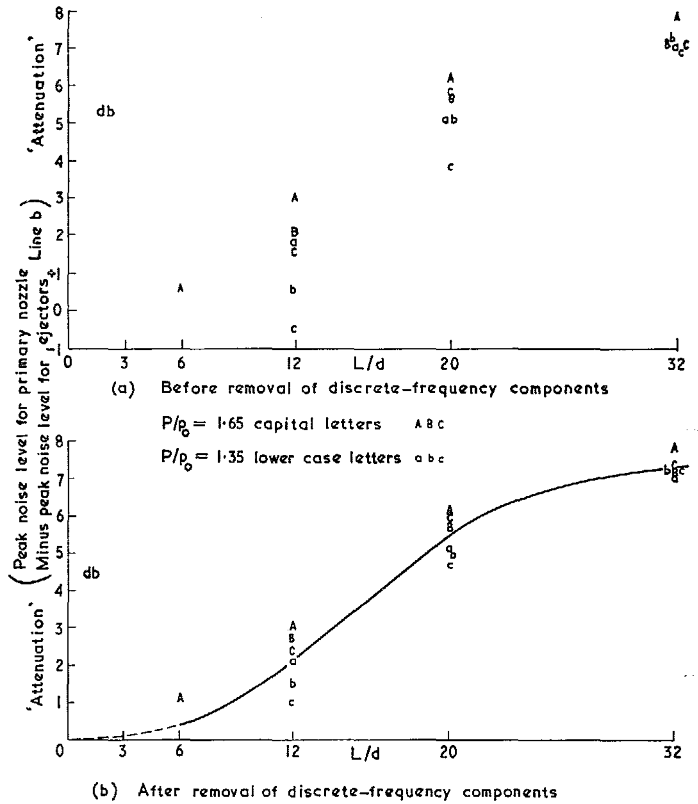


FIG. 21. Attenuation *versus* non-dimensionalised ejector length.

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