PROGRESS IN JET ENGINE NOISE REDUCTION

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INTRODUCTION

The comparatively rapid advent of the large civil jet airliner has in several fields stretched technical resources to their limits. Indeed, in some particular cases, at the time when these aircraft were being purchased off the drawing board by the world's airlines, requirements arose which could be met in time for production only by undertaking very costly research and development programmes.

One such case is the work associated with reduction of jet noise which is being carried out by several companies in the aircraft industry and a number of research organizations in the U.S.A. and Great Britain. This work is aimed at reducing annoyance to communities in the vicinity of airports caused by the noise of jet aircraft—annoyance which might compel the Airport Authorities to restrict operation of the aircraft.

In this respect the jet silencer is unique in that it is the only item of equipment which has to be installed yet does not contribute to the safety of the aeroplane or the comfort of the passengers. The cost to the aircraft industry, and ultimately to the airline passengers, covering research, development, production, and performance penalties of this otherwise unnecessary article is considerable. (In this connexion we acknowledge gratefully the support of the Ministry of Supply towards the research work.) Competition between manufacturers has no doubt added to these costs by causing some duplication of effort although there is an agreement between the Boeing Airplane Company and Rolls-Royce Limited to interchange all information on silencing.

Owing to the *ad hoc* nature of much of the work and differences in technique of measurement and analysis, overall correlation of results is difficult. The paper therefore will not summarize all of the work in this field, and except in one or two instances will refer only to that of Rolls-Royce.*

The most satisfactory solution of the problem is undoubtedly the low jet velocity engine of which several examples will be available for use in

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* The experimental work described has been carried out by Mr. R. S. Brain and his colleagues at Hucknall, whose assistance in preparing this paper is gratefully acknowledged. The authors wish to thank Rolls-Royce Limited and the Chief Scientist of the Ministry of Supply for permission to publish the paper.

the next generation of aircraft. It should however be borne in mind that this first stage necessitated using existing engines whose relatively high jet velocity had to be accepted. Thus the silencer was required to reduce jet noise with no change in velocity, the most powerful of the variables affecting its generation.

However we have now reached a stage where there are silencers available in various forms, but based on similar principles. Three such silencers, designed by Rolls-Royce, are shown (Figs. 1, 2 and 3) installed

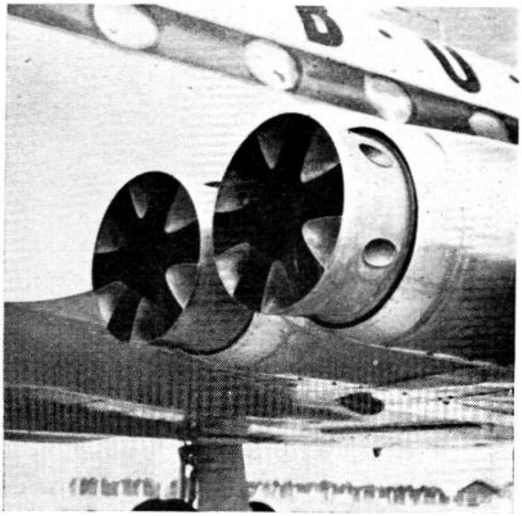

FIG. 1. De Havilland COMET. The Avon silencer.

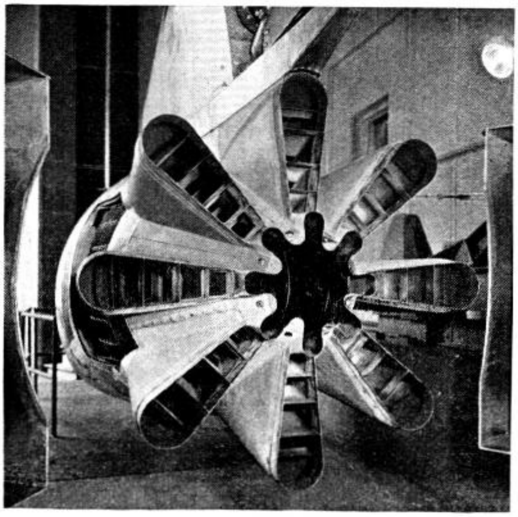

FIG. 2. BOEING 707–420 Pod. The Conway silencer.

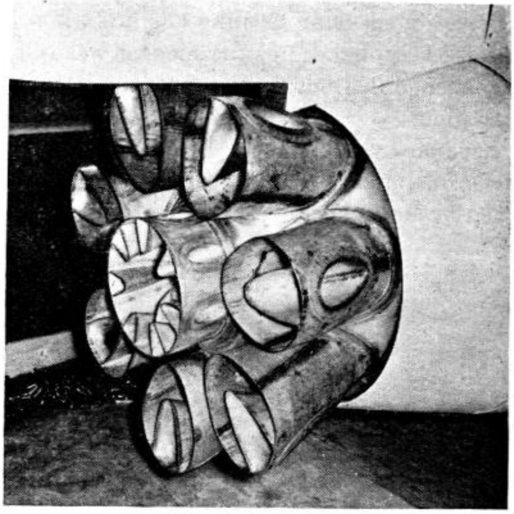

FIG. 3. DOUGLAS D.C.8. The 7-lobed nozzle.

on the COMET, on a BOEING 707 Pod, and on the DOUGLAS D.C.8 respectively.

The paper will outline the work which has led to these silencers, the first two of which are now in production.

TEST EQUIPMENT

All of our earlier tests reported in Ref. 1 were carried out on a relatively crude test stand sited to permit noise measurement in a large unobstructed area around the jet nozzle, which was then the only requirement. The intensive development consequent on fixed production dates howover introduced three further factors.

Firstly the need to carry out aerodynamic and silencing development in parallel involved accurate measurement of performance. Secondly in order to obtain systematic data on series of nozzles, it was clear that a considerable economy in both time and material could be effected by use of a small scale jet. This was considered somewhat reluctantly in view of earlier difficulties in correlating model and full scale test results to the required degree of accuracy. Thirdly as silencing during take-off and initial climb was the primary object an accurate measurement of flight attenuation was needed.

To meet these requirements two new beds have been constructed, one full scale and the other approximately a quarter scale, both capable of accurate performance measurement. In addition a CANBERRA aircraft used for engine development is available periodically for measurements of flight noise. A brief description of these follows:

Full Scale Rig

This consists of an open air test bed specially constructed for noise measurement and accurate performance assessment. The siting of this rig was carefully considered to enable free field noise measurements to be made without obstruction or risk of reflections at distances up to 200 ft radius from the nozzle and angles up to 120° from the jet axis.

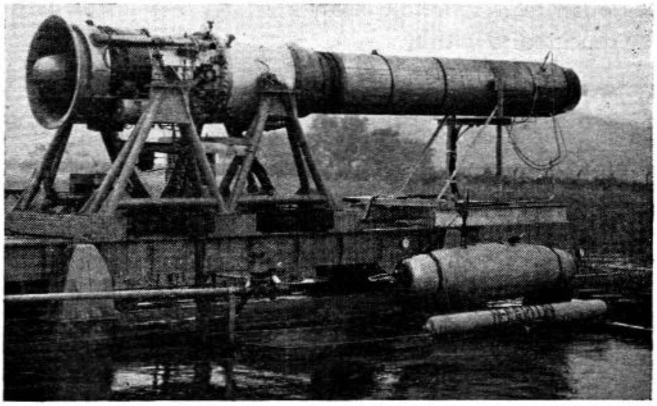

FIG. 4. The noise test bed.

Figure **4** shows an engine rigged on the test cradle which is designed to accommodate engines of up to 30,000 lb thrust, operating with either forward or reverse thrust. The control room is 75 ft away in line with the engine intake which allows full 360° traverses at a radius of 50 ft.

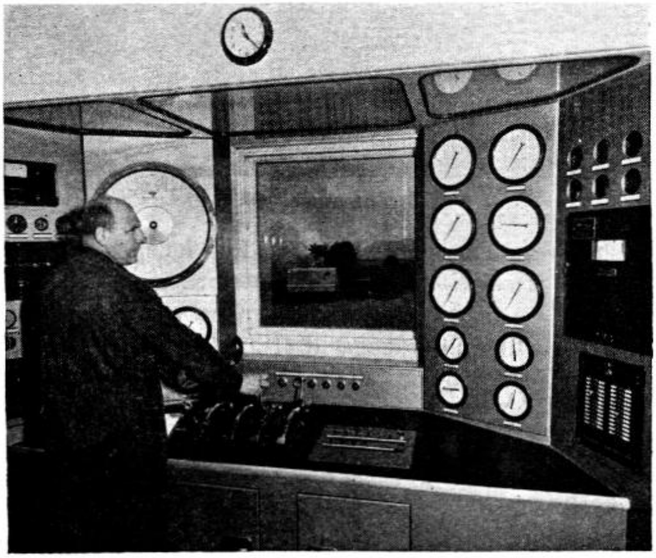

FIG. 5. The noise test bed control room.

The performance penalty associated with a silencing device is just as important as its efficiency as a silencer. Therefore, in developing full scale nozzles for particular projects, small performance penalties must be assessed to a high degree of accuracy. Figure 5 shows part of the control room which contains instrumentation for full performance testing of any type of engine. Special attention has been paid to thrust and speed measurement which, together with the fact that the test engine is in no way obstructed by a test cell or muffler, enables thrust measurements to be repeated to within $\pm\frac{1}{4}\%$.

Quarter Scale Rig

This is a smaller open air bed carrying a Blackburn Palas 600, which is a development of the Turbomeca engine. The engine has a nozzle diameter of 5·52 in. and although the maximum jet velocity for continuous running is limited to approximately 1670 ft/sec, this has proved high enough for accurate comparisons of noise characteristics.

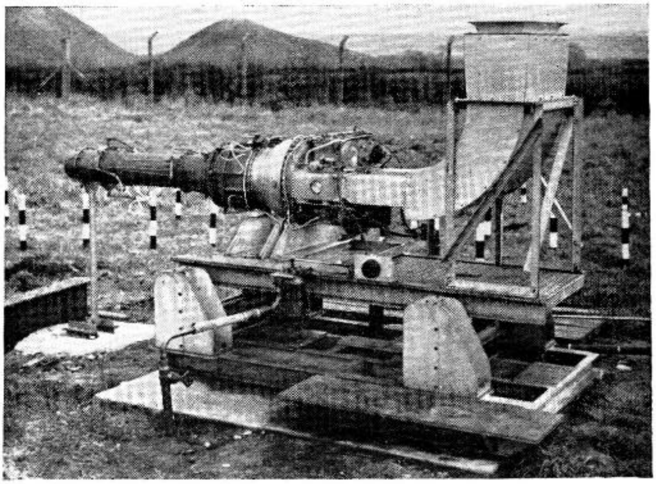

FIG. 6. The model test rig.

Figure 6 shows the Palas engine mounted on its specially constructed thrust measuring cradle, which enables performance as well as noise measurements to be made. An intake silencer was fitted to eliminate compressor noise which predominated at angles of 120° to 180° to the jet axis. The only other modification carried out on the engine was to fit a long jet pipe to accommodate the various test nozzles and instrumentation required.

Flight Test Facility

The CANBERRA aircraft used is shown in Fig. 7 fitted with a test silencer. It is a twin engined aircraft capable of flying at a satisfactorily wide range

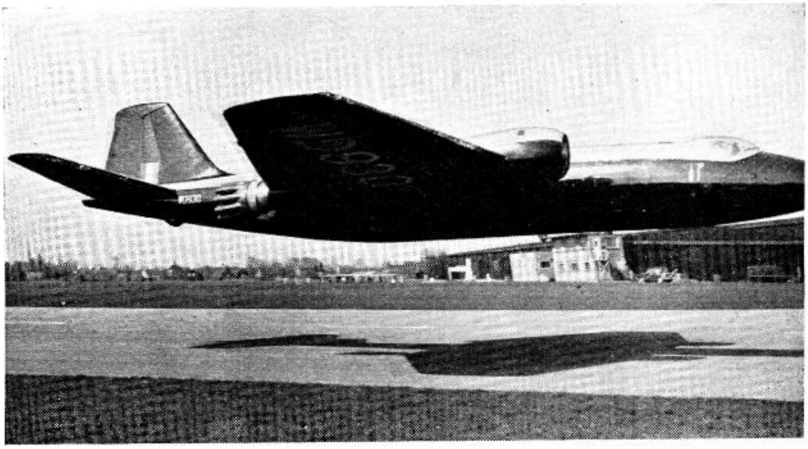

FIG. 7. The CANBERRA test aircraft.

of conditions on one engine only. Thus a direct comparison can be made between the standard conical nozzle fitted to one engine and the silencer fitted to the other in alternate flights past the measuring station. This most important point will be discussed further in section 2 on Test Technique.

2. TEST TECHNIQUE

The general test technique to obtain consistent results in static and flight tests is best described by considering in turn the significant variables, some of which cannot be controlled. Aside from the characteristics of the measuring equipment, the absolute noise level recorded depends on engine operating condition, distance, atmospheric conditions, and local terrain. In flight the additional variables, aircraft speed, and attitude, are also important.

Atmospheric Conditions

Lighthill's dimensional analysis⁽²⁾ predicts that the total acoustic power output varies as $\rho_j A_j V_j^{3}(\rho_j/\rho_0)\,(V_j/a_0)^n$ where n lies in the range 5 to 7. (See Appendix for list of symbols.) This has been established by noise measurement for at least the jet velocity and area factors. Measurements of peak sound pressure level (S.P.L.) in ground and flight tests are also correlated satisfactorily by this expression using velocity indices 5·3 and 7 respectively. Our procedure is therefore to correct measured results to I.S.A. conditions for $\rho_0 a_0^n$.

In Figures 8 and 9 measured peak noise levels for circular nozzles under ground and flight conditions respectively have been scaled to unit jet density and area so that the ordinate is corrected S.P.L. minus $10 \log_{10} \rho_j^2 A_j$. These results are plotted against fully expanded jet

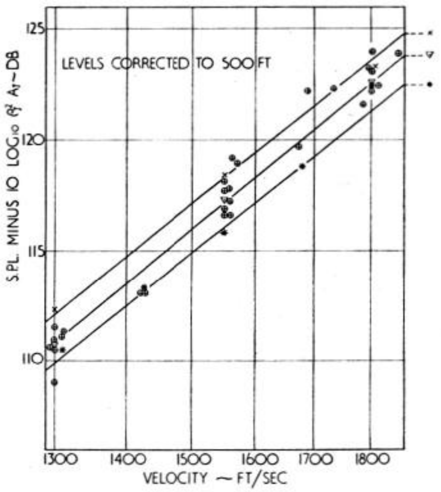

FIG. 8. Correlation of polar peak noise measurements from the full scale rig.

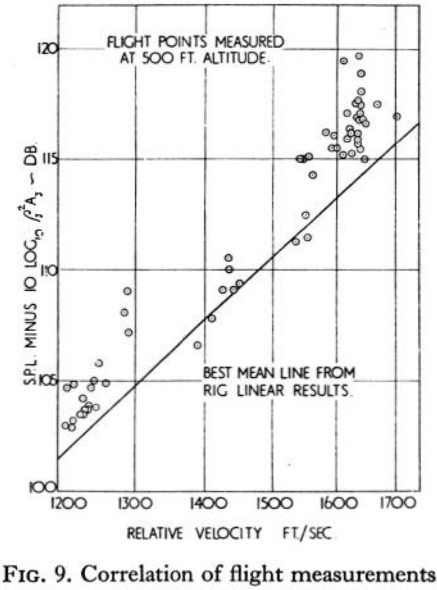

FIG. 9. Correlation of flight measurements.

velocity calculated sufficiently accurately from the instrument readings normally used for engine performance assessment. They show that even with most careful control of the variables, the absolute noise level, measured on a given engine and nozzle under apparently constant conditions, varies over a period of time by as much as $\pm 1{\cdot}5$ db in ground tests and ± 3 db in flight tests. This appears to be distinct from normal experimental scatter since results of any group of tests, some of which are indicated, carried out within a short period of say two or three hours seem to form a satisfactory set.

If therefore a silencer and standard nozzle are tested within a short period the attenuation recorded remains consistent in subsequent repeat tests. For this reason the CANBERRA aircraft, which is capable of operation over a satisfactorily wide range of flight speeds on one engine, is particularly suitable for flight measurements. With a silencer fitted to one engine and a standard nozzle to the other the adopted technique is to carry out four or five runs per nozzle at each condition, the engine carrying the other nozzle being throttled to idling. These runs are made along the fixed course and its reciprocal alternately.

Terrain

In view of the difficulty of prediction of the effect of ground reflections the simplest precaution is to maintain constant measuring points. As the effect would be expected to vary with distance from the source a circular traverse probably gives results which are most reliable for extrapolation. Conversion to a straight line traverse suitable for correlation with flight results is simple enough.

Again in flight a fixed measuring station and a fixed overhead course and altitude give satisfactory results.

Distance

At distances of 100 ft to 500 ft noise measurements on a constant full scale source of jet noise appear to obey a $(\text{distance})^2$ law. Below 50 ft the deviation from this increases rapidly owing to the pronounced directionality of the field. We have therefore chosen 100 ft as the standard radius for the circular traverse.

The standard altitude for flight tests is 500 ft. This is capable of accurate measurement and approximates to the condition at which we are most interested in the attenuation.

Analysis of Results

The full lines of Fig. 10 are typical curves of sound pressure level (S.P.L.) versus angle, α, from the jet axis on a 100 ft circular traverse for a standard nozzle and a silencer. This is really a polar diagram although it is presented here on a square grid for convenience. The difference in S.P.L. between the peaks of the two curves irrespective of the angle at which they occur is termed peak-to-peak attenuation. This is by no means a complete measure of a silencer's effectiveness in diminishing annoyance due to noise, since the latter depends on so many factors, but it is a significant and useful measure in a single number. Although the subjective aspect of noise will be raised where appropriate the majority of this paper is concerned with peak-to-peak attenuation.

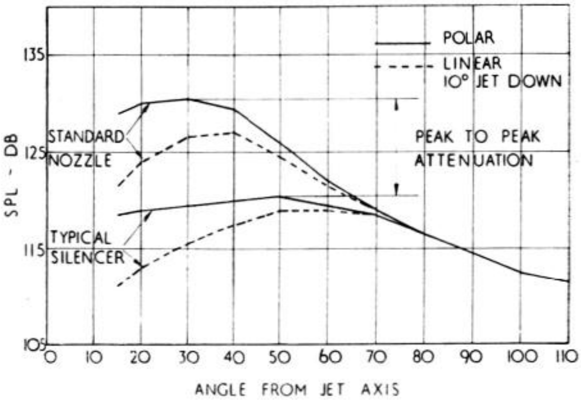

FIG. 10. Typical noise measurements at 100 ft for circular and silencing nozzles.

As we are primarily interested in the noise emitted from an aircraft in flight it is clearly desirable to obtain from the ground test results, if possible, a measure of the flight attenuation. Figure 11 indicates how a suitable correction can readily be made. The circular traverse used for static measurements is represented by the arc AB. Movement of the observer relative to the aircraft, with its jet axes parallel to the line of flight, is indicated by the straight line AC. The S.P.L. at a point C on the straight line is obtained from that at B on the circular traverse by means of the (distance)^2 law. For example at 30° to the jet axis the S.P.L. on the straight line will be 6 db lower than that on the circular traverse. A curve of S.P.L. versus angle along the straight line is termed a linear diagram. If the jet axis is inclined, say $\theta°$ down, relative to the flight path the required line for converting results on Fig. 11 is DE inclined at $\theta°$ to AC. The difference between polar and linear S.P.L.'s on any radius is $20 \log_{10} \sin (\alpha + \theta)$.

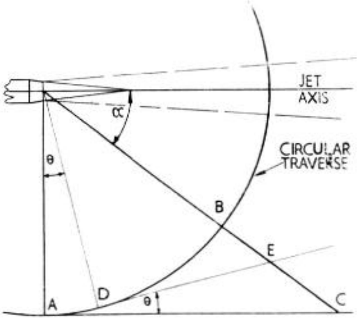

FIG. 11. Derivation of linear from polar diagram.

The linear diagram obtained from the typical polar is also shown in Fig. 10. In general the linear peak-to-peak attenuation is lower than the polar, and the angle of peak noise is greater.

The polar peak S.P.L.'s measured on circular nozzles and given in Fig. 8 have been replotted as linear peak S.P.L.'s for 5° jet down in a similar manner. This graph is not included but the computed best mean line is indicated in Fig. 9 for comparison with the actual flight results. The velocity indices are in quite good agreement, 9·5 and 10 respectively, and in absolute level the flight measurements are on average about 2 db higher.

3. SILENCER GEOMETRY

Having taken peak-to-peak polar attenuation as at least a useful measure of a silencer's effectiveness it was clearly desirable for design purposes to be able to derive it from the silencer geometry. This had the additional advantages of permitting an assessment of the trend of performance penalties for a given type of nozzle, so that tests on one of the type fixed the absolute values; and as it seemed likely that for a given type, e.g. a corrugated nozzle, several geometries would give the same attenuation such a correlation would fix optimum designs.

A first attempt to express attenuation in terms of geometry was made on the following lines, to determine suitable parameters.

Area Ratio

Consider a circular nozzle and ejector configuration as shown in Fig. 12. Assume that the ejector tube is acoustically lagged, and sufficiently long to permit complete mixing of jet gas and induced air. The area, density, and velocity of the issuing jet are then expressible in terms of ejector area ratio A_a/A_J, primary nozzle pressure ratio and primary jet temperature ratio. If for present purposes we confine the latter two parameters to a sufficiently small range appropriate to a primary jet velocity of say 1800 ft/sec, the outlet conditions and consequently the noise level of the issuing jet is determined by the ejector area ratio only.

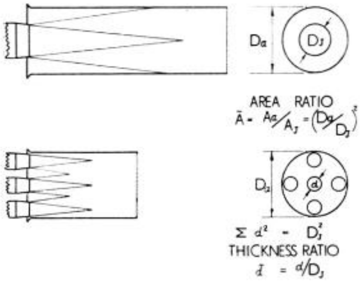

FIG. 12. Ejector nozzle and illustration of terms.

Division of the circular nozzle into a number of smaller equal nozzles reduces the characteristic mixing length and permits a shorter ejector tube for the same outlet noise. The mixing length tends to zero with increasing number of nozzles and in the limit we have an infinite number of nozzles distributed uniformly within a circle of the same area ratio and producing the same noise as the original ejector. The latter statement is not strictly accurate since the outlet velocity profile changes, becoming squarer with increasing number of nozzles. Nevertheless this can be regarded as an ideal nozzle whose attenuation can be predicted in trend if not in absolute value from measured ejector performance.

The shape of the curve of attenuation versus area ratio for an ideal nozzle (infinite number of corrugations) is shown in Fig. 14.

Number of Corrugations

A further parameter was required to express the degree of division of the nozzle. As measurements on corrugated nozzles were the only full scale results available number of corrugations, N, was the obvious first choice. All of the full depth corrugated nozzles tested were of the area ratio 2. The attenuations obtained are plotted against $1/N$ in Fig. 13 to include the theoretical value for the ideal nozzle. A straight line fits the points satisfactorily.

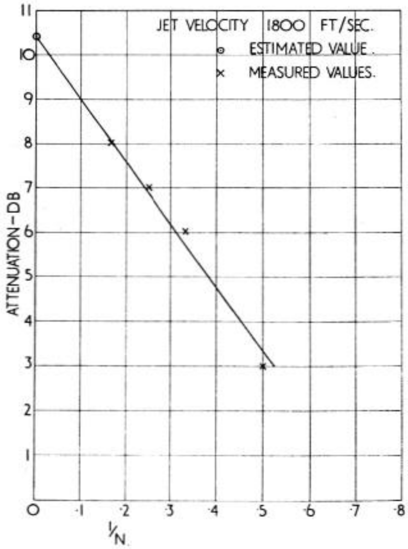

FIG. 13. Peak polar attenuation due to N-corrugated nozzles at an area ratio of 2.

To extrapolate to area ratios higher than 2 we made two assumptions.

The first was that the total acoustic power generated remained substantially constant irrespective of nozzle shape but that due to interference some of the noise was redirected or scattered. Referring to the region between the nozzle plane and the stage at which individual jets coalesce as the initial mixing region (Subscript 1), the remainder of the jet as the final mixing region (Subscript 2), and the unsilenced circular jet as the standard (Subscript 0), we can then relate the total acoustic powers generated by the standard and silencing nozzles by $E_0 = E_1 + E_2$.

For a particular direction and distance the intensity due to the silencer, $I_s = I_1 + I_2$.

For the circular jet fields 0 and 2, having similar directional properties, $I = KE$ where K is a factor depending on direction and distance, but for field 1 $I_1 = \lambda KE_1$ where λ is the ratio of the actual intensity from the region 1 to that from the equivalent region of the circular jet field, O. Then

$$\frac{I_s}{I_0} = \lambda \left(1 - \frac{E_2}{E_0}\right) + \frac{E_2}{E_0}$$

and the attenuation for this direction is $-10 \log_{10} I_s/I_0$ whereas $-10 \log_{10} E_2/E_0$ is the ideal attenuation.

The second assumption was that λ, the proportion of noise escaping from the initial mixing region, was a unique function of N the number of corrugations. This enabled the characteristics of Fig. 14 to be produced.

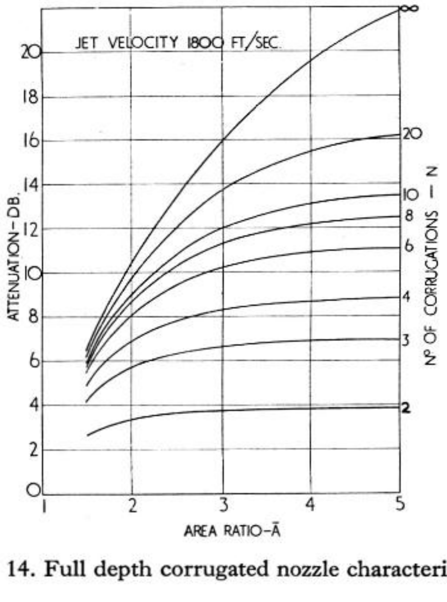

FIG. 14. Full depth corrugated nozzle characteristics

Thickness Ratio

As corrugation was by no means the only way of dividing the final nozzle, to attempt any correlation with other types it was necessary to replace N, the number of corrugations, by an equivalent geometric parameter.

At any area ratio the significance of N appeared to be no more than that of determining the thickness of the individual jets and correspondingly the length of the initial mixing region. As the majority of the noise is generated by the thickest portions of the subdivided jet (i.e. those requiring the longest mixing length) it was presumed that a parameter defining this would serve the purpose.

The simplest measure applicable to all shapes of nozzle is the diameter, d, of the largest inscribable circle, and the parameter chosen, termed thickness ratio was $\bar{d} = d/D_j$. (Where D_j is the diameter of the standard circular nozzle.)

The original characteristics are shown replotted in terms of $\bar{d}$ instead of N in Fig. 15.

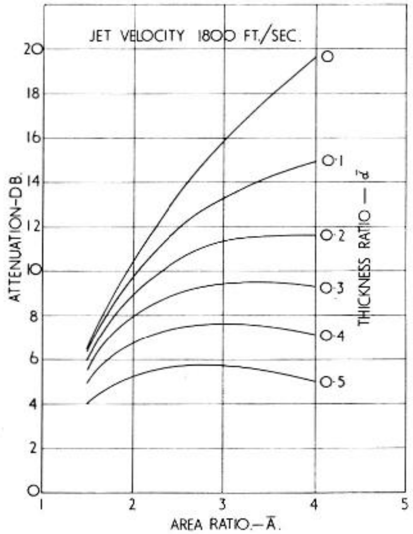

Fig. 15. Uniformly divided nozzle characteristics.

Effect of a Central Nozzle

It is seldom practicable to use a full depth corrugated or otherwise uniformly divided nozzle owing to drag of the base fairing between individual segments of the nozzle. To obtain a satisfactory base fairing shape within a reasonable length usually involves leaving a large central nozzle of thickness ratio greater than that of the outer divided nozzle. This clearly affects the attenuation and if we are to consider practical nozzles it is necessary to produce further empirical characteristics to allow for the loss in attenuation. The simplest approach to this appeared to be to increase the estimated noise output from the silencer by an amount equivalent to that produced by continued mixing of the central jet remaining at the end of the initial mixing region. The theoretical

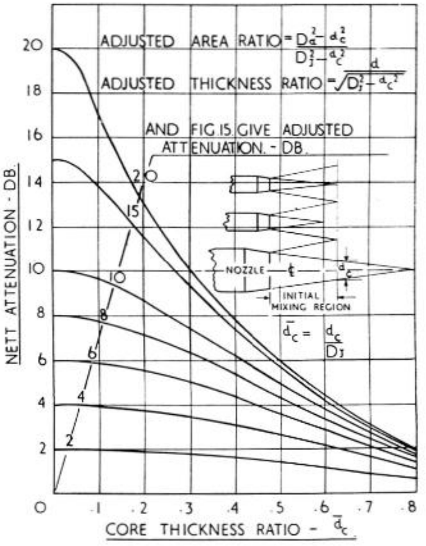

FIG. 16. Effect of large central nozzle.

characteristics appropriate to this are shown in Fig. 16 together with an "adjusted" area ratio and thickness ratio to be used with Fig. 15 in assessing the "adjusted" attenuation. This merely amounts to omitting the central jet in estimating the attenuation due to the outer portion of the nozzle.

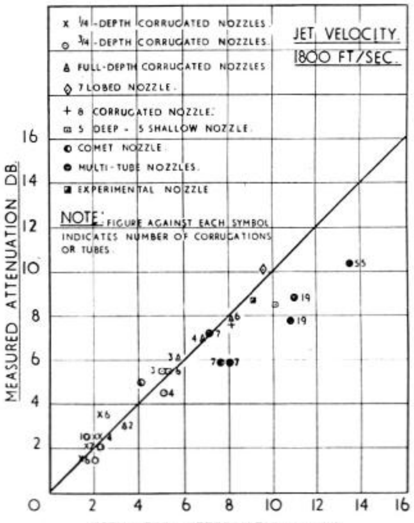

FIG. 17. Measured vs. estimated attenuation.

Comparison with Measurements

Measured attenuations for all full scale nozzles tested are shown in Fig. 17 against the values estimated by the above method. (The terms $\frac{1}{4}$ depth, etc., used in the figure signify that $(Ra - r)/Ra = \frac{1}{4}$ where r = the central nozzle radius and Ra = the overall nozzle radius.) The agreement is generally good.

Shown also on the figure (black circles) are $\frac{1}{4}$ scale results on multi-tubed nozzles, which fall 2 to 3 db lower than predicted. These silencers, however, consisted of hexagonal arrays of circular pipes with poor secondary air access to the centre, following the devious path. BOEING model tests have indicated the importance in constructing such nozzles, of placing the tubes in radial lines for this reason. The deficiency from estimated attenuation agrees well with their results, and further tests are in hand to investigate this.

Ejector Silencers

Combinations of divided nozzle and ejector, the object of the latter being to absorb or redirect some of the initial mixing region noise, can be analysed in a similar manner. This involves two further parameters to fix the geometry of the mixing tube and a third to define its effectiveness in intercepting noise. In fact, to keep the ejector size to a minimum the optimum geometry would probably be that which just enclosed the initial mixing region, that is area ratio as for the divided nozzle and a length ratio of $6\bar{d}$ to $8\bar{d}$ leaving only the third paramater as a variable. At present there are insufficient results available to attempt a correlation although we have a model test programme in progress.

A complication involved in the ejector arrangement is the need to retract the mixing tube as soon as possible in flight owing to loss of thrust. Under static and low speed conditions thrust is augmented with any ejector area ratio; in high speed flight, however, the area ratio required for a useful silencer (2 to 3) is far too large to match the nozzle pressure ratio and with a fixed arrangement a serious loss of thrust occurs.

A Different Approach

To investigate the mode of operation of silencers a simple element was constructed of two circular nozzles with a variable distance between centres. Preliminary results, although of uncertain reliability, are interesting and are shown in Fig. 18. Considering first spacing ratios of four diameters or more, the implications are that:

1. In the plane through nozzle centre lines the attenuation is in the region of 3 db. As the interference between the jets spaced so far apart is negligible the obvious conclusion is that the noise of the rear jet is intercepted completely.
2. At right angles to the plane joining centre lines the attenuation appears to be zero as might be expected.

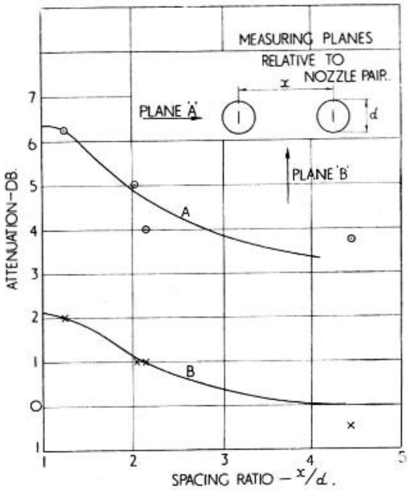

FIG. 18. Measured attenuation for a pair of nozzles.

At closer pitching than 4 dia. there is some additional attenuation due presumably to interference of the mixing regions.

Accepting these implications for the moment some further interesting deductions may be made.

Consider a square array of M^2 equal nozzles, pitched sufficiently far apart to avoid interference. Viewed at right angles to any face we would expect to measure the noise of the front rank only, i.e. M of the M^2 nozzles, and the attenuation should therefore be $10 \log_{10} M$. For a practical nozzle of area ratio 2 to 4 the interference would be considerable and should result in some additional attenuation.

The only multi-tubular nozzles we have tested, referred to in Fig. 17, have consisted of hexagonal arrays of area ratio 2 to 4. The number of nozzles in a complete array is $3R^2 + 3R + 1$ where R is the number of rows around the central nozzle. Viewed from the direction of a vertex the number of nozzles in the front rank is $2R + 1$ and the attenuations due to blanking would thus be

$$10 \log_{10} \frac{3R^2 + 3R + 1}{2R + 1}$$

In addition the nozzle pitching fixed by the area ratio determines a further attenuation due to interference. A specimen set of characteristics of attenuation versus area ratio is given in Fig. 19. The measured results are also indicated and agree quite well in trend. In absolute value the results are 1 to 1·5 db lower than estimated but this could be due to restricted secondary airflow as already mentioned.

It seems reasonable therefore to accept that the operation of a silencer consists of two independent effects:

(1) Interception of generated noise.

(2) Reduction of noise generated by interference of mixing regions.

Application of these to the "initial mixing region" of the discussion in section 3·2 does not conflict seriously with the argument presented there although some refinement is required to combine them satisfactorily.

Performance Penalties

A primary object in attempting to express attenuation in terms of geometry was to deduce the trend of performance penalties with attenuation. Expression of penalties in terms of geometry is not of course straightforward. If, however, it is assumed that for a well designed nozzle internal loss and external drag approximate to skin friction, and that a constant gauge of material may be used for a range of sizes of a given type of nozzle, then surface area of the silencer gives a measure of the penalties.

Consider two full depth corrugated nozzles of area ratios $\bar{A}_1$ and $\bar{A}_2$ and numbers of corrugations N_1 and N_2. If the internal loss is to approximate to that due to friction alone, flow separation must be avoided. This occurs most readily at the change of direction on entering a corrugation. The limiting change of direction will therefore be fixed for all nozzles and this involves corrugations of geometrically similar side view. The surface area ratio for these two nozzles is therefore approximately:

$$\frac{N_2 \bar{A}_2}{N_1 \bar{A}_1}$$

the required penalty factor.

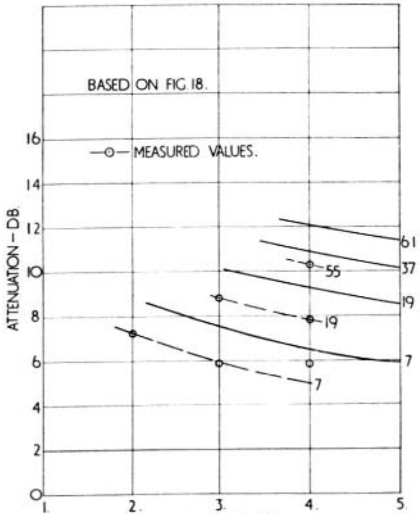

FIG. 19. Estimated attenuation for hexagonal arrays of circular nozzles.

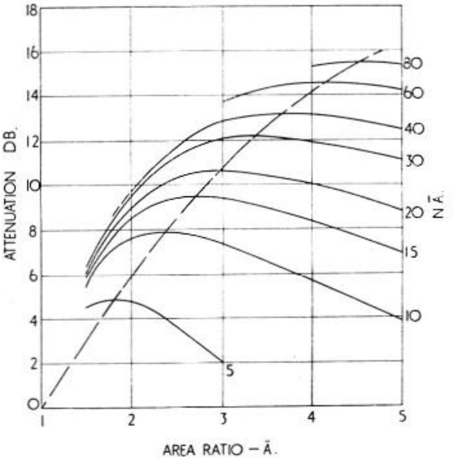

FIG. 20. Derivation of optimum nozzles. (Maximum attenuation for a given penalty, NA.)

Lines of constant $N\bar{A}$ derived from Fig. 14 are given in Fig. 20 and the optimum line is indicated showing the maximum attenuation for a given penalty. If we take arbitrary penalties for a developed silencer giving 10 db attenuation as:

T.O. thrust loss	1%
Cruise S.F.C. increase	1%
Cruise external drag	1% of net thrust
Weight penalty	1% of maximum T.O. thrust

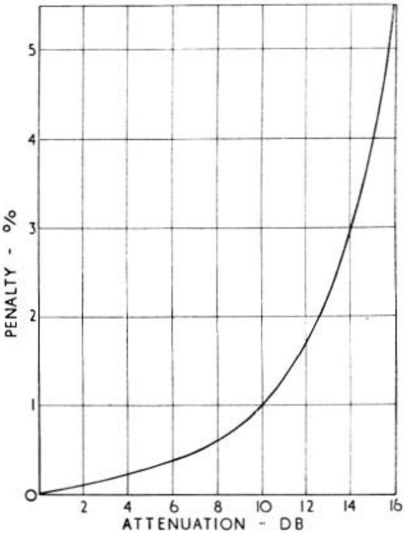

FIG. 21. Variation of minimum penalties with attenuation.

the common curve of Fig. 21 gives the estimated variation of these penalties with attenuation along the optimum line of Fig. 20. It seems therefore uneconomic to obtain much larger attenuations by means of divided nozzles owing to the rapid increase in penalties.

A similar assessment may be made for multi-tubular nozzles, or to allow for the effect of a large central nozzle, and of course the relation between penalty and geometry can be refined, but this example serves to illustrate the value of reliable generalized characteristics.

Engine/Aircraft Arrangement

As the position of one engine relative to another or to an aircraft surface might be expected to affect noise output and field directionality these effects are being investigated.

Proximity of engines. Test results available on this aspect are shown in Fig. 18 already discussed. It is of interest to note that on the basis of flight noise measurements on a COMET II we have previously assumed (see Ref. 1) an attenuation of 1½ db due to the closely pitched nozzles. The actual spacing ratio of the COMET II nozzles was 1·5 and using the lower curve (in considering overhead flight) the agreement is good.

With closely pitched silencers on the other hand the interference is probably effective only for adjacent segments of the divided nozzles rather than the complete nozzles. As the few segments which can be adjacent represent a very small proportion of the total nozzle area the effect on overall silencing is probably insignificant.

Proximity of aircraft structure. It was considered that the reflection characteristics, at a plane surface, of noise emitted by a silenced jet would probably be different from those of a circular jet. Owing to the reduced mixing length of a divided jet, the high intensity noise is produced nearer to the nozzle; it seemed possible therefore, for instance on an under-wing installation, that a larger proportion of the noise would be reflected with a silenced jet than with the circular jet. This could have diminished the effective attenuation. However tests with plates of varying gauges and representative areas showed no loss of peak attenuation, although small reductions (1 to 2 db) occurred at greater angles to the jet axis, around 90°.

4. FULL-SCALE SILENCERS

Avon Nozzle

This nozzle, shown in Fig. 22, was adopted on the basis of early measurements on partial depth six-corrugated nozzles which indicated that attenuations up to the required 4 or 5 db were obtainable for relatively little penalty in thrust. The corrugation shape was improved aerodynamically and the nozzle weight much reduced as a consequence of shortening the corrugations and pressure balancing them on to the secondary air feed tubes.

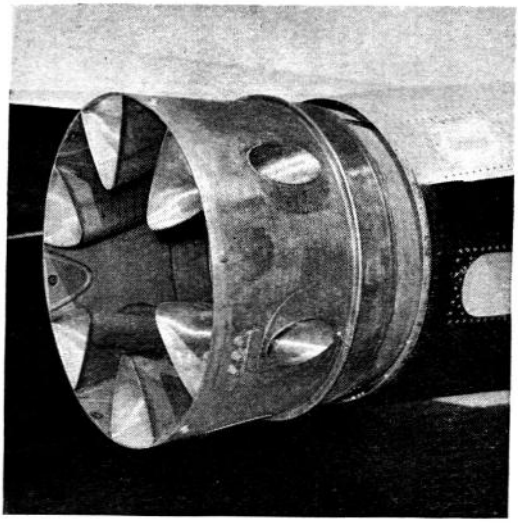

FIG. 22. Six-corrugated nozzle (AVON).
$\bar{A} = 1{\cdot}57$ $d = 0{\cdot}24$ $\bar{d}_c = 0{\cdot}5$

Conway Nozzles

The attenuation required in this case, about 5 db more than an AVON silencer (allowing for typical aircraft climb characteristics), was slightly greater than we had previously obtained on experimental nozzles. The required optimum geometries were an area of 2·75, and eight corrugations or a thickness ratio of about 0·22.

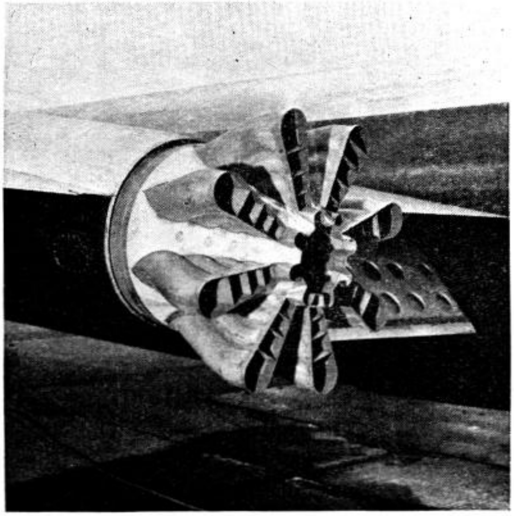

FIG. 23. Eight-corrugated nozzle (CONWAY).
$\bar{A} = 2{\cdot}74$ $d = 0{\cdot}18$ $\bar{d}_c = 0{\cdot}27$

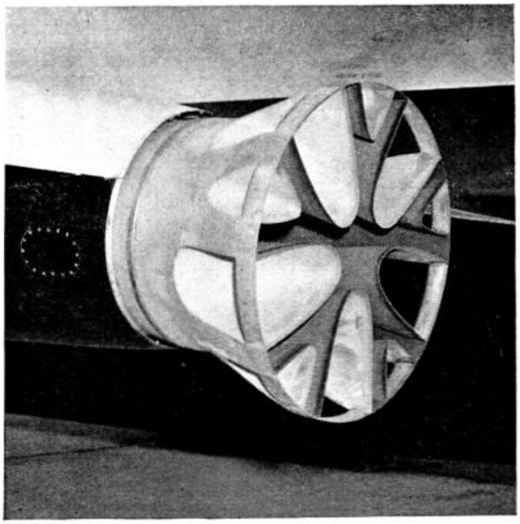

FIG. 24. 5 deep, 5 shallow nozzle (CONWAY).
$A = 2{\cdot}72$ $d = 0{\cdot}21$ $d_c = 0{\cdot}13$

Three silencers were designed on this basis:

(1) An eight-corrugated nozzle shown in Fig. 23.

(2) A nozzle (Fig. 24) with ten alternately deep and shallow corrugations of the type used in the Avon nozzle. This permitted a fairly uniform thickness ratio.

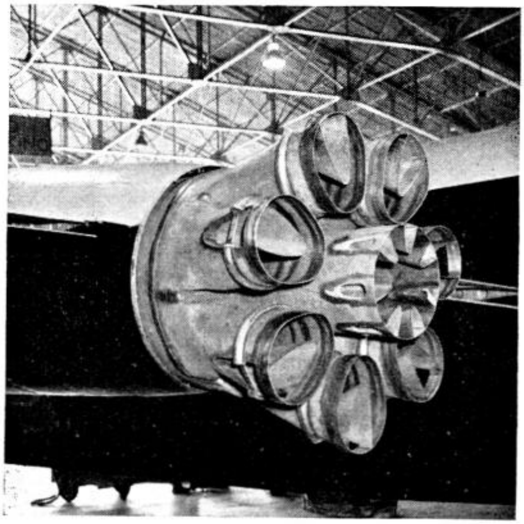

FIG. 25. Seven-lobed nozzle (CONWAY).
$A = 2{\cdot}60$ $d = 0{\cdot}116$ $d_c = 0{\cdot}23$

(3) A nozzle (Fig. 25) consisting of seven substantially circular tubes around the central nozzle with further subdivision, again by means of corrugations similar to those used in the Avon nozzle. During design of this nozzle it was found more convenient to reduce thickness ratio and area ratio together to give about the same attenuation.

The measured peak polar attenuations for these nozzles have already been indicated on Fig. 17 but their characteristics are presented in more detail below.

Noise Measurements

A specimen polar diagram for each nozzle in comparison with a standard nozzle is given in Fig. 26 for a jet velocity of 1800 ft/sec. Curves of peak S.P.L. from a series of polar diagrams versus velocity are shown for all nozzles in Fig. 27 and a corresponding set derived from linear diagrams in Fig. 28. An indication of the effect of the silencers on noise spectrum is given for an angle from the jet axis of 30° and a velocity of 1800 ft/sec in Fig. 29. Finally, curves of peak S.P.L. measured in flight test versus velocity are shown in Figs. 30 to 33 corrected to a standard altitude of 500 ft and a jet axis 5° down relative to the aircraft flight path.

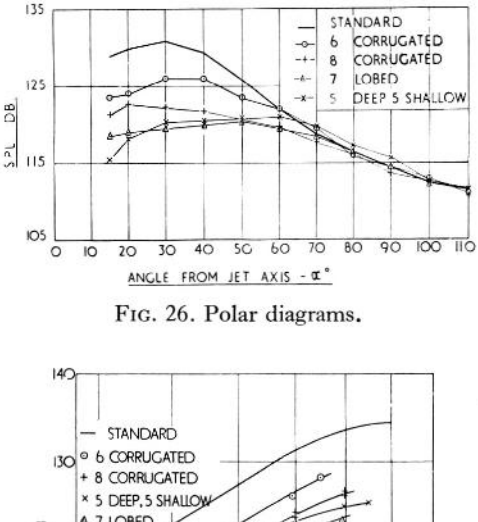

FIG. 26. Polar diagrams.

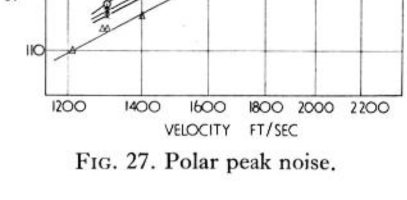

FIG. 27. Polar peak noise.

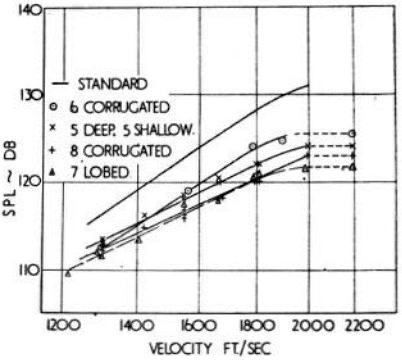

Fig. 28. Linear peak noise.

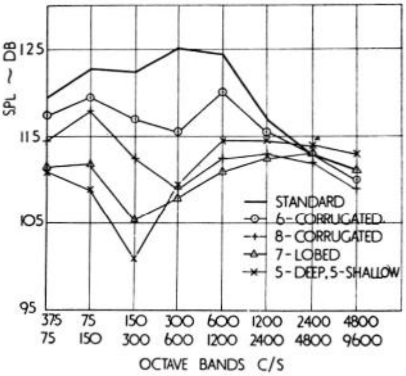

Fig. 29. Spectra at 30° jet axis.

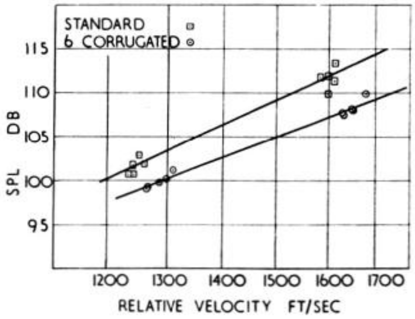

Fig. 30. Flight test peak noise, 6-corrugated nozzle.

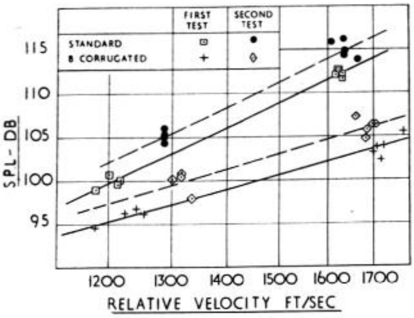

FIG. 31. Flight test peak noise, 8-corrugated nozzle.

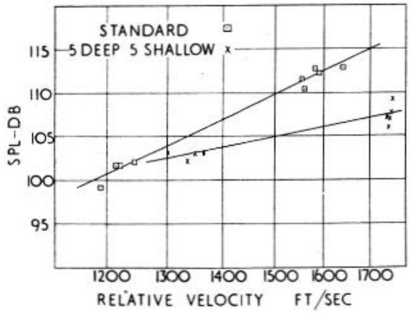

FIG. 32. Flight test peak noise, 5 deep, 5 shallow nozzle.

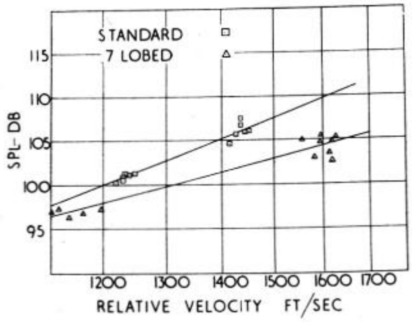

FIG. 33. Flight test peak noise, 7-lobed nozzle.

The results of two test series carried out on different days are given for the eight-corrugated nozzle. These illustrate further the point discussed in Section 2 concerning the difficulty of repeating absolute S.P.L. over a long period. The agreement between the two tests in attenuation from the datum level is however quite satisfactory.

Relation of Ground and Flight Noise

We have indicated in Section 3 how ground measurements may be converted to a form, the linear diagram, suitable for correlation with flight measurements. Comparison of the best mean line from ground tests with flight measurements on circular nozzles in Fig. 9, shows reasonable agreement both in absolute level and velocity index. For corresponding results on silencers, however, the agreement is not good, the discrepancies increasing with increasing attenuation. This can be seen by comparison at any velocity, of the linear peak attenuation shown for each silencer in Fig. 28, with the corresponding flight results from Figs. 30 to 33.

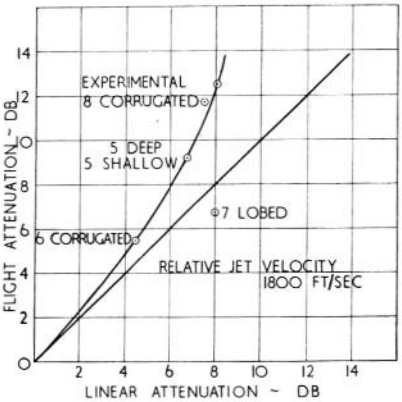

FIG. 34. Comparison of peak attentuations from ground and flight measurements.

Such a comparison is shown in Fig. 34 for a relative velocity of 1800 ft/sec. These results for a number of silencers do in fact lie on a reasonable curve, with the exception of that for the seven lobed nozzle. It is considered that as each point is based on a sufficient number of consistent results an error so large is unlikely and a possible explanation follows.

The divided jet produces its highest intensity noise nearer to the nozzle than the circular jet owing to the shorter mixing length required to entrain a given secondary air flow. Thus, while the relative velocity (V jet — V aircraft) may be a satisfactory parameter for analysis of standard nozzle flight measurements, it is possible that the silencer is more sensitive to stream velocity through the divided nozzle. A better correlation would then be expected using a relative velocity (V jet — V local). With an aerodynamically clean fairing between the individual nozzles of the silencer, the measured local velocity does not differ appreciably from that in the free stream. The seven lobed nozzle however had no fairing when tested and air access to the space around the central nozzle was in any case severely restricted by the close pitching of the outer tubes. The resultant lower local velocity would therefore increase the effective relative velocity and produce a higher noise output, and hence lower attenuation, at the same nominal relative velocity.

The other silencers were relatively well faired and although the negligible deviation from a smooth curve may be fortuitous, the scatter on the above argument would be expected to be small.

Choice of CONWAY *Nozzle*

In choosing the eight-corrugated nozzle for CONWAY production many factors had to be taken into account, but the two, possibly related, advantages of high flight attenuation and low drag undoubtedly carried the heaviest weight. The slightly inferior static silencing performance was considered insufficiently important to offset these advantages. Weight penalty and internal loss were clearly to be encountered, whatever the silencer configuration, and these could only be improved by development. The internal loss of the first eight-corrugated nozzle was in fact high but by careful investigation of the sources of loss this was reduced to a little more than skin friction.

5. REQUIRED ATTENUATION

No discussion of the aircraft noise problem can be complete without some reference to acceptable noise level. This is a controversial subject on which a considerable amount of work has been, and is being carried out. Some methods have been evolved to assess subjective response notably that presented in Ref. 3, which expresses this as a function of a composite noise rating obtained by consideration of many factors: spectrum character and level, duration of exposure, repetition rate, background noise, time of day and adjustment to exposure.

A refined version of this method has been applied to noise measurements on a COMET aircraft(4) and to avoid too much detail it is convenient to use the conclusions of this report. The statements concerning measured noise levels and subjective effects are:

(1) The Comet with four Avon RA.29's at 70% maximum thrust is 8 to 9 db quieter than D.C.-7's and Super Constellations as they fly over the same measuring point.

(2) Subjectively it is quieter by "possibly 3 to 4 db" (or conversely, owing to difference in spectrum, to produce similar subjective effects the jet aircraft peak S.P.L. must be 5 db lower than that of the piston-engined aircraft).

It is of interest before using these conclusions to compare the latter with the results of a simpler assessment. In Fig. 35 measurements of peak noise from a number of jet and propeller aircraft have been converted to phons(5) and are shown as phons versus decibels. The two types fall on to two distinct parallel lines with little scatter and indicate that to produce the same loudness level in phons the jet aircraft must be

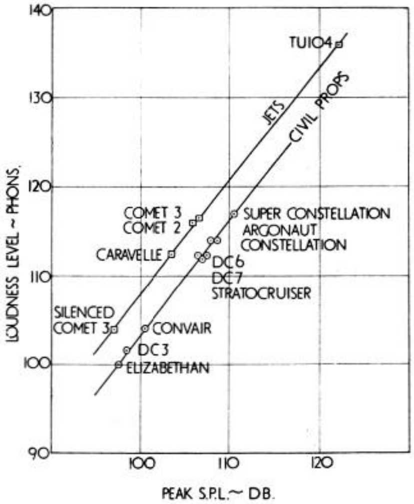

FIG. 35. Comparison of loudness levels of jet and piston-engined aircraft.

$3\frac{1}{2}$ db quieter on peak S.P.L. than the propeller aircraft. Thus in assessing desirable attenuation the method of Ref. 3 requires $1\frac{1}{2}$ db more than the simple comparison of loudness levels.

A point worth noting is that the COMET III with silencers falls on the line for jet aircraft. This indicates that for the relatively small attenuation produced at this condition (3 to 4 db) by the AVON silencer the spectrum is insufficiently altered to diminish the effective attenuation. For silencers

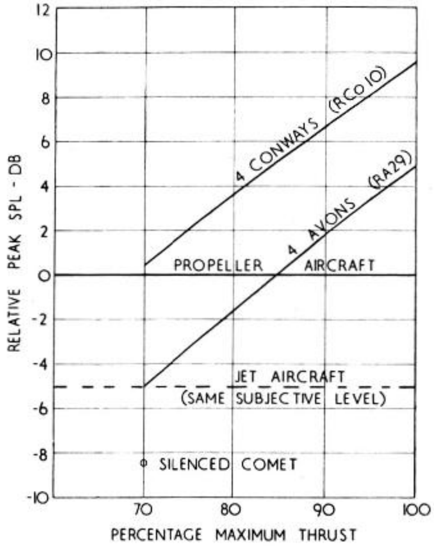

FIG. 36. Comparison of jet and propeller aircraft noise, including an allowance for subjective effects.

producing larger reductions the effective attenuations tend to be slightly lower than the peak values.

Using now the conclusions of Ref. 4 we have constructed Fig. 36 a graph of relative peak S.P.L. heard on the ground at a station about three miles from the take-off starting point versus percentage maximum thrust used when flying overhead. Relative peak S.P.L. is referred to the datum level produced by D.C-7's and SUPER CONSTELLATIONS. Thus at −5 db we have indicated the level for a jet aircraft of comparable subjective effect.

The measured value for the silenced Comet is shown at 70% thrust and $-8\frac{1}{2}$ db. As the silencers are worth $3\frac{1}{2}$ db at this condition an aircraft with four unsilenced RA.29's would produce a relative peak S.P.L. of −5 db at 70% thrust. The known characteristics of the Avon RA.29 and CONWAY R. Co. 10 have been used to construct the curve for two typical four-engined aircraft. We have made a representative allowance for higher wing loading of the CONWAY engined aircraft by assuming an altitude of 1000 ft instead of 1500 ft at the three-mile point. Now the climb ratings used will lie in the range 70% to 80% of maximum thrust, and relative to the "permissible standard" for jet aircraft these two aircraft will be noisier by:

(1) 0 to 3·5 db (AVON), and

(2) 5·5 to 9 db (CONWAY).

Under these conditions therefore, with silencers fitted, the AVON engined aircraft would be satisfactory up to 80% thrust. The CONWAY eight-corrugated nozzle gives 8·0 db to 9·5 db attenuation over this range, and even allowing a small loss of 1 to 2 db in effective attenuation due to change in spectrum, this aircraft too should be satisfactory.

CONCLUSION

We have attempted in this paper to describe briefly our own progress over the last two years in reducing the noise output from existing jet engines for civil operation. In carrying out this work, aimed at reaching a production stage on silencers for two different engines, we have accumulated and to some extent correlated a useful amount of data. We feel we have now a sufficient insight into the mechanism of divided nozzles to make a reasonable assessment of silencing performance from the geometry. To summarize the present position therefore we would say it is now possible to design a silencer to give a specified attenuation (within reasonable limits) and in addition to optimize the design from the aspect of penalties. In fact we have two such silencers at a production stage.

Nevertheless we feel we must insert a word of caution. In discussing penalties we chose an arbitrary round figure of 1% applicable to take-off thrust, cruise S.F.C., drag and weight for 10 db attenuation. These figures are in fact not far off actual practical values, and in considering the effect on payload for a route involving take-off limited operations each 1% penalty costs between 1% and 2% in payload—that is 4% to 8% total. It seems prudent therefore to be practical rather than idealistic in choosing acceptable noise levels for the jet aircraft just going into service. If the level chosen is that of presently operating aircraft the attenuations realized so far are not unreasonable. Obviously there may be methods of supplementing that already obtained but it would seem that the reduction of penalties is of paramount importance at the present time.

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SYMBOLS

$A_a = \frac{\pi D_a^2}{4}$

A_j = Standard nozzle area.

$\bar{A}$ = A_a/A_j = Area ratio of silencer

D_a = Silencer overall diameter.

D_j = Standard nozzle diameter

d = Diameter of largest circle inscribable in the segments of the silencer nozzle.

$\bar{d}$ = d/D_j = Thickness ratio.

d_c = Diameter of central jet core at the end of the initial mixing region.

$\bar{d}_c$ = d_c/D_j = Core thickness ratio.

E = Total acoustic power.

I = Intensity at a point in the noise field.

N = Number of corrugations.

V_j = Jet velocity (fully expanded).

α = Angular position of measuring stations relative to the jet axis.

θ = Angle of jet axis relative to flight path.

ρ_j = Jet density (fully expanded).

ρ_0 = Ambient air density.

a_0 = Ambient air velocity of sound.