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The Testing and Development of a Ground Muffler for Jet Engine Exhaust Noise

By

D. Middleton

Department of Aeronautics and Astronautics,
University of Southampton

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SUMMARY

In A.R.C.20,724 Professor E. J. Richards made recommendations for a form of portable light-weight ground muffler for jet engine exhausts designed to combine in optimum manner the basic methods of jet noise suppression. A muffler based on the non-reheat version of this design was manufactured by Hall Engineering Ltd., of Shrewsbury, and has been in use on jet engines. Simultaneously, using a two-inch diameter cold jet, a one-fifth scale model has been under test by the Department of Aeronautics & Astronautics of the University of Southampton in order to investigate the improvements which might be made to the full scale muffler.

The report commences with descriptions of the components of the muffler, namely diffuser, 'pepper-pot', and absorber box, together with the principles on which their design is based. The tests carried out in the Acoustics Laboratory are then covered in detail. It was shown firstly that a fairly low pressure ratio across the nozzle was adequate for determining the general aerodynamic behaviour of the muffler. The most uniform velocity profile across the mouth of the diffuser was obtained with a small gap between the nozzle and muffler intake, with the muffler itself positioned so that the exhaust gases were turned through 95°. Most pitot traverses were therefore taken for such a condition. Such traverses across the pepper-pot with the absorber box removed revealed a peaky velocity distribution and attempts were therefore made to improve this by using baffles to alter the efflux regions of the pepper-pot. In all these tests it was necessary to check that no back flow occurred from the mouth of the muffler. However, the optimum baffle shape gave no improvement in the noise attenuation achieved by the complete muffler. It was then found that the use of gauze in place of the pepper-pot increased the noise reduction of the muffler. It also became apparent that noise was being radiated from the walls of the diffuser due to the loading action of the gases on them.

This/

Previously issued as A.R.C.23,507

This noise was reduced by encasing the diffuser and absorber box in a sand box of three inches minimum thickness.

The results of these two modifications of replacing the pepper-pot with gauze of the same shape, and reducing the forced vibrations by the addition of mass, show a reduction of noise levels of 7 or 8 db compared with the original muffler and over 20 db compared with the unsuppressed jet. By considering the noise spectra, in subjective units the reduction is about 10 db PNdb better than the original muffler, 25 PNdb better than the original jet. These figures are for typical positions for a jet velocity of 1000 ft/sec. For 1240 ft/sec the attenuations are about 30 db or PNdb.

Full scale tests have shown a definite improvement with the replacement of the pepper-pot with gauze, and a further improvement when the bottom and sides of the muffler had sand added. Finally, a comparison with some other ground mufflers for which results are available show that the muffler in its final version compared favourably with any of these.

1. The Muffler and Model Rig

This muffler was designed to fulfil the need for a lightweight and portable ground silencer of optimum performance for use with jet aircraft running either with or without reheat. In the non-reheat version, i.e. without the water injection facility, there are three principle stages. These are the diffuser, 'pepper-pot', and absorber-box and are depicted in the model diagram of Fig. 5. The ideas underlying this design are as follows:-

The efflux from the jet is accepted by the diffuser which is curved so that its outlet points vertically upwards. Except for a slight flare at the entry the cross-sectional area of the diffuser is constant. However, the shape of the cross-section changes from square to thin rectangular of aspect ratio approximately 30:1, to make use of the fact that when a gas turns a sharp corner it naturally tends to splay out and so the use of internal vanes or grids is avoided. After this realigning and splaying, the exhaust expands quickly through a pepper-pot with graded circular holes, the system being designed to achieve a high velocity reduction in a short length of pipe. The function of the box mounted vertically around the pepper-pot on the diffuser is to absorb the relatively high-frequency noise created by the gas expanding through the holes of the pepper-pot. The final exhaust velocity, which will be very low, is directed vertically upwards thus minimising the noise heard at any point on the ground.

A photograph of the initial full scale muffler appears in Fig. 1. It is shown complete with muffler intake baffle positioned behind a Viper Mark 102 engine at the Larkhill testing site of Bristol-Siddeley Engines Limited. The results of some free-field noise measurements taken there are given in Figs. 2, 3 and 4. Fig. 2 shows the attenuations produced by the muffler for the 100 ft. radius case for the range of engine settings investigated, and Fig. 3 the 500 ft. radius results. That the attenuations were higher for the greater radius suggests that the muffler produced a higher frequency spectrum than the jet alone, and consequently atmospheric absorption plays a larger rôle in reducing the levels over a distance. The actual noise levels measured at 100 ft. radius for the engine running at 50% of maximum r.p.m. are shown in Fig. 4, together with the 100% r.p.m., 500 ft. radius case. The peak measured level of 108 db at 500 ft. for the unsuppressed engine is in good agreement with the value of 110 db calculated from an empirical formula based on the engine parameters for 100% r.p.m. on an ISA day. The polar field shapes show that at the lower engine settings a considerable amount of engine intake noise exists, and this masks the ability of the muffler to reduce exhaust noise.

The/

The model constructed for use on the cold jet in the Acoustics Laboratory of the University was approximately one-fifth linear scale, but the absorber box was not in proportion due to manufacturing limitations of the absorbent lining. A sketch of the model is given in Fig. 5 and Fig. 6 is a general view of the model in the Laboratory. An additional feature was the mounting adjustment which enabled the gap between the diffuser mouth and the nozzle to be varied and also the angle between them to be changed. A photograph of this detail is shown in Fig. 7. This also shows the actual manner of mounting the muffler behind the conical nozzle by bolting to flanges on the settling chamber. The laboratory dimensions were such that it was necessary to mount the muffler so that it exhausted horizontally as the photograph in Fig. 8 shows. To have had the muffler in its 'normal' attitude would have brought the end of the absorber box to within a few inches of the roof, with consequent danger of damage to the laboratory acoustic lining and also possible distortion of the noise field. The mounting used made it easier to take pressure measurements but as the ground plane of the muffler was now in fact vertical this introduced difficulties as far as noise measurements were concerned. This is referred to later. A further photograph of the mounted muffler in Fig. 9 shows more clearly some static tapping holes. These were not used during these tests and were blanked off with Mohl clips. The conical nozzle used throughout was of 3.354 inches internal diameter. This gives a 2:1 ratio of diffuser cross-section area to nozzle efflux area. No inlet shroud was used during testing.

2. Testing and Development

The operating condition of the jet was controlled by manual manipulation of a valve connected to the compressed air system. An effective indication of the total head across the nozzle was given by a mercury manometer connected to a static tapping on the wall of the settling chamber. The jet velocity was evaluated for this series of experiments using standard compressible flow formulae and assuming standard atmospheric conditions for the atmospheric pressure and stagnation temperature of the jet.

In assessing the aerodynamic performance of the muffler the first stage clearly was to establish the effect of pressure ratio (or jet velocity). Thus the first test was to consider the velocity profiles across the exit of the diffuser for a low pressure ratio $P/p = 1.085$ (corresponding to 2.55 inches of mercury, gauge) and a higher one, $P/p = 2.25$ (corresponding to 37.5 inches of mercury), i.e. above choking. Traverses were made with a small-bore pitot tube connected to a mercury manometer. The non-dimensional graphs plotted in Fig. 10 for the semi-major and minor axis traverses show the great similarity in the profiles, and it was therefore concluded that it would usually be adequate to use this lower pressure ratio for the determination of general aerodynamic behaviour. Not only did this make easier the experimental side, there was the advantage of using a smaller amount of air from the (limited) compressed air supply.

This last test had been conducted with a gap of one fifth of an inch between the plane of the nozzle and the plane of the diffuser mouth. The nozzle was then placed 1.4 inches inside the diffuser, and the result of the semi-major axis traverse is also plotted on Fig. 10. This shows significantly higher velocities towards the edge of the slit.

The results of a further test are shown in Fig. 11. All tests described to date had been for the diffuser in an attitude so that the exhaust gases were turned through 95°. The diffuser was now adjusted so that the angle was just 90°. The velocity profiles in Fig. 11 show that for the 95° angle, which was the maximum obtainable, the jet is emitted with a more uniform velocity and lower peak value than for 90°. Thus for all future tests the "95° twist" was adopted together with a nozzle-diffuser gap of one fifth of an inch.

The manner of mounting the diffuser having been thus determined, the pepper-pot was remounted and velocity measurements taken across each face. The directions of outflow from the faces of the pepper-pot were found using tufted streamers. These velocity contours are contained in Fig. 12 and indicate an uneven velocity distribution with high peaks. These contours also show that more air was passing out of the 'convex' side than out of the 'concave'. It was concluded from this that the diffuser-pepper-pot combination was inefficient in reducing and diffusing the jet velocity and consequently the muffler was not very effective. Attempts were therefore made to improve the pepper-pot velocity profiles and minimise the peak velocities by using baffles on the pepper-pot.

These baffles were made of light alloy plate and were simply bolted to the outside faces of the pepper-pot. A series of baffle shapes and combinations were tested and some of the velocity contours obtained are shown diagrammatically in Figs. 13, 14 and 15. The peak velocities through the two sides of the pepper-pot were first balanced, and the shapes systematically changed to improve the velocity distribution stage by stage. For balanced outflow it was found necessary to make the baffle area nearly twice as large on the 'convex' side as on the 'concave'. As this blanking restricted the effective outlet area, it was necessary to check that there was no backflow from the mouth of the diffuser for any obtainable mass flow. The maximum jet mass flow for which the set-up was tested was about 1.0 lb/sec/sq.in. of nozzle efflux area. With balanced outflow it was observed that increasing the size of the baffles towards the backflow limit tended to move the peak velocity across the pepper-pot face along the diffuser axis towards the diffuser.

The configuration which gave balanced flow with the lowest peak velocities and no backflow was the one consisting of two truncated triangles, the results for which are shown in Fig. 15. These metal triangles had been attached on the outside of the pepper-pot, and in order to fit the absorber box in its usual position over the pepper-pot it was necessary to replace the baffles by cardboard copies, fitted internally. Pitot-traverses were then taken across the major and minor axes of the absorber-box exit face. It was discovered that the velocity head was fairly uniform over the efflux area, and was consequently small. Even for a pressure ratio of 2.7 the total head lay in the range 1.3 to 1.7 inches of mercury, (except in the relatively thin boundary layer) and this represents a velocity reduction of about 75%. This also showed that the final efflux velocity was too low to explain the measured noise levels. It was concluded that no simple modification to the existing pepper-pot to improve the velocity profiles would consequently improve the muffler attenuation properties.

A systematic noise analysis was then undertaken to try and establish the 'mechanism' of the noise. All noise measurements were taken using:-

Brüel and Kjaer Audio Frequency Spectrometer type 2109

Brüel and Kjaer Level Recorder type 2304

and either Brüel and Kjaer condenser microphone (1") type 4111
or condenser microphone ($\frac{1}{2}$") type 4133

The noise levels were recorded in 27 one-third octave bands covering the range 35-18,000 c/s, together with overall noise. Results are presented in this paper after summation into octave levels. The two microphones used were calibrated against each other, and a correction factor enabled the absolute levels of the signals to be determined. (The half-inch microphone can be seen in a recording attitude in Fig. 6).

Most/

Most noise measurements were taken at a gauge pressure of 12.5 p.s.i., corresponding to an expanded jet velocity of 1000 ft/sec. The overall noise results for this condition are presented in Table 1. Results for the final configuration, which will be referred to later, were also taken for the gauge pressure of 25.0 p.s.i., (equivalent to 1240 ft/sec.) which was as high a value as the system could hold for a sufficient time for noise measurements to be made. These results are given in Table 2.

As has been mentioned it was necessary to mount the muffler in the plane at right angles to its "commercial" attitude. Consequently, representative positions for noise measurements had to be selected with care and these are shown in Fig. 16. The angle of 30° relative to the conical nozzle axis, which points A, C and E subtend at the centre of the conical nozzle exit plane, is approximately the angle of peak noise propagation for an unsuppressed jet. (As positions A and C are symmetrically placed relative to the conical nozzle a check was afforded on the noise results obtained when the muffler was not in position.) Measurements were made on the diffuser alone, the diffuser plus pepper-pot, diffuser plus absorber box, and muffler complete.

The spectra in Fig. 17 are for position A for the jet velocity equal to 1000 ft/sec. From this figure it can be seen that the addition of the pepper-pot to the diffuser alters the spectrum only slightly, apart from some high-frequency noise clearly due to the secondary jets issuing from the holes of the pepper-pot. As the figure shows the absorber box produces a large reduction in this high-frequency noise. It is clear from this that the pepper-pot in its design form was not having an important role, and in an attempt to increase the efficiency of this part of the muffler it was decided to examine the effect of replacing this pepper-pot with a fine mesh gauze.

Two shapes were examined, both gauzes being made of 32 s.w.g., 30 mesh brass. One was placed flat across the diffuser outlet, and the second was moulded to have the same shape as the pepper-pot. However, as the effective outlet area of the flat gauze was too small and caused backflow to occur at the higher velocities it was discarded. The second gauze was satisfactory in this respect, and the noise results are plotted in comparison with those of the pepper-pot in Fig. 18. This figure shows that the absorber box produced a greater reduction in the noise levels from the gauze than in those from the original pepper-pot.

When using the gauze in conjunction with the absorber box it was noted that unless a good seal was obtained between the diffuser and absorber box, very large high-frequency noise levels - easily hearable as a shriek - were recorded. This was apparently due to a thin sheet of air escaping from a gap between the two sections. The effect was removed by placing a shielding strip of sorbo-rubber round the circumference of the join. All noise levels quoted were obtained with this shielding strip in position where necessary.

The results of this systematic analysis showed that the use of the gauze in place of the pepper-pot improved the attenuation of the complete muffler to about 17 db for the particular jet velocity considered. However, with this reduction of exhaust noise, it then became apparent that noise was coming from the region of the diffuser itself. It was discovered that the convex side of the diffuser was vibrating together with, to a lesser extent, the concave side and the area of the absorber box close to the pepper-pot. Thus the noise radiated from the region was apparently the result of this forced vibration of the diffuser walls. This therefore suggested the possibility of further improving the muffler attenuation by mass addition to the vibrating surfaces.

Mass/

Mass addition to these surfaces was first attempted simply by using sand-bags draped over the muffler and tied in position. An increase in attenuation was observed, but, as this method of mass addition was regarded as unsatisfactory, a 'sand-box' was then built around the whole muffler. This encased it completely with a layer of sand of about 3 inches minimum thickness. Photographs of this encasement are shown in Figs. 19 and 20. Figs 21 to 25 show the noise spectra for the 5 positions A-E for the cases of the original design, the gauze replacing the pepper-pot, and the effect of the addition of mass to this second condition. All the figures illustrate that this lagging produces a small benefit in the lower octaves with a really appreciable increase (the order of 10 db) in attenuation in the higher ones. This last result was so encouraging that measurements were taken for this final configuration at the higher jet velocity of 1240 ft/sec mentioned, and the results are shown in Fig. 26.

The reduction of noise by adding mass becomes especially valuable when the subjective aspect is assessed. The spectra shown in Figs. 21 and 25, i.e. for positions A and E, have been converted into Perceived Noise Levels (PNdb) which are estimates of the annoyance of given sounds. The spectra have been changed into subjective units in two ways. Firstly a straightforward conversion of the usual eight octaves in the range 35 - 9000 c/s has been made, and these are the PNdb levels given in section I of Table 3. Then bearing in mind the fact that the model used was approximately one-fifth scale a shift of two octaves has been allowed (equivalent to a scale factor of 4), and by extrapolating the measured curves upwards by a single octave it has been possible to estimate the relative PNdb levels for the full-scale engine and the muffler. These are the figures given in section II of Table 3. Actually these indicate that little difference is made whether section I or II is used. The results show that an attenuation of about 15 db (or PNdb) for the original model design has been increased to about 25 db (PNdb) in the final version tested, a really appreciable reduction in noise levels.

3. Conclusions

Although several difficulties were encountered in trying to assess the noise performance of this muffler, these did not vitiate the procedure and deductions made. Such problems were the incorrect size of the absorber box on the model, the difficulties of taking noise measurements at representative positions and the inability of the cold jet to reach the velocities of the full-scale jet engine. The maximum jet velocity of the Viper engine on which the full scale muffler was tested would be about 1750 ft/sec which is about 500 ft/sec more than the maximum velocity attempted in the Acoustics Laboratory. On the other hand the velocities which have been considered in this report are of the order expected when the engine is running at 'low' or 'intermediate' ratings. As significant noise reductions have been measured on the model for these conditions, failure to achieve these in a full scale trial would indicate that sources of noise other than the efflux noise are dominating over this range, and consequently no matter how efficient is the exhaust suppressor little difference will be made to the apparent noisiness of the engine.

The tests have shown that the diffuser itself lowers the noise, and that the absorber box produces a large reduction in the higher frequency noise produced from the pepper-pot. However this attenuation can be increased by better matching of the characteristics of the pepper-pot and box, as has been shown by the replacement of the pepper-pot with the gauze. The gas velocity from the box outlet was low, and would not give rise to high noise levels. The major fault in the design of the model was found to be that under the loading action of the jet the walls of the diffuser vibrated to radiate sound. This was overcome by adding mass in the form of a thick layer of sand around the diffuser and absorber box. A further lowering of

noise/

noise levels might have been recorded if an intake shroud for the mouth of the muffler had been employed. The noise levels had been reduced so much that the muffler intake ought no longer to be disregarded as a possible noise source. By the modifications introduced the attenuation of the original model had been increased by amounts which rise steadily from 5 db in the lowest octave to 15 db in the top one, making the actual attenuation for 1000 ft/sec velocity now 20 db in the lower octaves and 30 db in the higher. These latter values increase by about 5 db when the jet velocity rises to 1240 ft/sec, and would presumably therefore be even higher at more representative jet velocities.

Some results of free field engine tests have been made available, and indicate how these modifications have succeeded on the full scale muffler.

The top graph of Fig. 27 shows the original Larkhill test noise levels interpolated for 300 ft radius. The second graph gives the corresponding polar noise fields with the initial muffler in use with a Sapphire engine installed in a Hunter aircraft at Boscombe Down. The effect of replacing the pepper-pot by a stainless steel gauze in this set-up is shown in graph (c). As in the model, dry sand was then used as the mass additive for the vibrating surfaces of the muffler, and graph (d) shows the lower noise levels obtained thereby. The result is a low, non-directional exhaust noise field, with the engine intake noise the dominating source.

Finally, the attenuations produced by these configurations are compared with free-field results available for some of the other ground mufflers, Fig. 28. The most successful of these latter is the Punched Hole design, (A.R.C.20,552), but over the majority of the range this gives attenuations 2 db less than the final version of the muffler considered in this report.

Acknowledgements

The author wishes to thank Mr. R..J. Hale for assistance in the experimental work. Miss Carol Hayter and he helped in the preparation of this report.

Table I - Noise Results for a Jet Velocity of 1000 ft/sec

	MEASURING POSITION	A	B	C	D	E
1.	Jet alone	116½	-	116	-	119
	1. Original Muffler Components					
2.	Diffuser only	113	110½	106½		113
3.	Diffuser and pepper-pot	113	110	107½		
4.	Diffuser and absorber-box	106	105	103		
5.	Muffler complete	103½	101½	99½	96½	103½
	2. The Modified Pepper-Pot					
6.	Diffuser and original pepper-pot modified with cardboard (Fig. 15)	116½	115	113		117
7.	Diffuser and modified pepper-pot and absorber-box	106½	104½	102	99	107
	3. The Pepper-Pot Replaced with Gauze					
8.	Diffuser and gauze	115	114	110½	107	116
9.	Diffuser and gauze and absorber-box	100	99	97	94	102
	4. Effect of Sand Addition					
10.	Diffuser and gauze and absorber-box and some sand	99½	97	95½		
11.	Diffuser and gauze and absorber-box completely encased in sand	97	94	92	89½	95

Table 2 - Noise Results for a Jet Velocity of 1240 ft/sec

12.	Jet alone	129	-	127	-	130½
13.	Diffuser, gauze and absorber-box completely encased in sand	101½	98	94	93½	98½

Overall noise levels in db re .0002 dyne/sq.cm.

Table 3 - Perceived Noise Levels (PNdb)

I Direct conversion from measured spectra

Number in Table 1	MEASURING POSITION	1000 ft/sec A	1000 ft/sec E	1240 ft/sec A	1240 ft/sec E	Number in Table 2
1	Jet alone	130	133½	139	141½	12
5	Original muffler	113½	116			
9	Gauze replacing pepper-pot	113½	114			
11	Above encased in sand	106	105	112½	109	13

II Conversion allowing frequency shift of 2 octaves

Number in Table 1	MEASURING POSITION	A	E	A	E	Number in Table 2
1	Jet alone	127	130	136½	137½	12
5	Original muffler	114½	114			
9	Gauze replacing pepper-pot	109½	113½			
11	Above encased in sand	103½	101½	111½	106	13

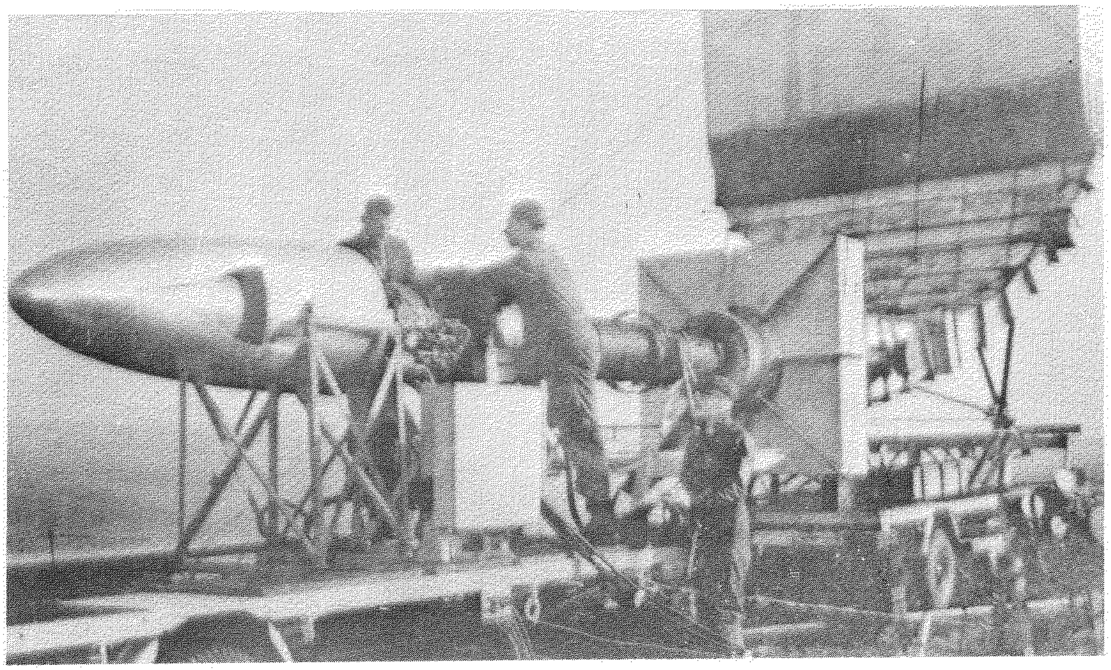
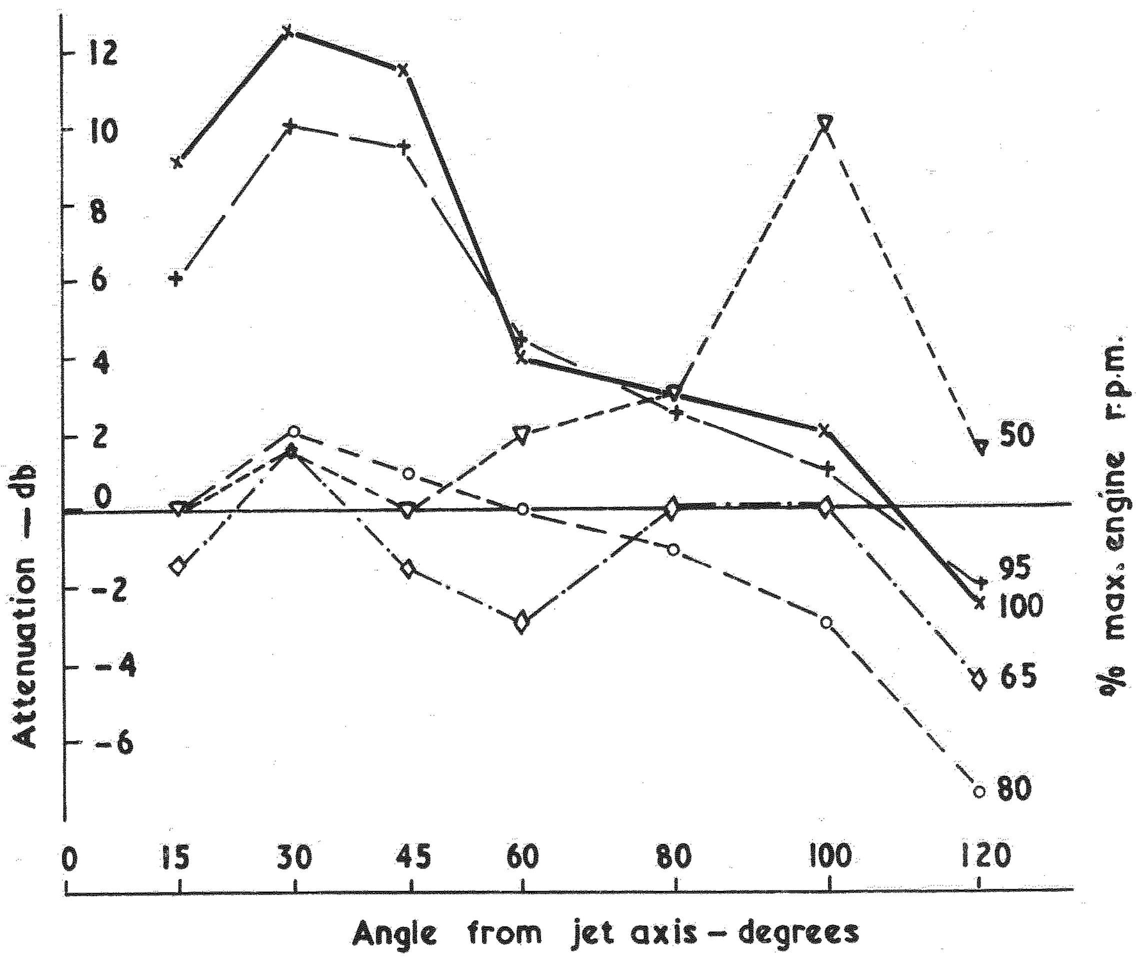


FIG.I. Full-scale muffler positioned behind Viper engine at Bristol-Siddeley's Larkhill testing site.



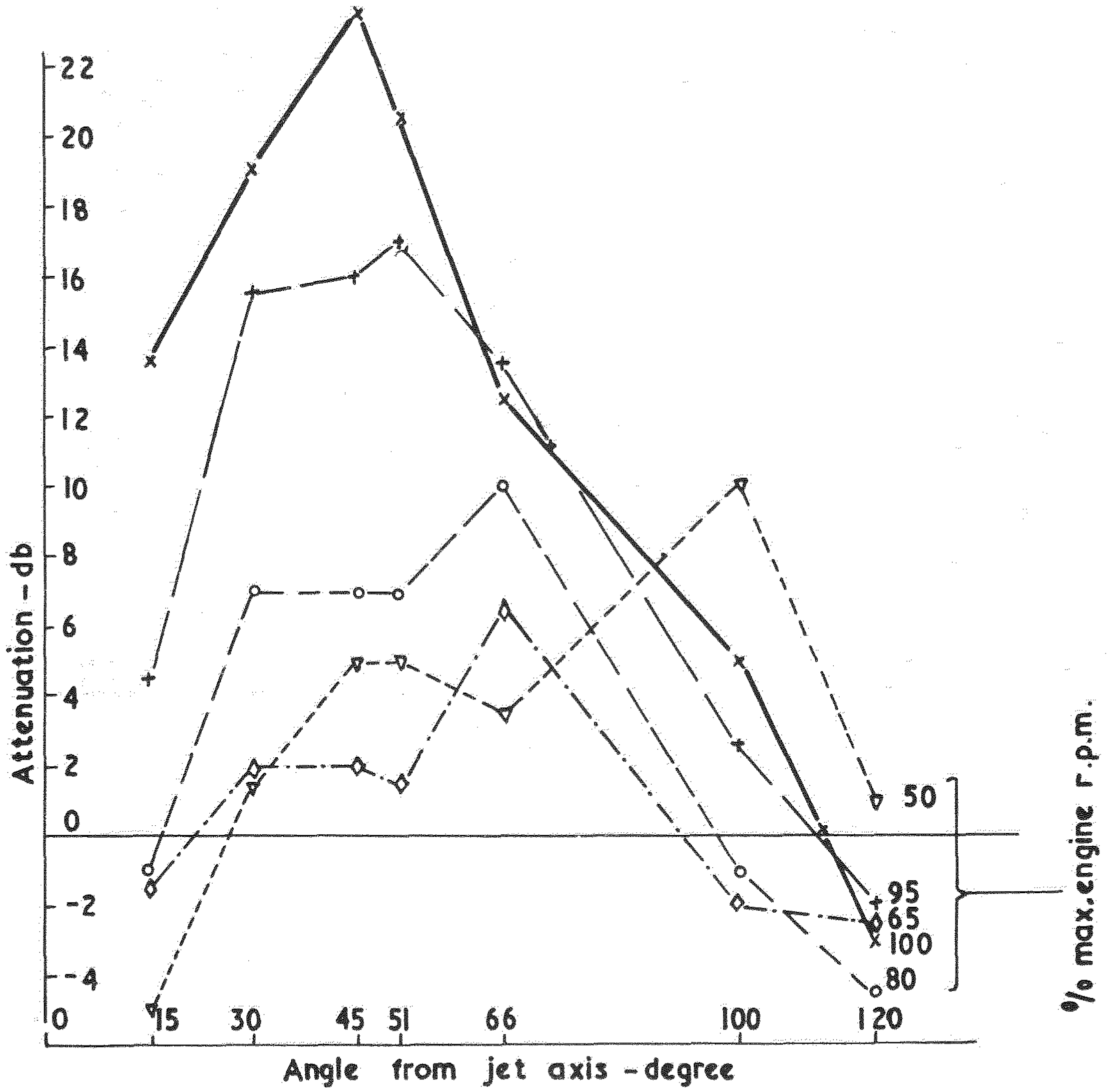


FIG. 3. Noise attenuations measured at 500 ft radius; full-scale muffler in Viper Viper engine at Bristol-Siddeley's Larkhill site.

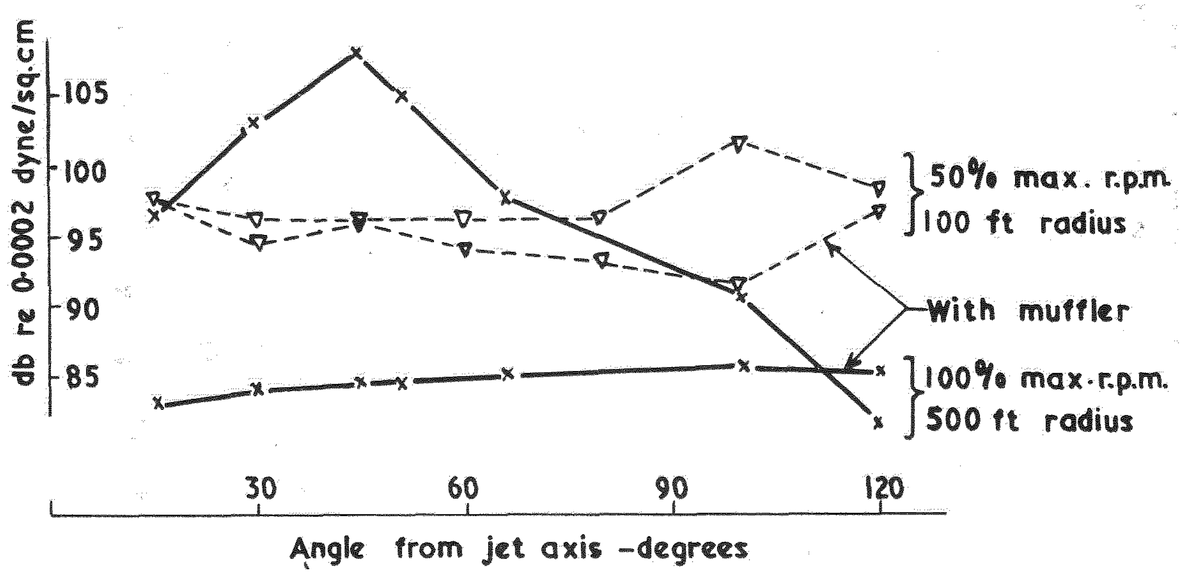


FIG.4. Overall noise levels of Viper engine with and without muffler for the indicated conditions, Larkhill site.

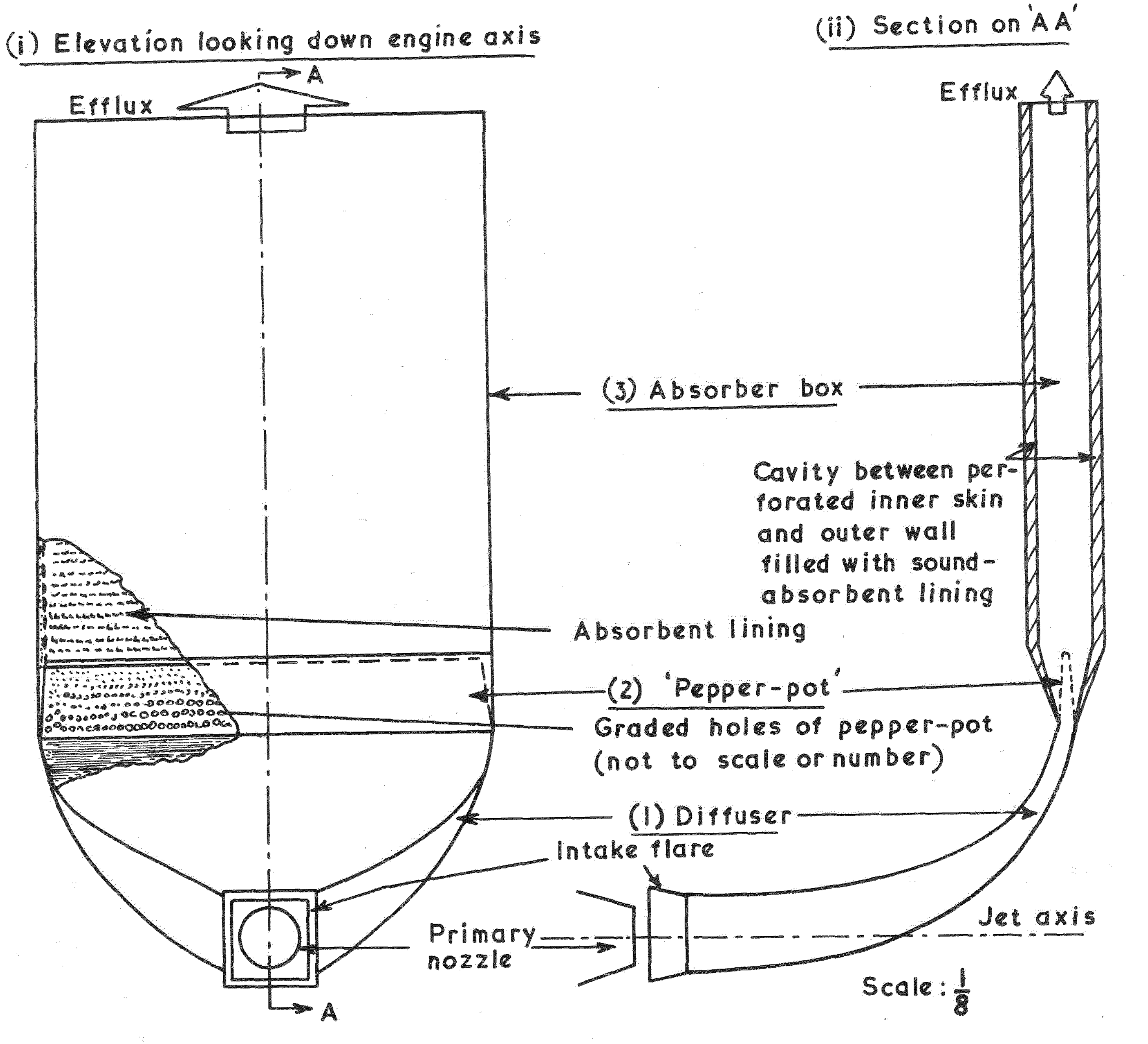


FIG.5 The one-fifth-scale muffler, tested in the Acoustics Laboratory (mounting adjustment for varying muffler attitude and nozzle-muffler spacing not shown)

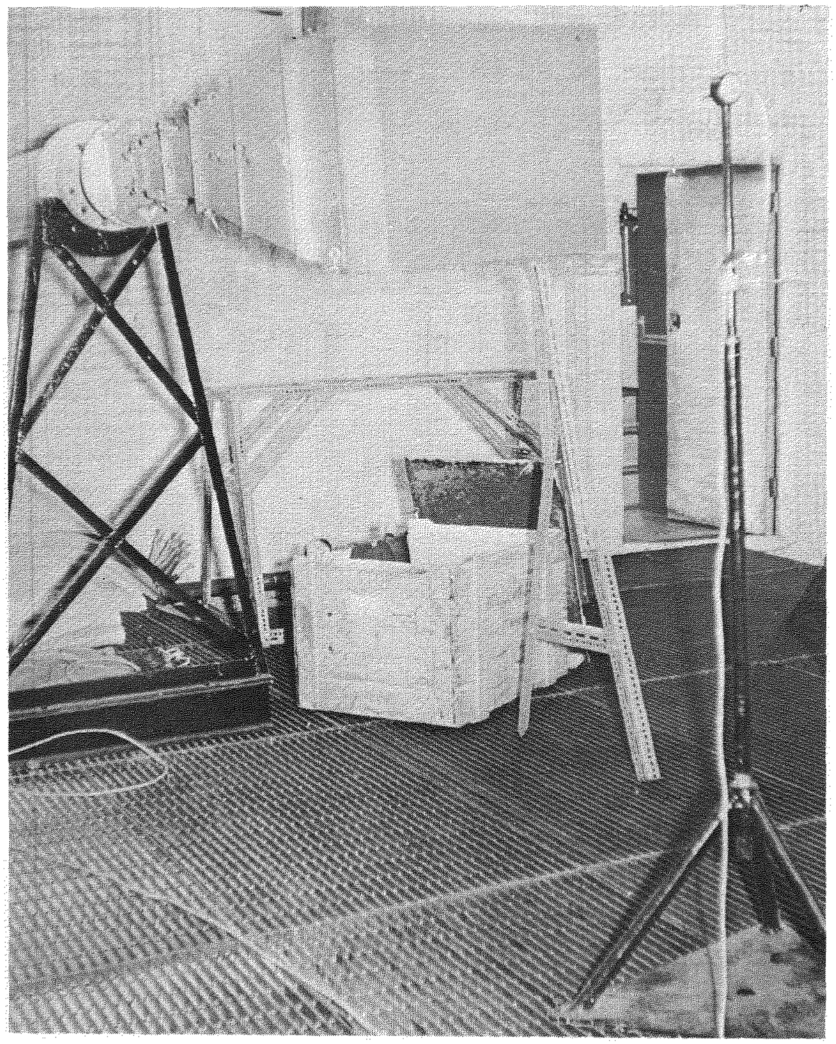


FIG.6 The muffler mounted in the Acoustics Laboratory with microphone

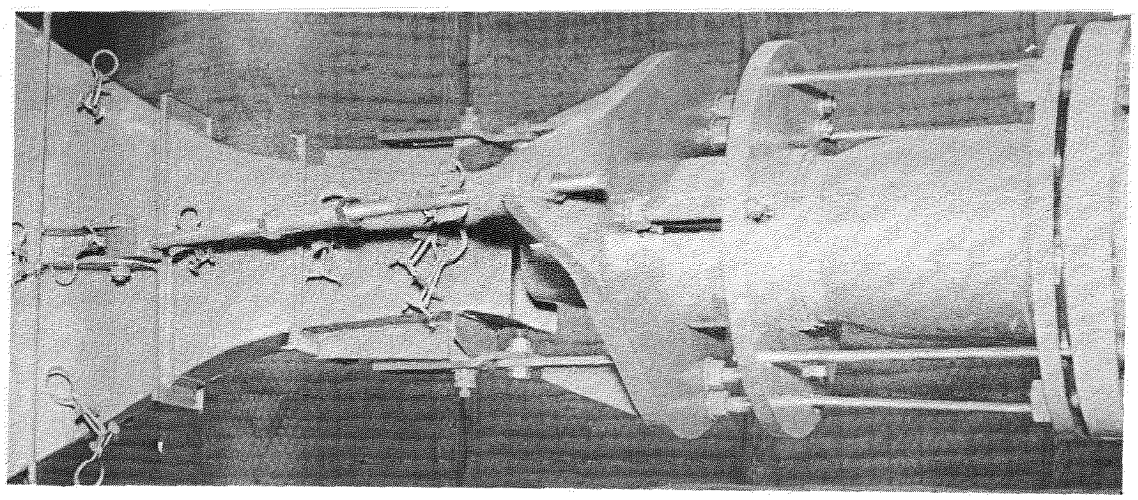


FIG.7 The muffler intake and mounting details

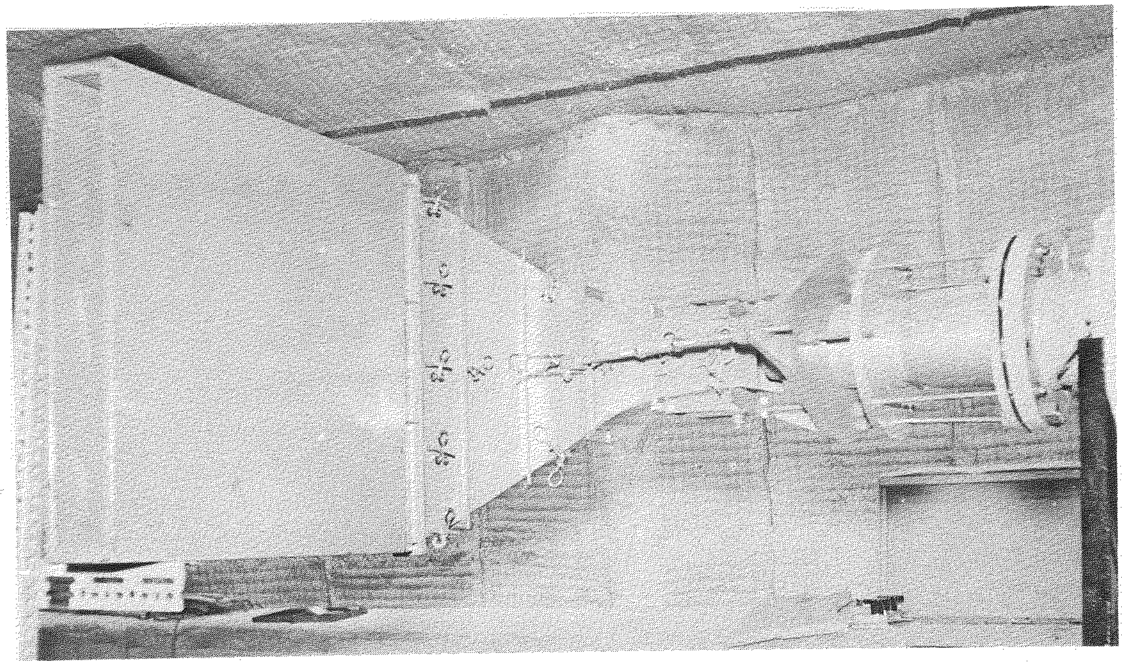


FIG. 8 The muffler; 'concave' side

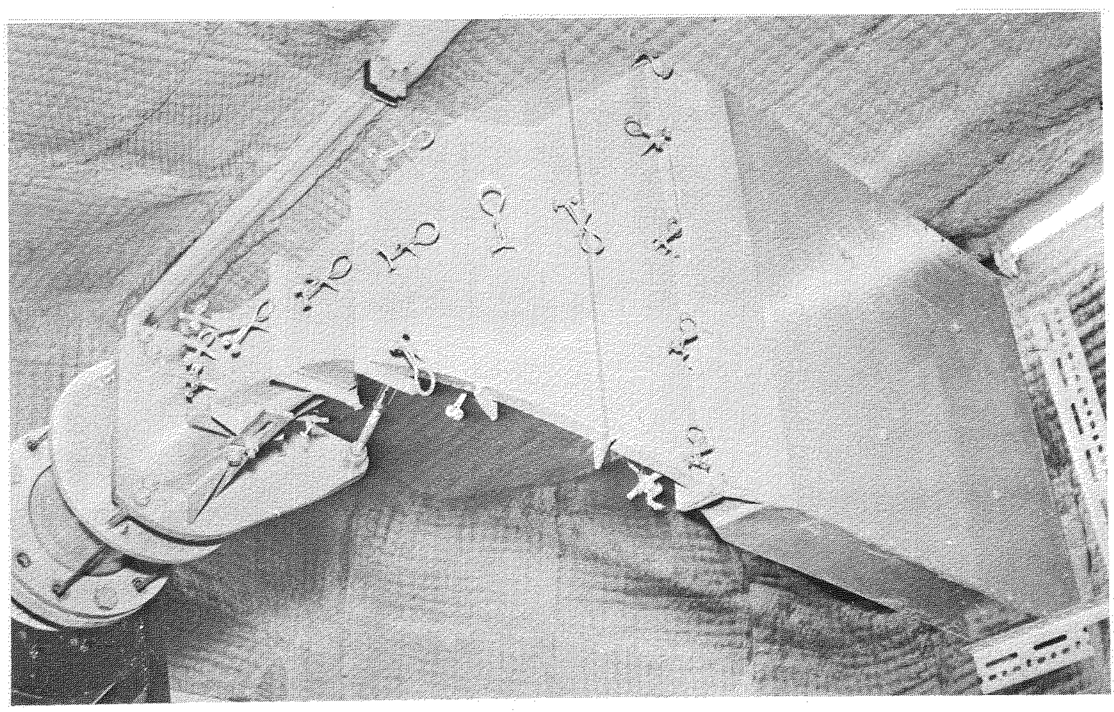


FIG. 9 The muffler; 'convex' side

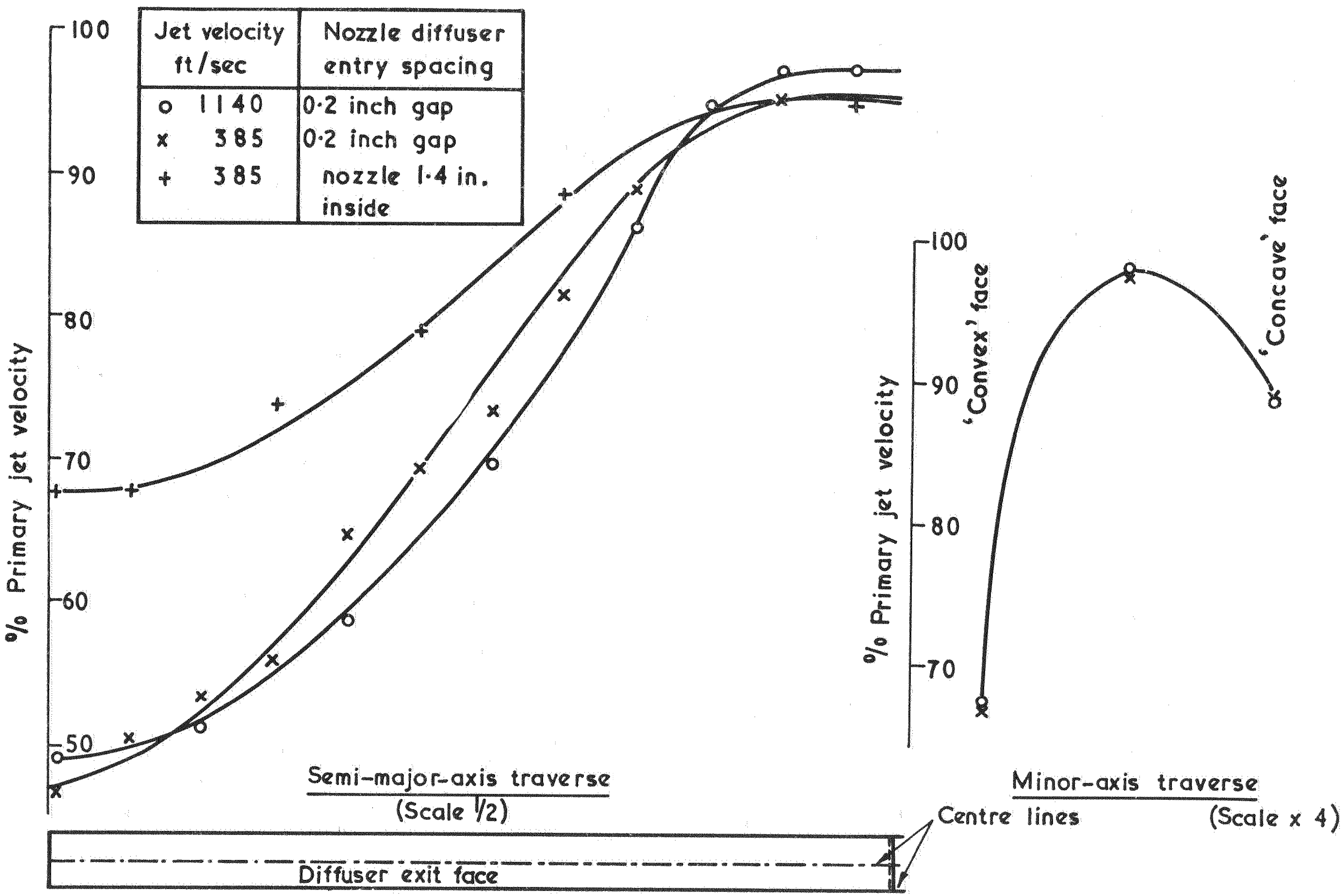


FIG. 10 Effect on the velocity profiles at diffuser exit face by alteration of entry spacing and jet velocity. (No pepper-pot or absorber box in position) $\theta = 85^0$

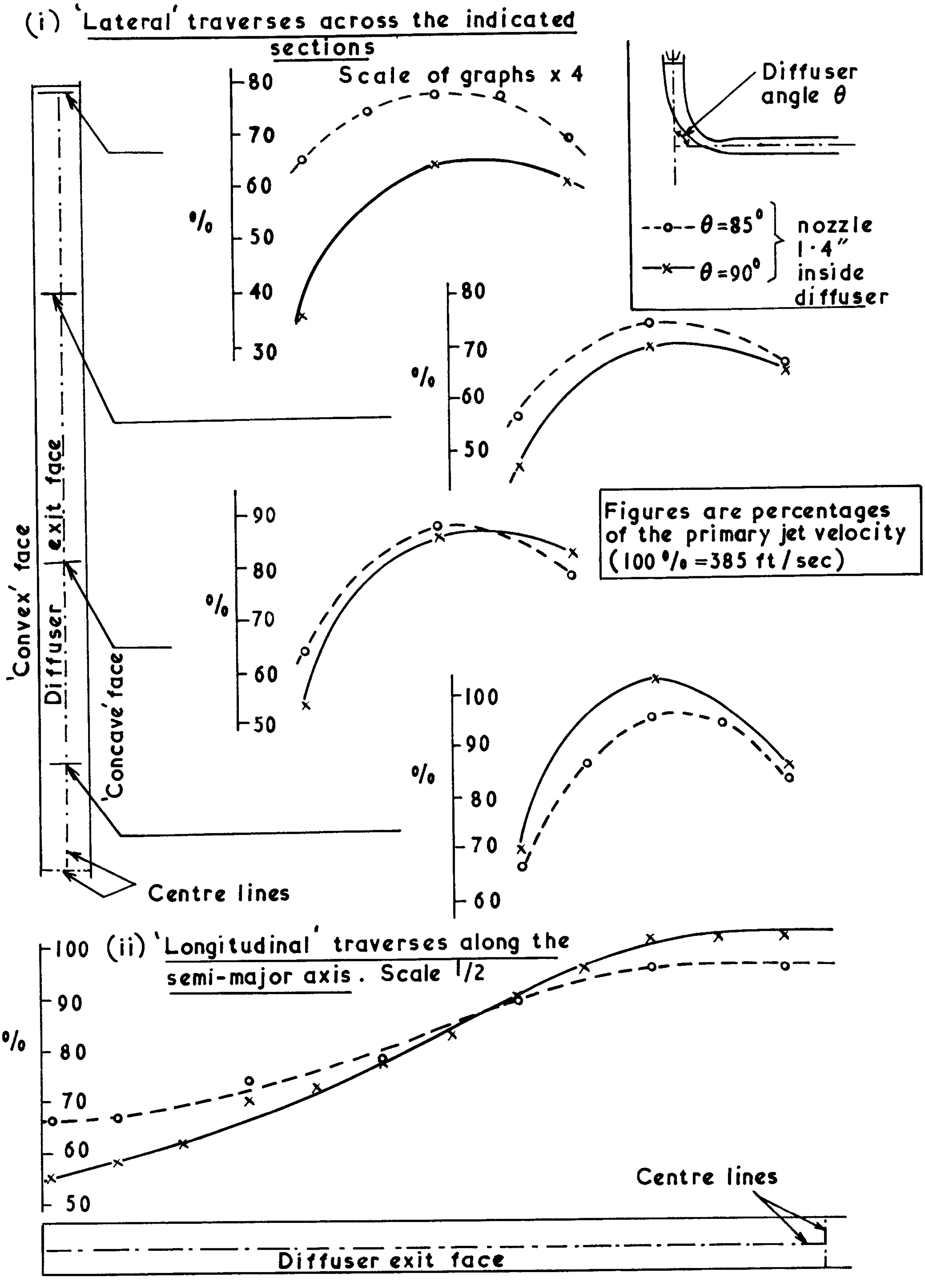


FIG.11 Effect on the velocity profiles at diffuser exit face by alteration of the angle of the diffuser.
(No pepper-pot or absorber box in position)

Velocity distributions over the 'pepper-pot' faces with modifications as indicated

(Contours given in percentages of the jet velocity; 100% = 385 ft/sec)

(No absorber box)

Scale: 1/2

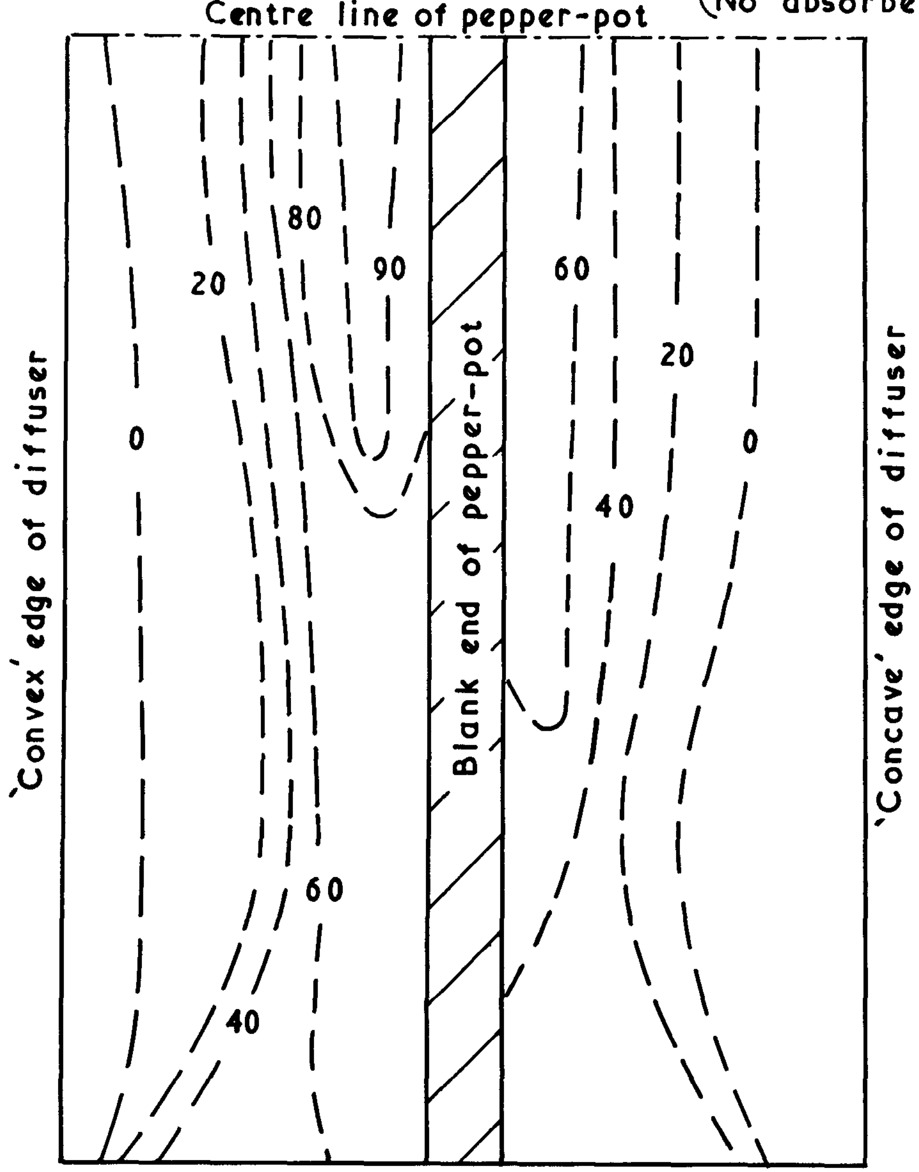


FIG. 12 Pepper-pot unmodified

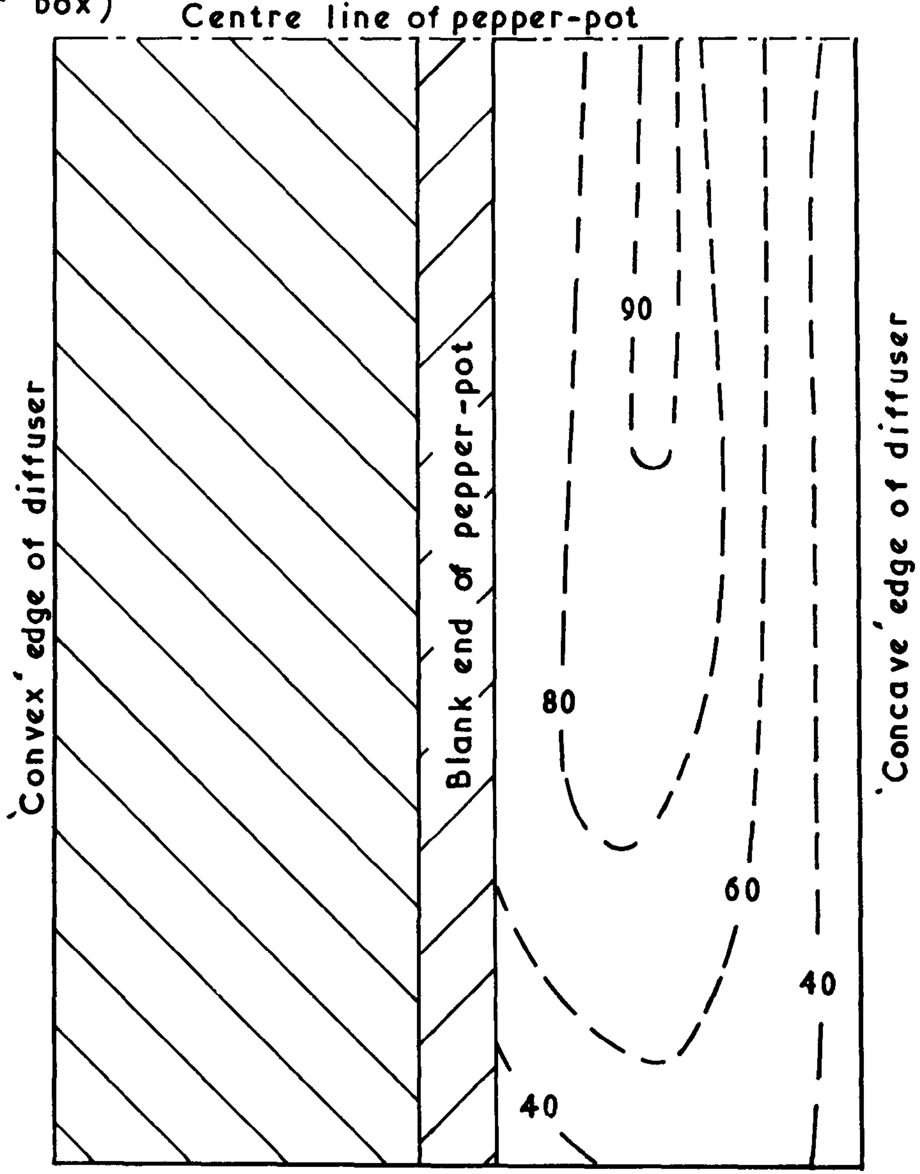


FIG. 13 'Convex' side blanked off

Velocity distribution over the 'pepper-pot' faces with modifications as indicated
(contours given in percentages of the jet velocity; 100% = 385 ft/sec)
(no absorber box)

Scale: 1/2

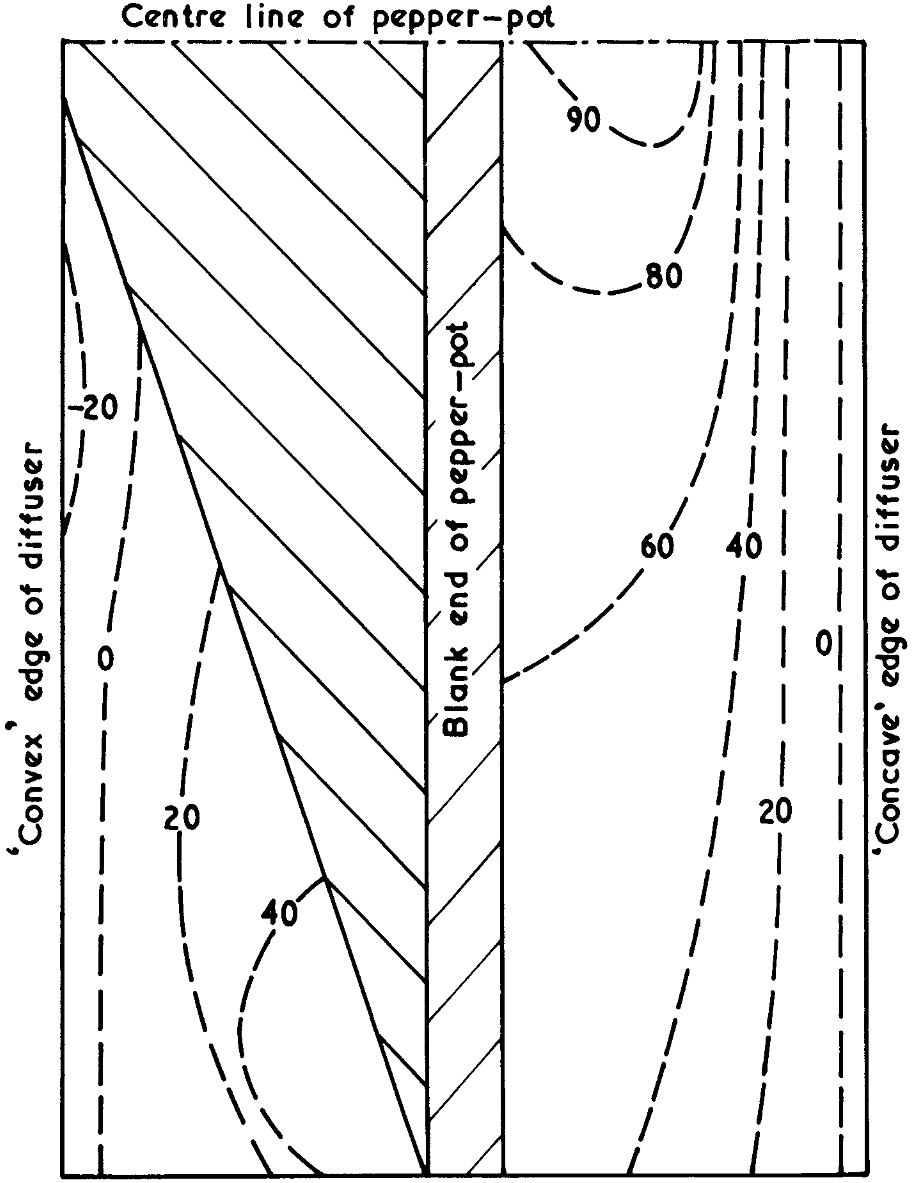


FIG. 14 Triangle on 'convex' side

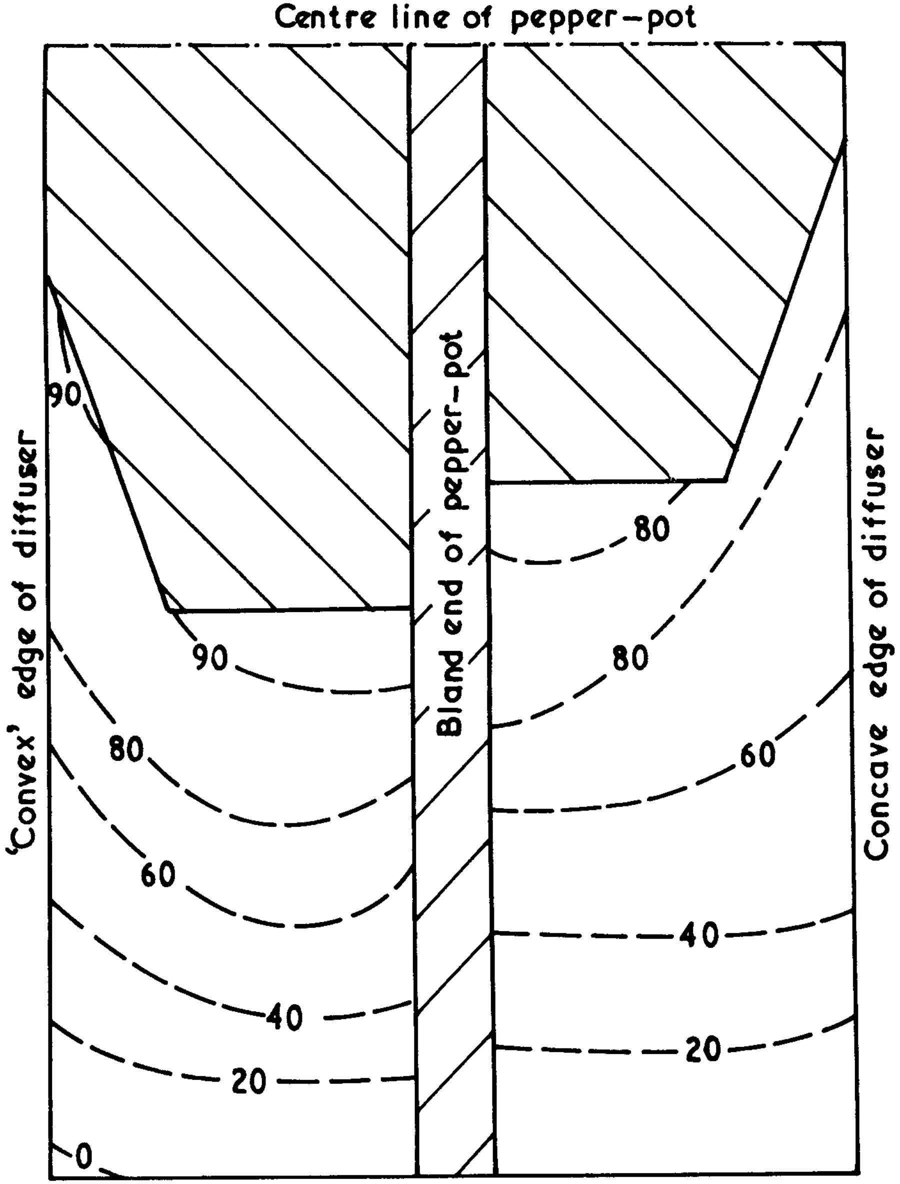
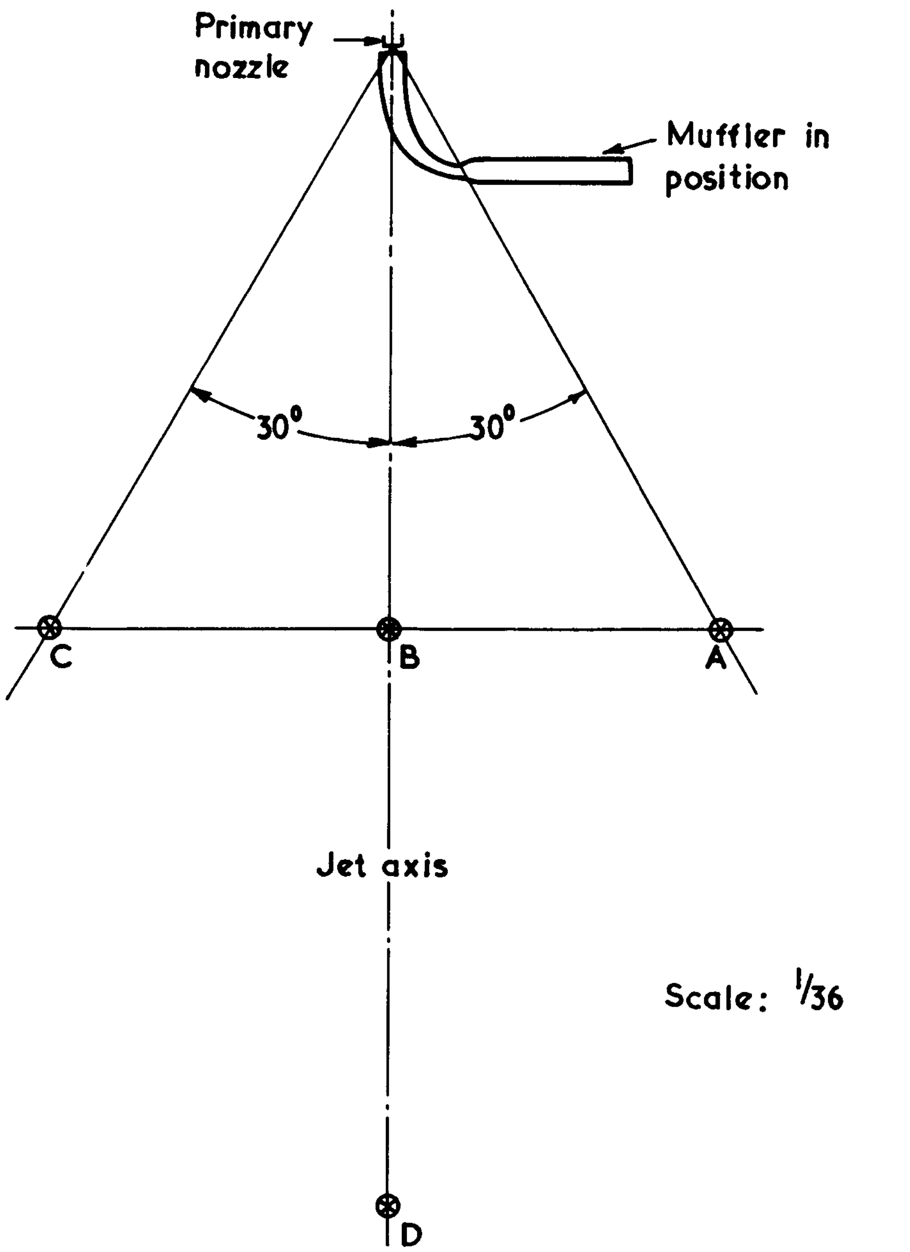


FIG. 15 Two truncated triangles

(i) Section through jet axis, parallel to laboratory floor



(ii) Section through jet axis, perpendicular to laboratory floor

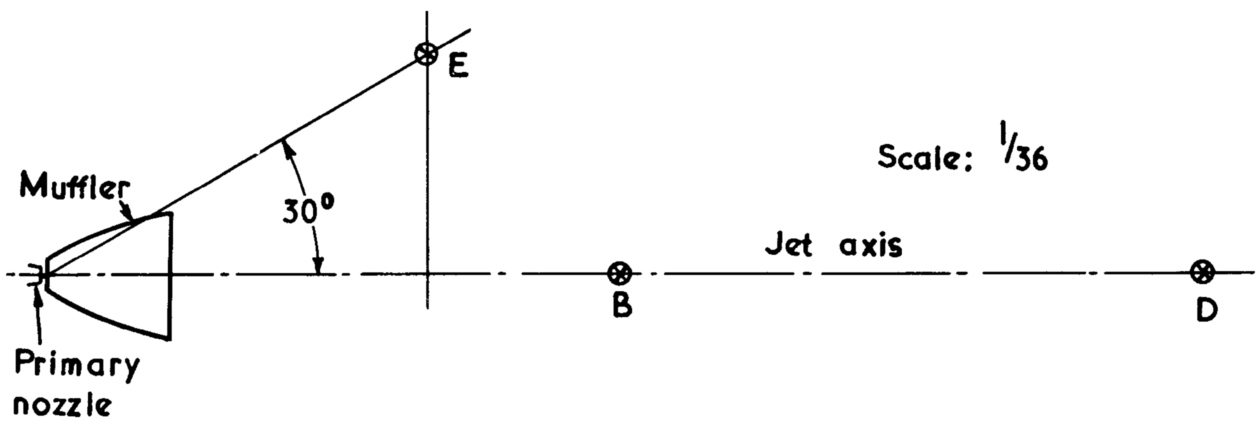


FIG. 16 Noise measuring positions

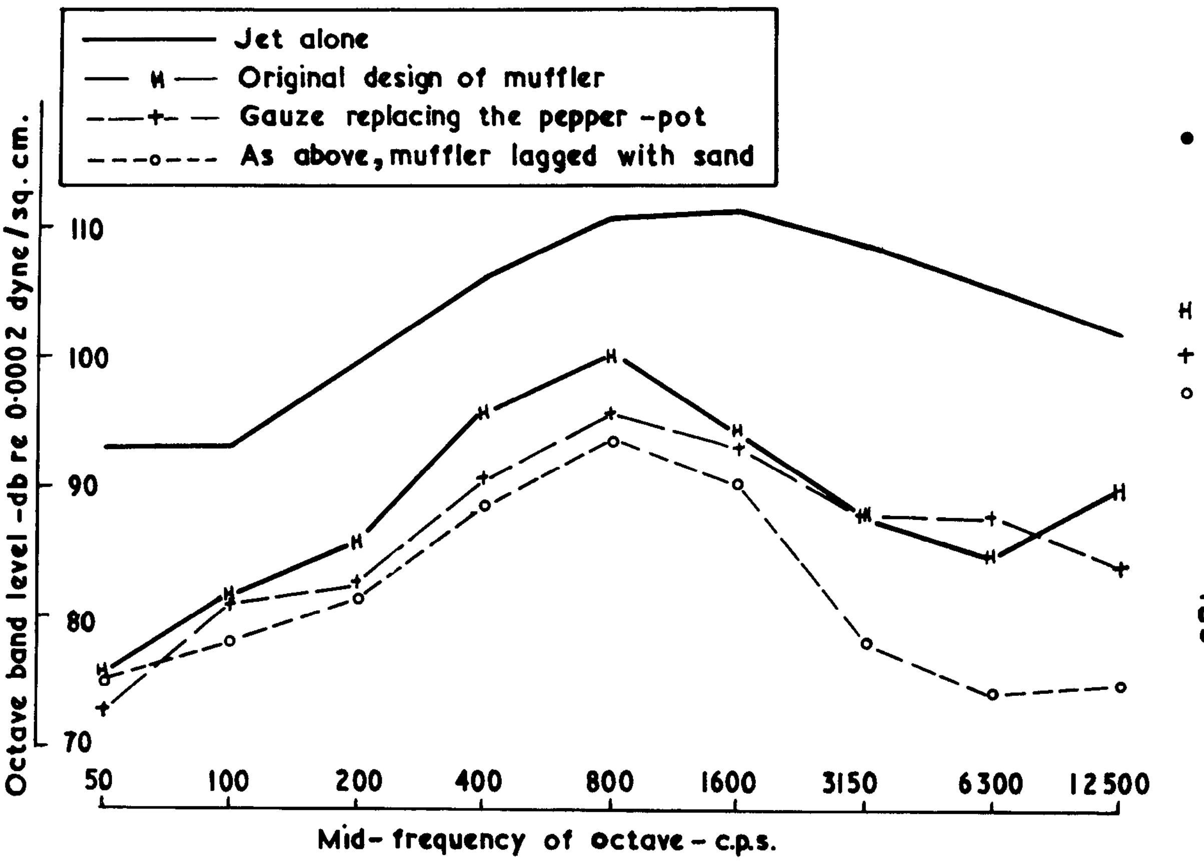


FIG. 21 Position A

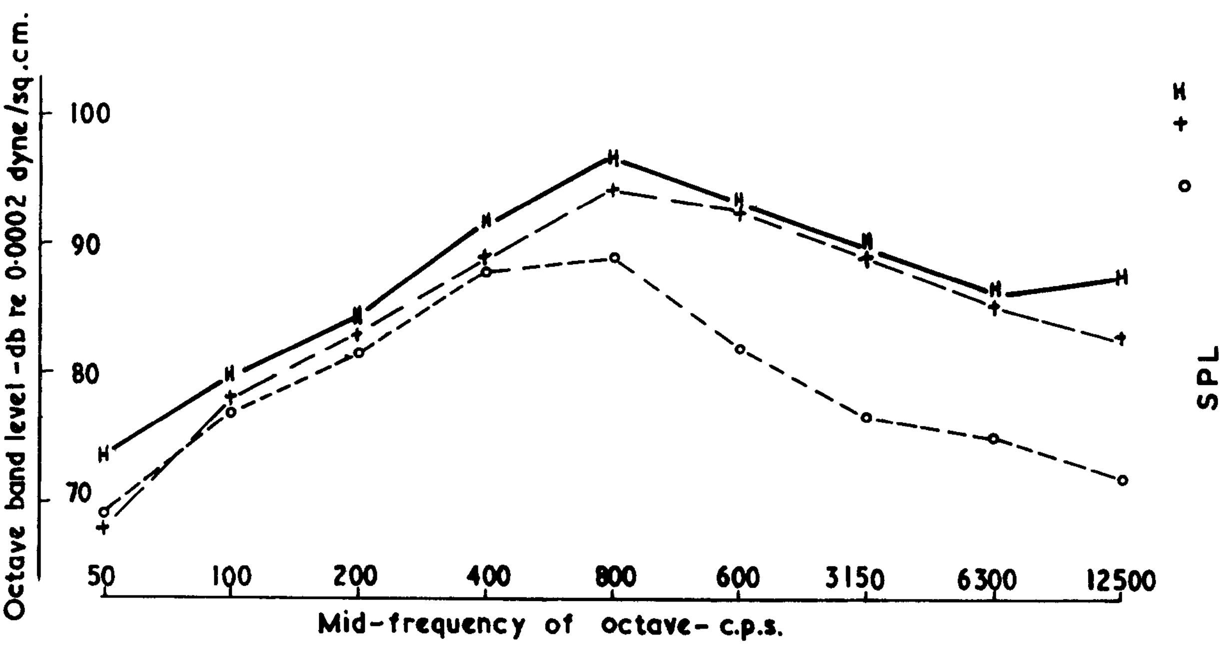


FIG. 22. Position B (key as Figure 21)

Figures 21 to 25 are the octave spectra and overall noise levels at positions A, B, C, D, E, on the indicated muffler forms, together with (where possible) the corresponding values for the jet alone. Jet velocity = 1000 ft / sec.

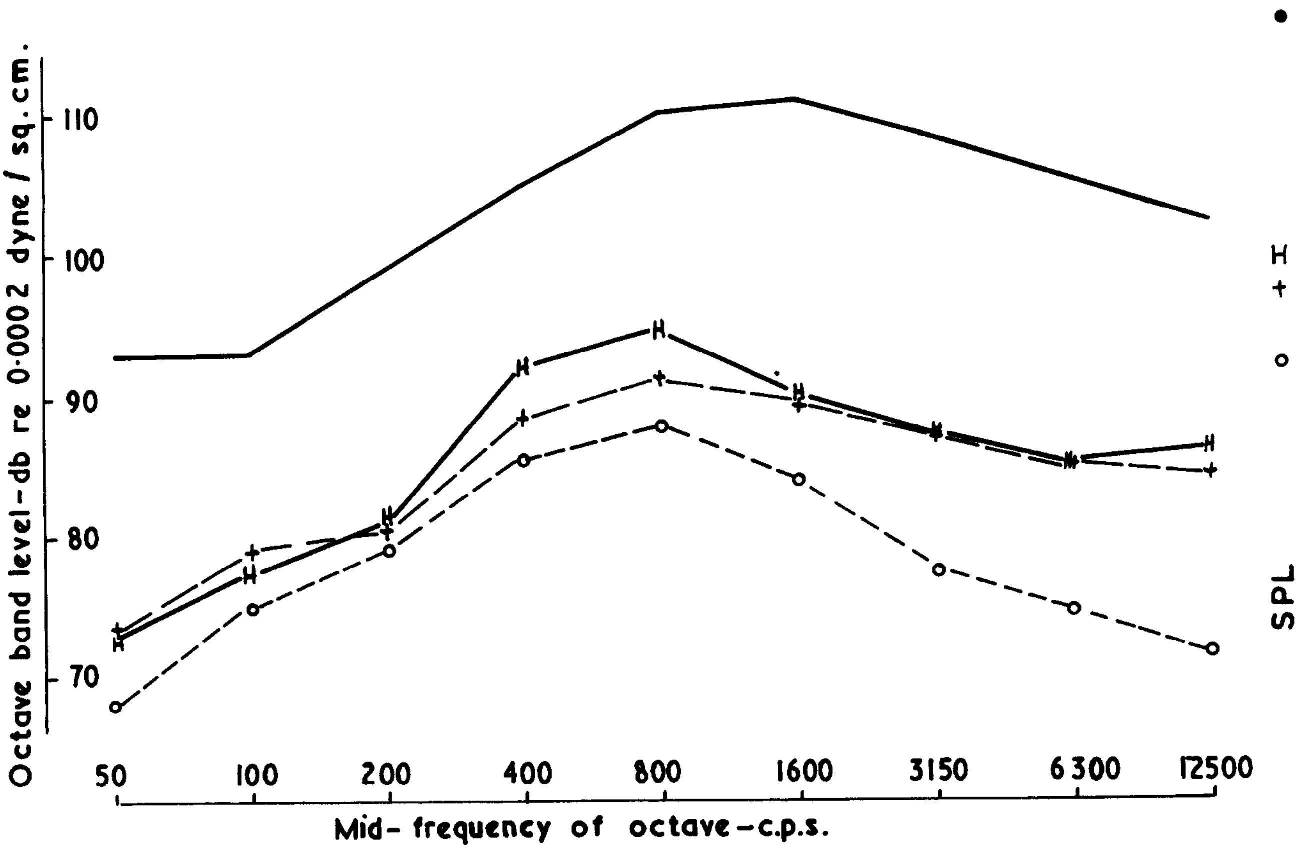


FIG. 23. Position C (key as Figure 21)

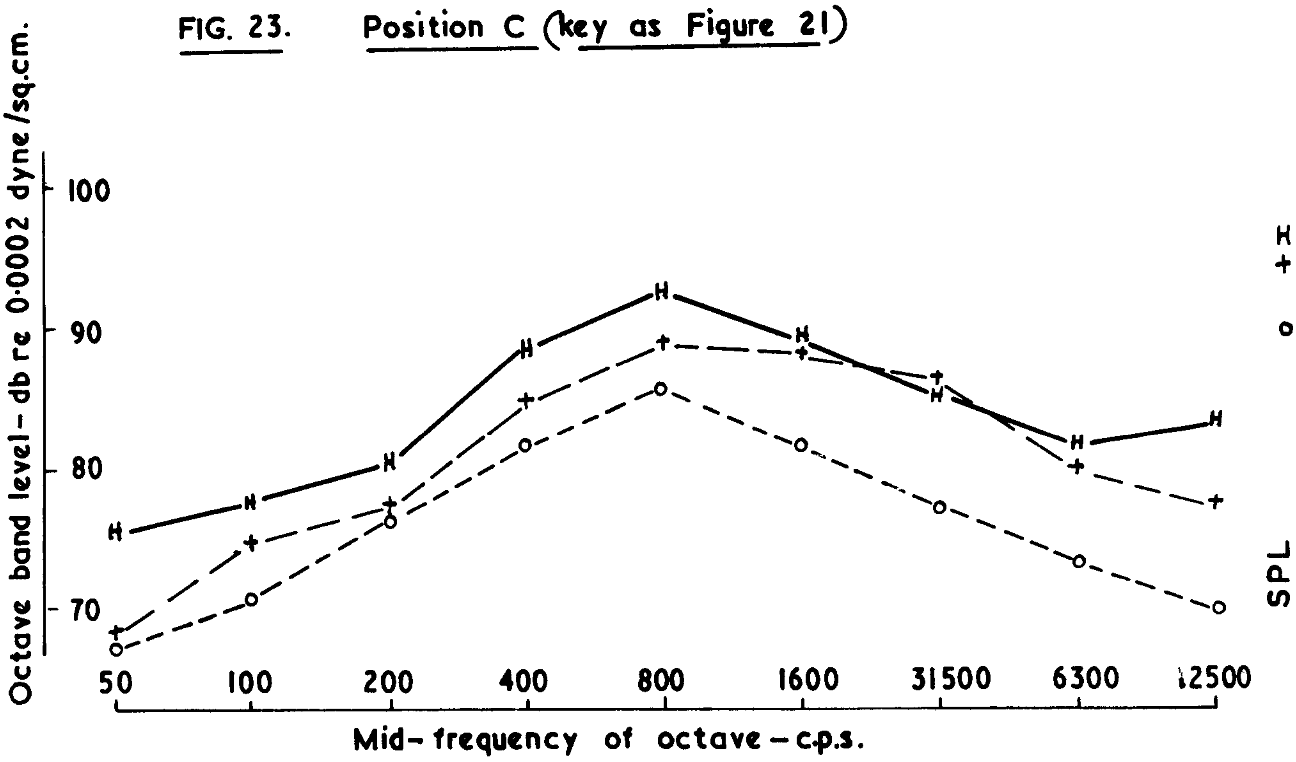


FIG. 24. Position D (key as Figure 21)

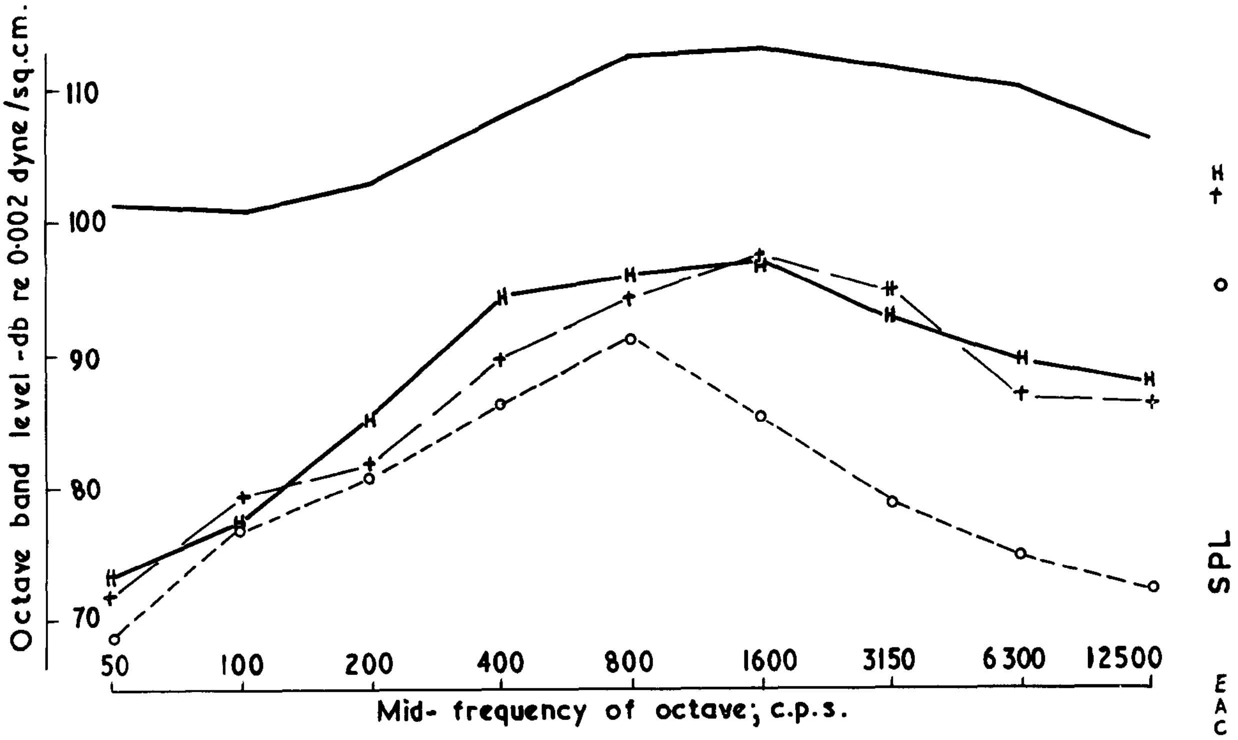


FIG. 25. Position E key as Figure 21

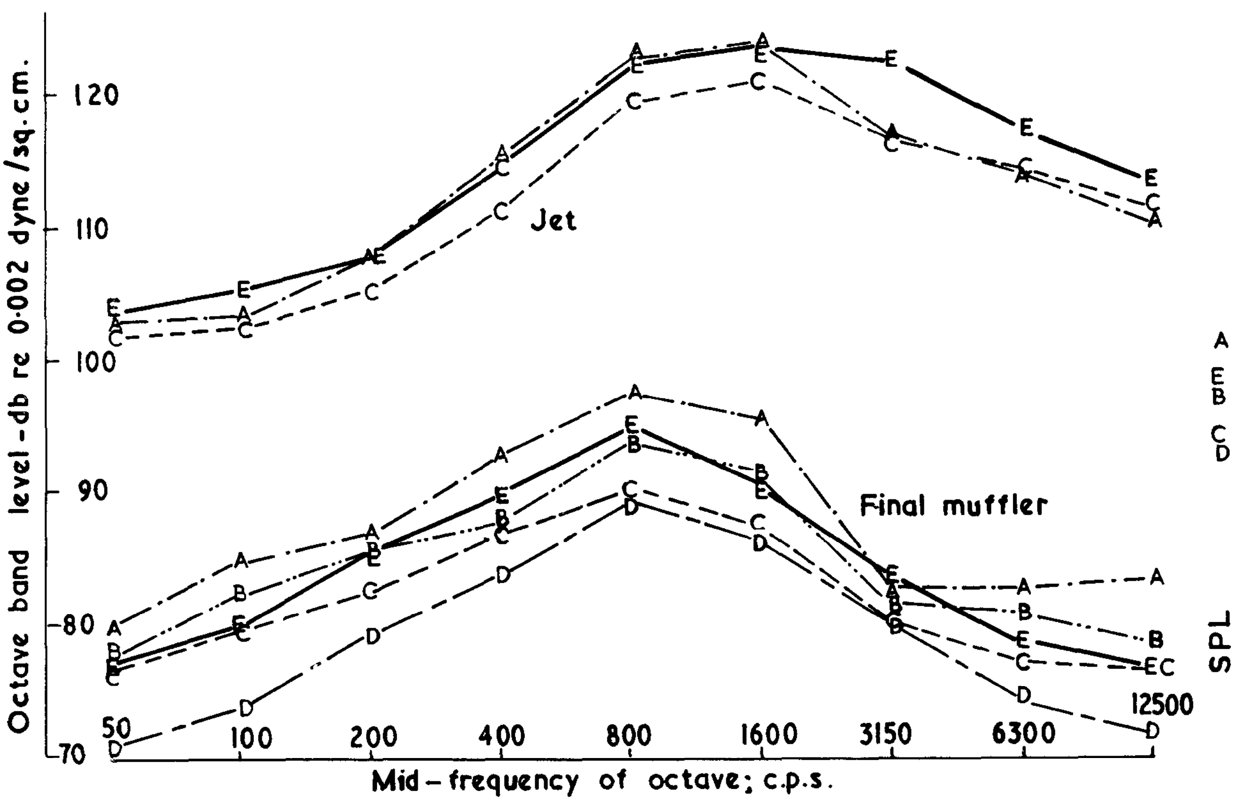


FIG. 26. Spectra for the jet and final muffler configuration. Positions as indicated. Jet velocity = 1240 ft/sec.

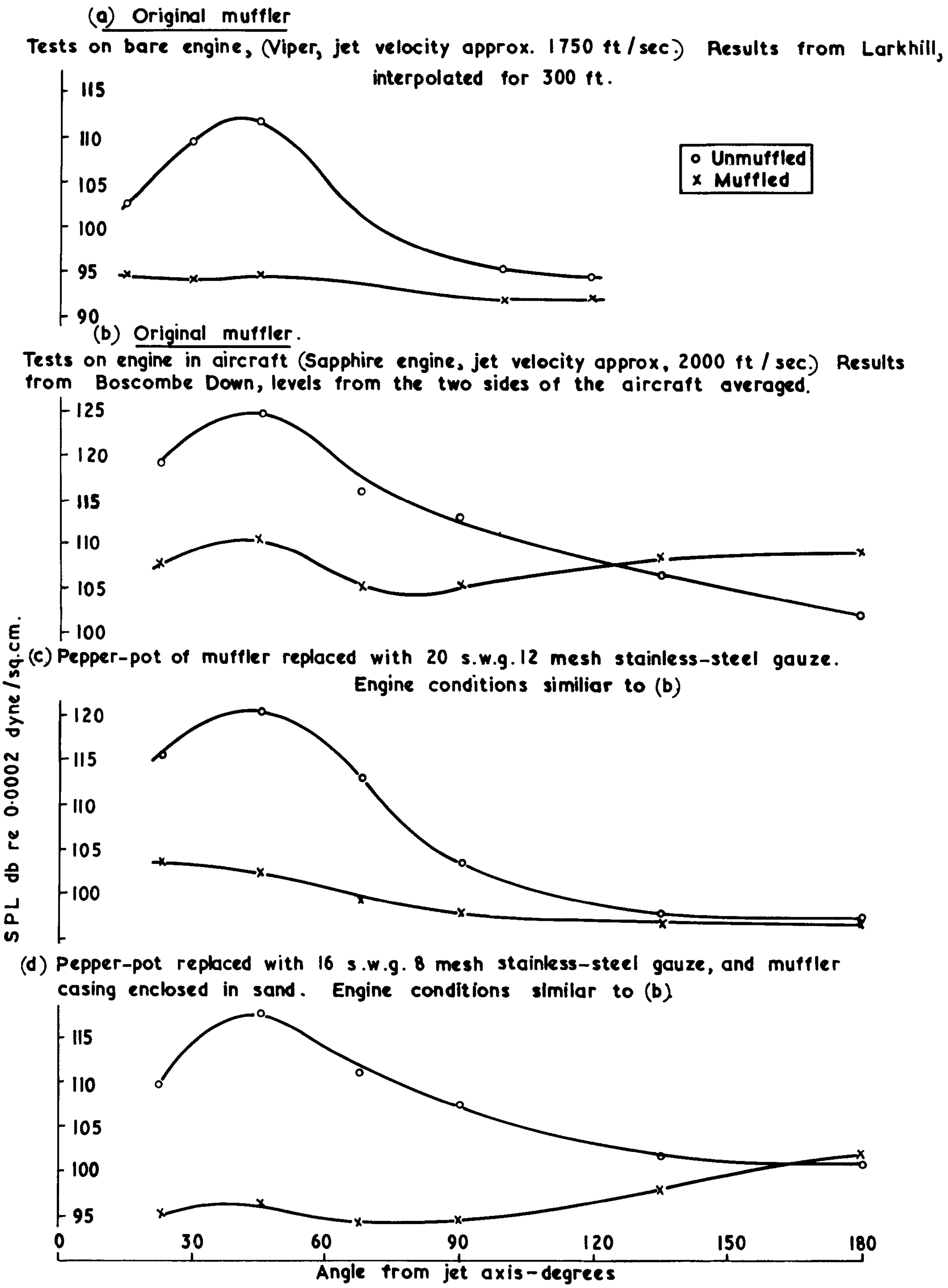


FIG. 27. Overall noise levels at 300 ft. radius for full-scale muffler and modified versions.

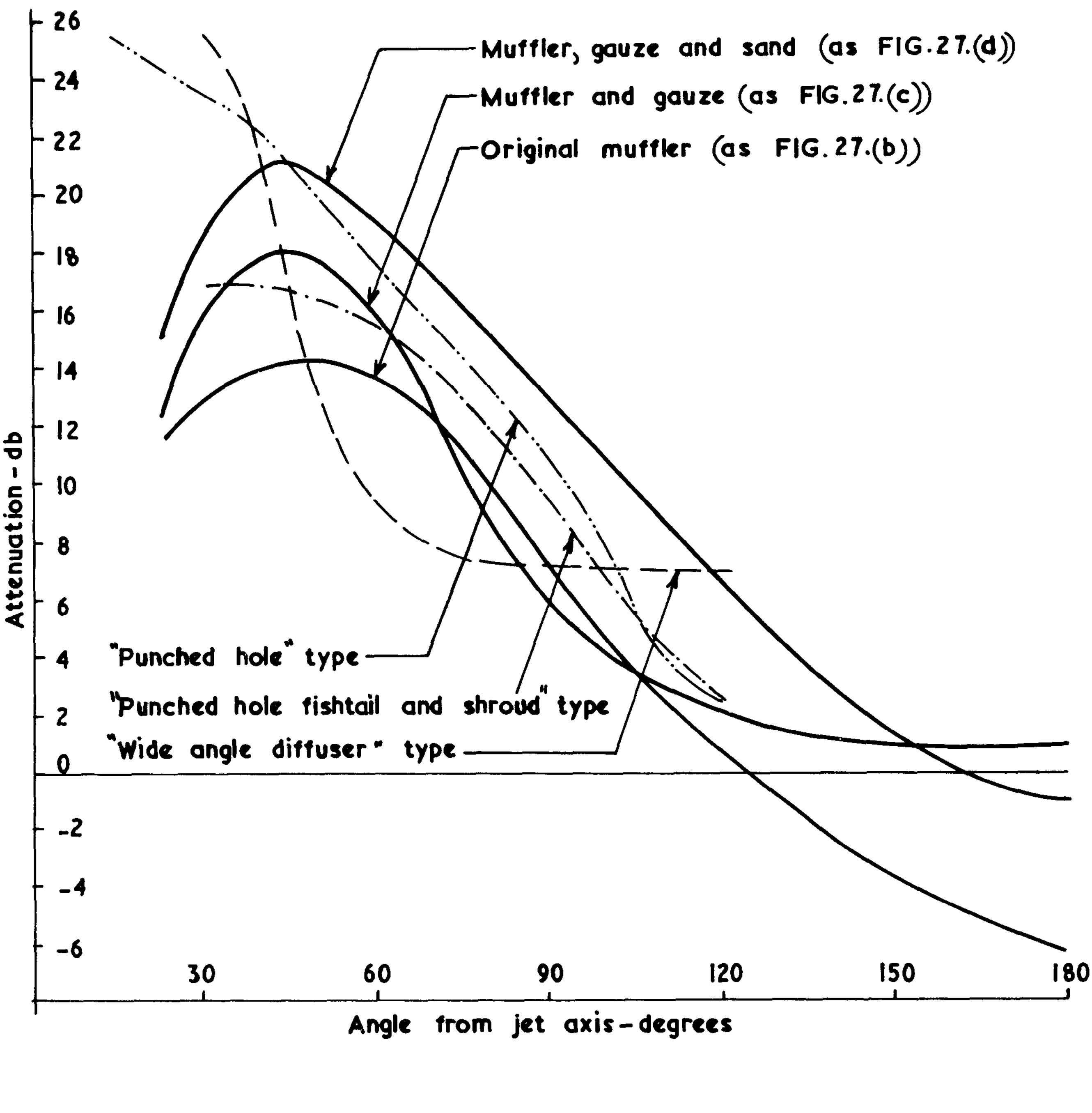


FIG. 28. The attenuations of various ground mufflers.

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