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## ENGINEERING DIVISION

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# Recent research on studio sound problems

PART I

## A SUBJECTIVE INVESTIGATION INTO PREFERRED MICROPHONE BALANCES

by

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(Formerly of Research Department, BBC Engineering Division)

PART II

## THE DESIGN OF A LOW-FREQUENCY UNIT FOR MONITORING LOUDSPEAKERS

by

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(Research Department, BBC Engineering Division)

BRITISH BROADCASTING CORPORATION

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BBC ENGINEERING MONOGRAPH

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# FOREWORD

This is one of a series of Engineering Monographs published by the British Broadcasting Corporation. About six are produced every year, each dealing with a technical subject within the field of television and sound broadcasting. Each Monograph describes work that has been done by the Engineering Division of the BBC and includes, where appropriate, a survey of earlier work on the same subject. From time to time the series may include selected reprints of articles by BBC authors that have appeared in technical journals. Papers dealing with general engineering developments in broadcasting may also be included occasionally.

This series should be of interest and value to engineers engaged in the fields of broadcasting and of telecommunications generally.

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| 67. | *Pulse Sound: A System of Television Sound Broadcasting Using Pulses in the Video Waveform* | MARCH 1967 |

# PART I

# A SUBJECTIVE INVESTIGATION INTO PREFERRED MICROPHONE BALANCES

## SUMMARY OF PARTS I AND II

This monograph presents the results of two recent projects in the Sound Section of the BBC Research Department.

Part I describes two series of subjective investigations in which members of the public and BBC staff were invited to assess the relative merits of different microphone balance conditions. It is shown that concert-going members of the public are able to make such assessments with remarkable consistency and that they prefer the sound obtained from a single distant microphone rather than that of a reinforced balance.

Part II begins by reviewing the present state in the design of low-frequency loudspeaker units and indicates the areas where improvement is desired. This is followed by experimental details leading to the design of a 12 in. (305 mm) unit incorporating a vacuum-formed cone of toughened polystyrene with a p.v.c. (polyvinyl chloride) surround, and it is shown by objective and by listening tests that this design is superior to existing units. An analysis of the price indicates that the new unit should not cost any more than those at present in use.

## 1. Introduction to Part I

It is some fourteen years since a subjective investigation was undertaken to determine the kind of microphone balance preferred by the public. Since that time the technique of microphone balance for gramophone recordings has changed somewhat, and modern recordings generally use multi-microphone techniques. This has influenced microphone balance techniques for broadcasting, since it has been tacitly assumed that the musical public is thereby conditioned to prefer such balances.

A pilot investigation was undertaken some three years ago to determine the ability and reliability of subjects in assessing the relative merits of different microphone balances. The techniques used, together with results obtained in the pilot investigation, are discussed in Section 2.

The work was carried out by the BBC Engineering Research Department with the close co-operation of representatives of Central Programme Operations and Sound Broadcasting Engineering Departments who were present throughout the recording sessions and gave valuable assistance with the technical arrangements.

The results of the preliminary investigation were discussed with the heads of the appropriate departments and it was agreed that further investigations should be undertaken using orchestral music of different textures. Arrangements were therefore made to record several excerpts of music during two successive Sunday afternoon transmissions from Maida Vale Studio 1. The final investigation involving ninety-eight subjects and using the methods described in Section 2.2 is described in Section 3.

## 2. Experimental Procedure

### 2.1 *Preliminary Investigation*

This investigation, in which subjects are asked to assess the rank order for several microphone balances, is of a purely subjective type, as the phenomena for assessment have no measurable physical dimensions. Thus all individual assessments must be considered correct, unlike an experiment in which subjects are asked, for example, to rank a group of individuals in order of height. In the latter case some of the answers may be demonstrably wrong because the heights of individuals can be measured, but one cannot assess quantitatively the merits of different microphone balances, nor classify answers as right or wrong.

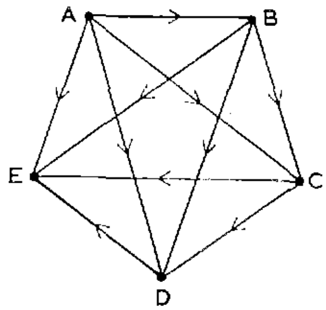


*Fig. 1 — Pentagon of preference for a consistent set of answers*

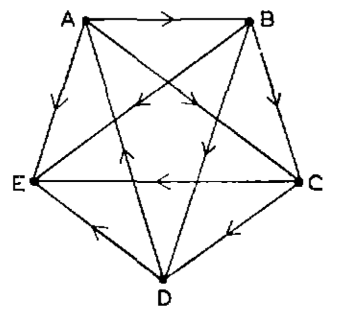


*Fig. 2 — Pentagon of preference illustrating one circular triad*

Bearing the above in mind, it was thought that the method of paired comparisons would be most suitable for this investigation.

### 2.2 *Paired Comparisons*

In the method of paired comparisons[1] the subjects are presented successively with all possible pairs of objects or conditions and are asked to state a preference for one in each of the pairs. For $n$ objects the number of pairs is $n!/2!(n\text{-}2)!$ which is written as $\binom{n}{2}$. Suppose that there are five conditions A, B, C, D, and E, then a preference of A to B can be expressed as A→B. All the ten preferences expressed can be shown in a pentagon of preference as in Fig. 1 and the rank order is obtained from the pentagon by counting the arrows leaving each corner. In Fig. 1 the ranking is A, B, C, D, E.

Suppose on the other hand that the subject had expressed preferences as in Fig. 2.

In this figure the triangle A, C, D is termed a circular triad since A is preferred to C, C is preferred to D, and D is preferred to A. If the heights of individuals were being ranked this would be an error since A cannot be taller than

C and C taller than D without A being also taller than D. The interpretation is probably that the subject assessed the pairs from different standards of reference. For instance, (AC), (CD) may have been assessed on the relative balance of woodwind and strings, while (DA) may have been assessed on string tone alone; the ensuing circular triad ACD may therefore be a perfectly valid result and is not necessarily an inconsistency. In ordinary ranking problems dealing with objective comparisons a necessary and sufficient condition for the possibility of expressing the preference as a rank order is that no circular triads shall be present.[2] On the other hand, for this highly subjective experiment a subject was regarded as 'consistent' provided he had no more than one circular triad in comparisons between five different conditions.

Simultaneous recordings of five different microphone balance conditions were made during a transmission of a short passage from the slow movement of Beethoven's Third Symphony. From these recordings a twin-track test tape was prepared in which each of the five balance conditions was compared with every other balance condition. Thus there were ten pairs of comparisons. The order of recording of the ten pairs of comparisons was so arranged that each condition appeared on each track the same number of times. The test tape was replayed to the subjects and the loudspeaker was switched, at intervals of 10 seconds, between the two tracks. An illuminated indicator panel showed the subjects which track was being replayed at any instant. The subjects were required to state which of the two tracks gave the most realistic, or natural, sound in each of the ten pairs of comparisons. The same passage of music was used for each of the ten tests.

### 2.3 *Microphone Balance Conditions in the Preliminary Experiment*

Fig. 3 is a photograph of the disposition of microphones in the studio. The five microphone balance conditions were as follows:

(A) A moderately distant single microphone at a height of some 8 m situated at a horizontal distance of 9 m from the rostrum (microphone 1 in Fig. 3).

(B) A more distant single microphone 4·3 m high (microphone 2 in Fig. 3).

(C) The reinforced balance transmitted, which consisted of a main microphone 5·5 m above the conductor's head (3 in Fig. 3), plus separate reinforcement of the woodwind and of the low strings (microphones 4 and 5 respectively in Fig. 3).

(D) A separate feed from the main microphone in condition C (3 in Fig. 3).

(E) A single microphone 3·6 m above the conductor's head (6 in Fig. 3).


*Fig. 3 — Photograph of Maida Vale Studio 1 showing the microphone positions used in the pilot experiment*

## 2.4 *Results of the Preliminary Experiment*

The test tape was first replayed to two groups of experienced listeners—engineers and studio managers respectively—and the results were analysed. Of the fifteen subjects in one group only six of the pentagons of preference had fewer than two circular triads. The answers were analysed in three different ways. The first method is given in Fig. 4, in which the number of subjects ranking a given condition at, or above, the indicated rank is plotted against the rank for each of the five conditions. The area under each of the curves is then a measure of the degree of preference, and absence of intersections of one curve with another may be regarded as indication of clear preference for the higher over the lower. Reference to Fig. 4 shows that the five curves lie close together and intersect, indicating that, taken as a group, the fifteen subjects did not share a definite preference for any one balance.

The second method of analysis was to draw the pentagon of preference for the combined answers given by all subjects for each of the ten comparisons. This pentagon is shown in Fig. 5 from which it can be seen that the group gives one circular triad (ABC). In this and subsequent pentagons for more than one subject, the overall preference in each comparison is taken to be the one which obtained the greater number of votes. When the opposing preferences each got the same number of votes, the points are joined with a dashed line.

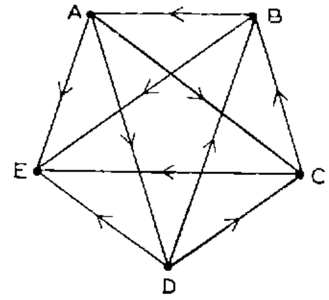


*Fig. 5 — Pentagon of preference for fifteen engineers*

The third method of analysis was by normal ranking methods[3] the results of which are given in Table 1. Each figure in the table represents the number of times the condition indicated at the left of the row was judged better than that at the top of the column.

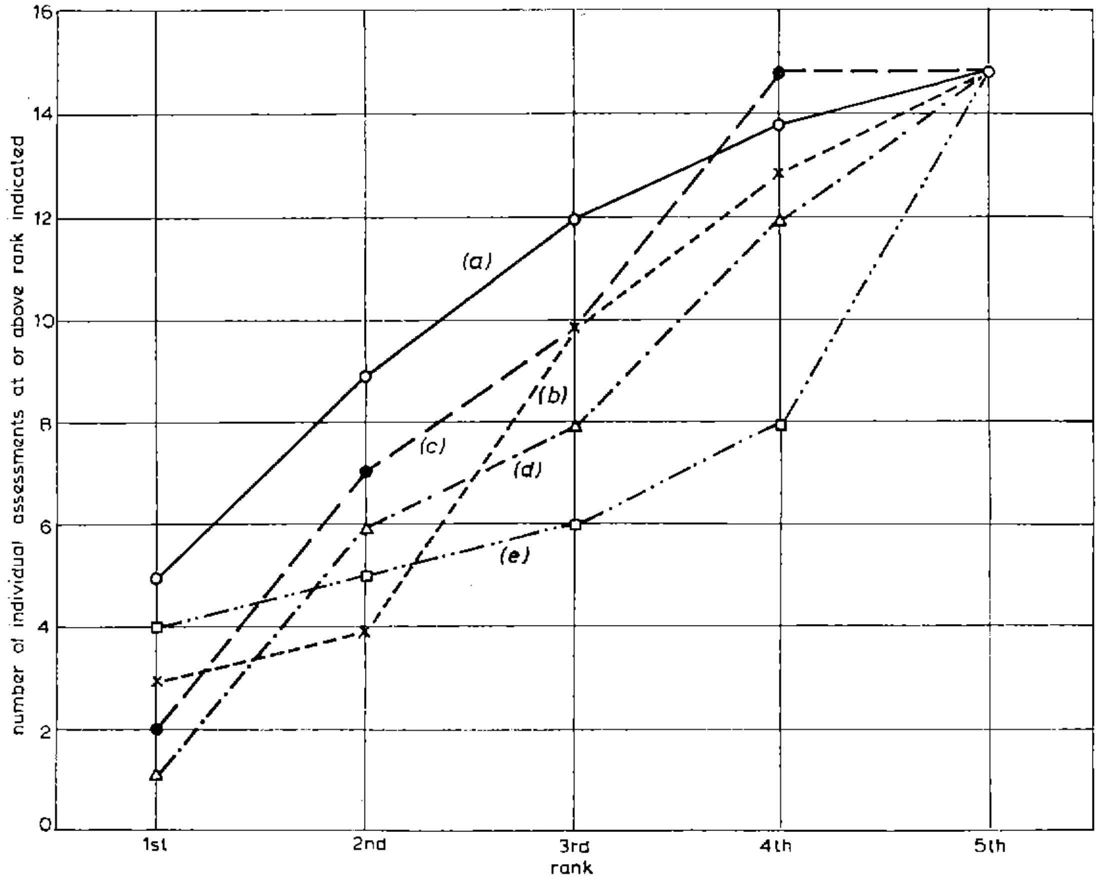


*Fig. 4 — Graphical analysis of the results for fifteen engineers*

(*a*) Condition A (*b*) Condition B (*c*) Condition C
(*d*) Condition D (*e*) Condition E

Table 1

| | *A* | *C* | *B* | *D* | *E* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| A | — | 10 | 7 | 12 | 9 | 38 | 1 |
| C | 5 | — | 8½ | 7 | 9 | 29½ | 2 |
| B | 8 | 6½ | — | 6½ | 8 | 29 | 3 |
| D | 3 | 8 | 8½ | — | 8 | 27½ | 4 |
| E | 6 | 6 | 7 | 7 | — | 26 | 5 |
| | | | | | | 150 | |

It will be noticed in Table 1 that the preference totals expressed for each of the five conditions do not differ greatly. This suggests that the subjects had no common preference for any condition.

The orders of preference for the group obtained by the three methods of analysis are shown in Table 2.

Table 2

| *Preference Order* | *1st* | *2nd* | *3rd* | *4th* | *5th* |
|---|---|---|---|---|---|
| Ranking (Table 1) | A | C | B | D | E |
| Graphical (Fig. 4) | A | C | B | D | E |
| Group pentagon (Fig. 5) | A, D | | B, C | | |

Conditions B and D are opposite extremes, one being a very close, and the other a very distant microphone. From Table 1 it is seen that nearly equal numbers of votes were cast for each of these conditions. At this stage the subjects were asked how frequently they attended live orchestral concerts, and with two exceptions the average attendance was one concert in fifteen months. (One subject had last attended a concert in the Queens Hall, which was destroyed by enemy action in 1941.) It was concluded that the subjects in this group could well have selected the balance condition which approximated most closely to the sound produced by their own sound reproducing equipment.

A second group of fourteen experienced listeners consisted of members of the BBC staff who are accustomed to monitoring the sound of orchestral music. In this group

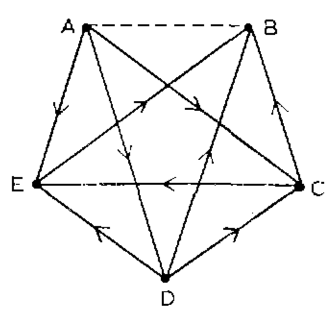


*Fig. 6 — Pentagon of preference for fourteen operational subjects*

only one subject gave answers with less than two circular triads. The answers obtained from this group were again analysed in the three ways discussed above, and the results are given in Figs 6 and 7 and in Table 3.

Table 3

| | *C* | *D* | *A* | *E* | *B* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| C | — | 5½ | 4½ | 13 | 11½ | 34½ | 1 |
| D | 8½ | — | 6 | 8 | 11 | 33½ | 2 |
| A | 9½ | 8 | — | 7½ | 7 | 32 | 3 |
| E | 1 | 6 | 6½ | — | 9½ | 23 | 4 |
| B | 2½ | 3 | 7 | 4½ | — | 17 | 5 |
| | | | | | | 140 | |

Table 4 shows the orders of preference expressed by this group obtained by the three methods of analysis.

Table 4

| *Preference Order* | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| By ranking method | C | D | A | E | B |
| Graphical (Fig. 7) | D | C | A | E | B |
| From group pentagon | A | D | C | E | B |

It will be noted from the total preferences column in Table 3 that the ranking is again very close. From Table 4 it can be seen that the three methods of analysis gave three different orders of preference. The fact that thirteen out of fourteen subjects gave answers with two or more circular triads suggests that the individuals in this group of subjects changed their reference standards during the test. It seems that these subjects, while able to assess critically the technical quality of programmes, had no common preference for any one balance condition.

In order to extend the investigation, it was decided that a group of concert-going members of the public should be included. These subjects were mostly amateur musicians who were familiar with the sound of live orchestras in different auditoria. A total of forty subjects participated in the experiment and twenty-three of them gave answers with no more than one circular triad. The forty sets of answers were analysed and the results are given in Figs 8 and 9 and in Table 5.

It can be seen from the column of total votes in Table 5 that the members of this group were able to differentiate between the different balance conditions, and it should be noted that all three methods of analysis gave the same preference order, that is, A, D, B, C, E.

Appendix A gives tests of significance for the three groups of subjects so far, and shows that the only statistically significant results were those obtained from the group of forty concert goers.

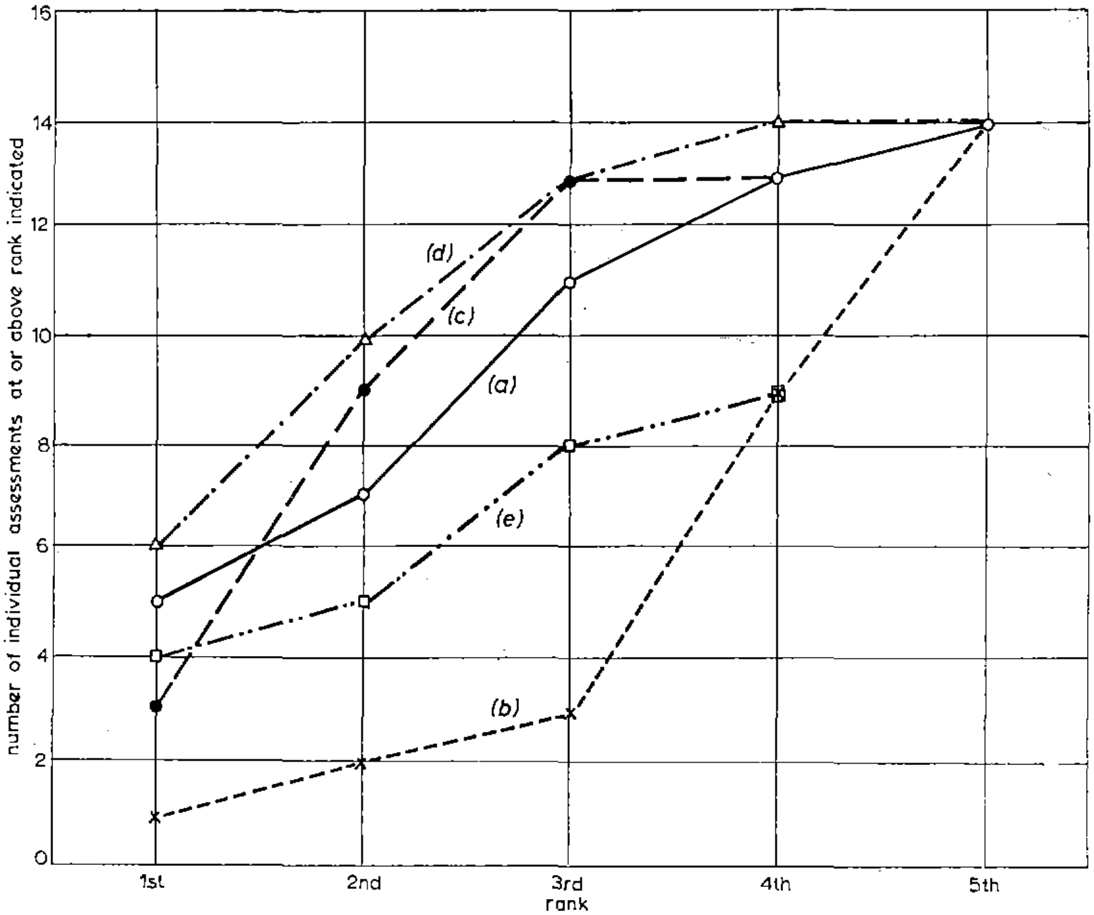


*Fig. 7 — Graphical analysis for fourteen studio managers*

(*a*) Condition A (*b*) Condition B (*c*) Condition C
(*d*) Condition D (*e*) Condition E

TABLE 5

| | *A* | *D* | *B* | *C* | *E* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| A | — | 27 | 20 | 28 | 35 | 110 | 1 |
| D | 13 | — | 24½ | 23½ | 34½ | 95½ | 2 |
| B | 20 | 15½ | — | 23 | 30½ | 89 | 3 |
| C | 12 | 16½ | 17 | — | 29 | 74½ | 4 |
| E | 5 | 5½ | 9½ | 11 | — | 31 | 5 |
| | | | | | | 400 | |

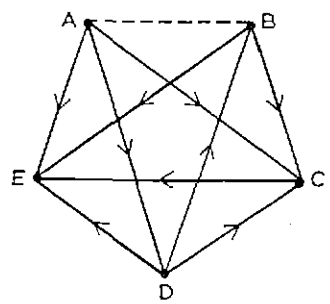


*Fig. 8 — Pentagon of preference for forty concert-going members of the public. Rank order: A, D, B, C, E*

2.5 *Discussion of Results*

The above investigation shows that the experienced technical listeners capable of assessing critically the technical quality of programmes could not agree on the ranking of a set of different microphone balances. This may be because the subjects, who were consistent as individuals, expressed their preference with respect to different reference standards, for instance, the sounds produced by their own monophonic sound reproducing systems. The subjects who were statistically inconsistent most probably changed their reference standards during the test as suggested in Section 2.2.

Members of the general public who are active concert goers would appear to be more consistent as individuals than the technical listeners, and this suggests that as a group these subjects had a common standard of reference

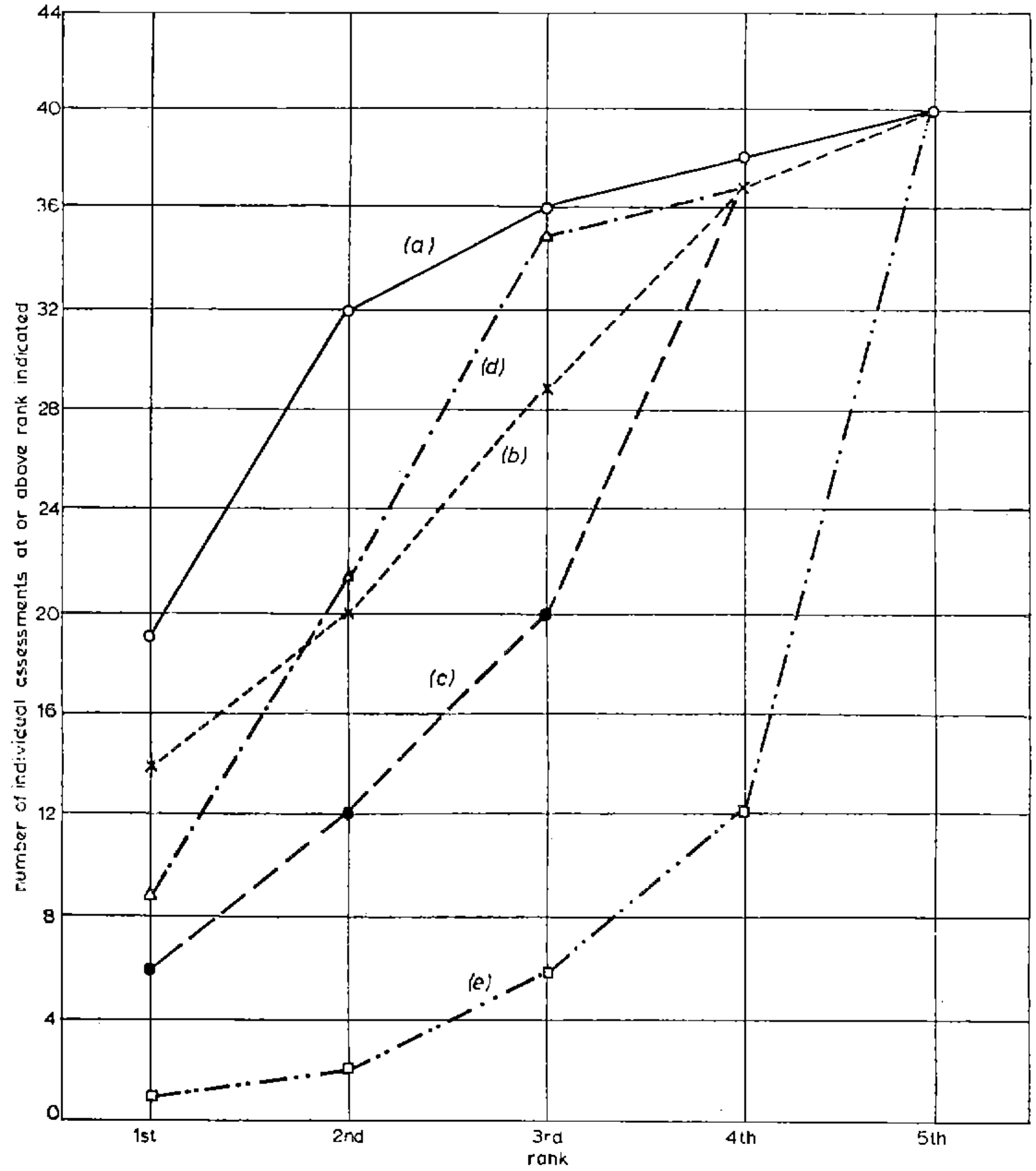


*Fig. 9 — Graphical analysis of results for forty concert-going members of the public. Rank order of areas under the curves: A, D, B, C, E*

(*a*) Condition A (*b*) Condition B (*c*) Condition C (*d*) Condition D (*e*) Condition E

which did not change during the test. This group was able to give a significant group preference order for the five microphone balance conditions.

It should be noted that in the comparison of the conditions C and D all three groups preferred the single main microphone (condition D) of the transmitted balance rather than the complete reinforced balance transmitted (condition C). The group of concert goers had a clear preference for a single microphone balance rather than a reinforced balance and also had a definite preference for a distant single-microphone balance rather than a close single-microphone balance.

## 3. Final Investigation

3.1 *Introduction*

As a result of the discussions mentioned in Section 1 above, it was decided to extend the investigation to music of different historical periods and of widely different orchestral texture. Simultaneous recordings were made of short passages from the following compositions:

Bartók: Concerto for Orchestra.
Berlioz: Symphony Fantastique.
Britten: Variations for string orchestra on a Theme by Frank Bridge.

Haydn: Symphony No. 93 in D.

The Haydn and Bartók excerpts were recorded with five different balance conditions similar to those described in Section 2.3.

Conditions A and B were distant single-microphone balances.

Condition C was the reinforced transmitted balance.

Condition D was a close single-microphone forming the main part of the Studio Manager's balance.

Condition E was another close single-microphone balance.

The transmitted reinforced balance and the single microphone balances were arrived at independently in separate listening rooms by the Studio Manager and the Research Department team respectively. During rehearsals for the Berlioz and Britten recordings, the Studio Manager found it necessary to modify his balance, adding an extra microphone to reinforce the lower strings in the balance for transmission. This, incidentally, resembled more closely the sounds obtained from the single microphones.

Five test tapes were prepared from the extracts. Two excerpts from the Bartók Concerto for Orchestra were used, together with one excerpt each from the Haydn, Britten, and Berlioz compositions. A total of ninety-eight members of the public participated in these tests, and the results obtained are given in Section 3.2.

3.2 *Results*

In view of the results obtained from the forty concert goers, as discussed in Section 2.4 the results in this part of the investigation are analysed only by normal rank correlation methods.

3.2.1 *Haydn*

A total of ninety-eight subjects participated in this test, of whom sixty-three were self consistent. Table 6 summarizes the results.

From Table 6 it may be seen that the ninety-eight subjects showed a preference for a distant single microphone balance rather than for a reinforced balance. The subjects had a pronounced dislike of a very close microphone balance. Appendix B1 gives the statistical analysis of the results tabulated in Table 6 and shows that the results are highly significant.

TABLE 6

| | *B* | *A* | *C* | *E* | *D* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| B | — | 58 | 62 | 59 | 79½ | 258½ | 1 |
| A | 40 | — | 58 | 74 | 61½ | 233½ | 2 |
| C | 36 | 40 | — | 62½ | 72 | 210½ | 3 |
| E | 39 | 24 | 35½ | — | 43 | 141½ | 4 |
| D | 18½ | 36½ | 26 | 55 | — | 136 | 5 |
| | | | | | | 980 | |

3.2.2 *Bartók, First Excerpt*

A total of eighty-seven subjects, of whom sixty-two were self consistent, participated in the tests in this section. Table 7 tabulates the expressed preferences:

TABLE 7

| | *A* | *B* | *C* | *D* | *E* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| A | — | 54½ | 48½ | 73 | 74½ | 250½ | 1 |
| B | 32½ | — | 49½ | 60 | 68½ | 210½ | 2 |
| C | 38½ | 37½ | — | 67 | 62½ | 205½ | 3 |
| D | 14 | 27 | 20 | — | 50½ | 111½ | 4 |
| E | 12½ | 18½ | 24½ | 36½ | — | 92 | 5 |
| | | | | | | 870 | |

Again this test indicated that the subjects had a marked preference for the single distant microphone balance and a pronounced dislike for the sound quality produced by close microphones. The statistical analysis summarized in Appendix B2 again shows the results to be highly significant.

3.2.3 *Bartók, Second Excerpt*

It was found that doubling the number of test subjects did not produce a significant change in the result and it was therefore decided that fifty subjects would be an adequate number to participate in the remaining tests. In this particular test forty-five of the fifty subjects were self consistent. Table 8 summarizes the preferences expressed.

TABLE 8

| | *A* | *C* | *B* | *D* | *E* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| A | — | 31 | 28½ | 31½ | 34 | 125 | 1 |
| C | 19 | — | 26 | 32 | 36½ | 113½ | 2 |
| B | 21½ | 24 | — | 30½ | 32 | 108 | 3 |
| D | 18½ | 18 | 19½ | — | 30½ | 86½ | 4 |
| E | 16 | 13½ | 18 | 19½ | — | 67 | 5 |
| | | | | | | 500 | |

There is a marked group preference for a single distant microphone and a pronounced dislike of close microphones. The statistical analysis in Appendix B3 shows that the results are significant.

3.2.4 *Britten*

In this excerpt thirty-five of the fifty subjects participating were self-consistent. As mentioned in Section 3.1 the reinforced balance was modified before recording the Britten and Berlioz excerpts. The modification was basically the addition of a separate microphone to reinforce the low strings thereby producing a sound which was much closer to the single microphone output. Microphone condition D was eliminated as the Studio Manager had decided to fade it down with the changed balance leaving four conditions A, B, C, and E. Table 9 summarizes the results:

TABLE 9

| | C | A | B | E | Total Preferences | Rank |
|---|---|---|---|---|---|---|
| C | — | 29½ | 21½ | 40½ | 91½ | 1 |
| A | 20½ | — | 28 | 41 | 89½ | 2 |
| B | 28½ | 22 | — | 36 | 86½ | 3 |
| E | 9½ | 9 | 14 | — | 32½ | 4 |
| | | | | | 300 | |

The total number of preferences expressed for conditions A, B, and C can be seen from Table 9 to differ by very small amounts, suggesting that no marked preference was held by the group for any one of the balances. However, Appendix B4 shows that there is a significant coefficient of agreement. Further analysis given in Appendix B4 shows that the significance lies in the groups' dislike of the close microphone balance and that the results for the comparisons of conditions A, B, and C could well have arisen by chance.

3.2.5 *Berlioz*

In this test twenty-seven of the fifty subjects were self-consistent. Table 10 summarizes the results:

TABLE 10

| | C | B | A | E | Total Preferences | Rank |
|---|---|---|---|---|---|---|
| C | — | 27½ | 30 | 27½ | 85 | 1 |
| B | 22½ | — | 25 | 27 | 74½ | 2 |
| A | 26 | 25 | — | 20 | 71 | 3 |
| E | 22½ | 23 | 24 | — | 69½ | 4 |
| | | | | | 300 | |

Appendix B5 shows that there is little agreement between observers and the results could have arisen at random.

3.3 *Discussion of Results*

During informal discussions at the end of each test section the subjects were asked to enumerate as far as possible the factors which governed their final choice of balance condition. The information obtained was that in general the concert goers could quite easily assess the relative merits of the different microphone balances both for classical and contemporary music in passages where the main theme was given to the violins with the remainder of the orchestra providing the accompaniment. This type of passage applies to the Haydn and first Bartók excerpts as well as to the Beethoven passage in the preliminary test. This is not unexpected since the acoustic radiation pattern for violins and viola shows that the high frequency energy is concentrated in a narrow lobe perpendicular to the belly of the instrument, thus the audience in an auditorium hears the somewhat unpleasant bowing noise at considerably reduced amplitudes compared with those of the fundamental and first few harmonics. A microphone suspended over the violin section of an orchestra will pick up sound energy of large amplitude in the high frequency region, thereby producing a harshness and stridency in the string tone which is not normally heard in the concert hall.

In the Berlioz excerpt the theme is given to the full brass and the subjects had great difficulty in expressing a preference for any balance condition. Similarly in the Britten variations, in which each string section is subdivided, it was difficult to assess the relative merits of the different pairs of comparisons. It should again be emphasized that for the Britten and Berlioz excerpts the reinforced balance had been changed and gave a sound more similar to that of the distant single microphone balances. It was to be expected that the subjects would experience difficulty in assessing the three conditions.

## 4. Conclusions

This series of tests has shown that musical members of the public are able, for certain types of music, to assess the relative merits of different microphone balances with a remarkable degree of consistency. It has been demonstrated that for music such as the Haydn, Beethoven, and Bartók excerpts a distant single microphone balance is significantly preferred to a reinforced balance. The three balance conditions A, B, and C were all adequate for the transmission of symphonic music and the improved string tone obtained with a single distant microphone was the decisive factor in arriving at the final order of preference in the Haydn, Beethoven, and Bartók excerpts. It would therefore appear that for transmissions of orchestral music the added complexity of reinforced balance techniques does not in general produce any improvement over a single distant microphone balance, and that in some cases a reinforced balance may be a definite disadvantage.


## 5. Acknowledgements

The author wishes to acknowledge with gratitude the help of those members of the public who gave their time to this investigation and particularly to members of the following music societies:

1. Wallington, Carshalton, and Beddington Music Society.
2. Croydon Youth Orchestra.
3. Croydon Philharmonic Society.
4. Sutton Music Society.


## 6. References


1. Kendall, M. G., **Rank Correlation Methods**, London, Griffin and Co., p. 121, 1948.
2. Op. cit., p. 123.
3. Op. cit., Table 8, p. 125.
4. Op. cit., p. 129.
5. Op. cit., p. 153.
6. Op. cit., p. 127.

# APPENDIX A

Suppose that $m$ observers each provide $\binom{n}{2}$ preferences between all possible pairs of $n$ objects. The coefficient of agreement $u$ between pairs of observers can be calculated[3] from

$$u = \frac{2\Sigma}{\binom{m}{2}\binom{n}{2}} \tag{1}$$

where $\Sigma = \Sigma\binom{\gamma}{2}$, the summation extending over all the $n(n-1)$ cells in the table of paired comparisons. The significance of the results can be determined[1] by calculating the $x^2$ distribution for the paired comparison data:

$$x^2 = \frac{4}{m-2}\left\{\Sigma - \tfrac{1}{2}\binom{m}{2}\binom{n}{2}\frac{m-3}{m-2}\right\} \tag{2}$$

The number of degrees of freedom $v$ is given by

$$v = \binom{n}{2}\frac{m(m-1)}{(m-2)^2} \tag{3}$$

Knowing $v$, the significance level $P$ of the result can be obtained from tables.[5] These equations will now be applied to the data in the paired comparison tables obtained during two series of tests.

A1 *Engineers*

The results for the fifteen engineers are given in Table 1, which is repeated here:

TABLE 1

| | *A* | *C* | *B* | *D* | *E* | *Total Preferences* | *Rank* |
|---|---|---|---|---|---|---|---|
| A | — | 10 | 7 | 12 | 9 | 38 | 1 |
| C | 5 | — | $8\frac{1}{2}$ | 7 | 9 | $29\frac{1}{2}$ | 2 |
| B | 8 | $6\frac{1}{2}$ | — | $6\frac{1}{2}$ | 8 | 29 | 3 |
| D | 3 | 8 | $8\frac{1}{2}$ | — | 8 | $27\frac{1}{2}$ | 4 |
| E | 6 | 6 | 7 | 7 | — | 26 | 5 |
| | | | | | | 150 | |

Providing that the table is laid out with the objects in rank order the summation $\Sigma\binom{\gamma}{2}$ taken over the $n(n-1)$ cells in the table can be shown to be given by[6]

$$\Sigma = \Sigma\gamma^2 - m\Sigma\gamma + \binom{m}{2}\binom{n}{2} \tag{4}$$

where the summation is now restricted to the $n(n-1)/2$ numbers below the diagonal.

From the data in the table of paired comparisons we have

$$\Sigma = 521\cdot 5$$

now

$$n = 5 \text{ and } m = 15$$

$$\therefore \qquad \binom{n}{2}\binom{m}{2} = 1150$$

Substituting these values in Equation (1) we have

$$u = -0\cdot 006$$

The negative sign indicates disagreement between pairs of subjects. Substituting for $n$, $m$, and $\Sigma$ in Equation (2) we find

$$x^2 = 14\cdot 9$$

Substituting for $n$ and $m$ in Equation (3)

$$v = 12\cdot 3$$

Hence from the tables $P = 0\cdot 3$. We conclude that there is a 30 per cent chance that the results could have arisen in random fashion.

A2 *Studio Managers* (*Fourteen subjects*)

Taking the data given in Table 3 and proceeding as in Appendix A1 we find

$$u = 0\cdot 29$$
$$v = 12\cdot 6$$
$$x^2 = 30\cdot 6$$
$$\text{whence } P = 0\cdot 01$$

The result is therefore statistically significant at the 1 per cent level. The significance rests in the dislike of the conditions E and B (the very close and very distant single microphone balances) rather than a preference for any one condition. This can be demonstrated if $u$, $v$, and $x^2$ are calculated from the data for the three conditions A, C, and D. The result of such calculations gives a negligibly small negative coefficient of agreement and shows that there is a 30 per cent chance that the preferences could have arisen at random.

A3 *Forty Concert-Going Members of the Public*

The relevant data is given in Table 5. Proceeding as in Section A1 of Appendix A we find

$$u = 0\cdot 246$$
$$v = 10\cdot 7$$
$$x^2 = 111\cdot 7$$
$$\text{whence } P < 0\cdot 01$$

Thus there is a considerable measure of agreement between pairs of subjects and it is highly improbable that the preferences could have been allotted at random.

# APPENDIX B

In this appendix the values of $u$, $v$, and $x^2$ are calculated from the results obtained in the final series of five tests.

B1 *Haydn*

In this test the relevant data are given in Table 6 from which we calculate, following Appendix A1.

$$u = 0 \cdot 11$$
$$v = 10 \cdot 3$$
$$x^2 = 120 \cdot 5$$
$$\text{whence } P < 0 \cdot 01$$

Thus there is a measure of agreement between pairs of subjects and it is most improbable that so high a value of $x^2$ could have arisen had the preferences been allotted at random.

B2 *Bartók, First Excerpt*

Calculations on the data in Table 7 give the following results

$$u = 0 \cdot 195$$
$$x^2 = 182$$
$$v = 10 \cdot 37$$
$$P = << 0 \cdot 01$$

The coefficient of agreement of $0 \cdot 195$ between pairs of subjects indicates a measure of agreement. The value of $P$ shows that so high a value of $x^2$ could not have arisen had the preferences been allotted at random.

B3 *Bartók, Second Excerpt*

The coefficient of agreement and its significance for this test are calculated from Table 8. We find:

$$u = 0 \cdot 05$$
$$x^2 = 38 \cdot 8$$
$$v = 10 \cdot 64$$
$$P = < 0 \cdot 01$$

Thus there is a very slight measure of agreement between pairs of observers but it is improbable that the preferences were allotted at random.

B4 *Britten*

The results of this test are given in Table 9 from which it will be seen that the total number of preferences allotted to conditions A, B, and C do not differ greatly.

The coefficient of agreement is calculated to be:

$$u = 0 \cdot 195$$
$$x^2 = 55$$
$$v = 6 \cdot 3$$
$$P = < 0 \cdot 01$$

Thus there is a certain amount of agreement between pairs of observers, and it is improbable[5] that the result could have arisen at random.

That the significance of the result lies in a general dislike of condition E may be demonstrated by recalculating $u$, $x^2$, and $v$ from the data relevant to the three conditions A, B, and C.

We find in this case

$$u = 0 \cdot 0002$$
$$x^2 = 3 \cdot 6$$
$$v = 3 \cdot 18$$
$$P = 0 \cdot 4$$

Thus there is negligible agreement between pairs of subjects; from the significance tables[5] we find that there is a probability of 40 per cent that these preferences could have been allotted at random.

B5 *Berlioz*

The data in Table 10 gives, on analysis, the following results:

$$u = -0 \cdot 009$$
$$x^2 = 3 \cdot 65$$
$$v = 6 \cdot 3$$
$$P = 0 \cdot 8$$

and thus there is no measurable agreement between pairs of subjects, and there is an 80 per cent chance[5] that the results could have arisen at random.

# PART II

# THE DESIGN OF A LOW-FREQUENCY UNIT FOR MONITORING LOUDSPEAKERS

## 7. Introduction to Part II

Wide-range loudspeakers, such as are employed for quality monitoring, generally consist of low- and high-frequency units mounted in a cabinet together with a crossover network. In the past colouration* has been so prominent in the reproduction from low-frequency units that the choice of unit has been made on the basis of comparative freedom from this effect rather than on that of power-handling capacity. As an example, a 15 in. (380 mm) unit is employed in the type LS3/1A† loudspeaker when a unit of smaller diameter would have been chosen if one of the necessary quality could have been found. In addition, owing to the restricted working frequency range of the high-frequency units available, it has been necessary to use low-frequency units beyond the frequency range in which the cone and surround behave as a simple piston, i.e. up to about 500 c/s, and into the region in which the amplitude/frequency response is irregular and dependent on the modes of cone resonance and their degree of damping. Furthermore, in existing loudspeaker units the frequency range over which the response is smooth appears, for reasons not fully understood, to be almost independent of cone diameter and from this aspect there is therefore no advantage to be obtained from employing units of smaller diameter.

Cones have generally been made of a paper felt material, but in practice the characteristics of this material, especially the damping coefficient, are not accurately reproducible in large-scale manufacture, and therefore the frequency characteristics are variable in the region of resonance modes. In an effort to improve matters some manufacturers have turned to materials having a higher stiffness to weight ratio than is obtainable with felted paper, the idea being to make the cone so stiff and light that the inevitable resonances lie outside the frequency range of interest. For this purpose expanded polystyrene has been employed, generally with a reinforcing skin of some other material such as aluminium. The results are rather disappointing as resonances are found to occur within the middle-frequency band and by its very construction the cone is of such a high mechanical impedance that it is very difficult to secure adequate damping.

In the BBC, the loudspeakers types LS5/1A, LS5/2A,‡ and LS3/1A all use a special commercial 15 in. (380 mm) diameter low-frequency unit, and have a crossover frequency of about 1,600 c/s, and some difficulty has been found in obtaining units which will meet the BBC test specification in the 500 to 1,600 c/s region where various resonances occur; furthermore, the axial frequency characteristic in this region is not as smooth as could be desired. It was therefore decided to see whether it would be possible to make, for future designs, loudspeaker units which would have more uniform and more reproducible characteristics than those of the type at present in use.

One of the difficulties restricting the development of paper cones has been the fact that the cost of a new mould has been in the region of £200, making experimental procedure very expensive. It was therefore decided to investigate the use of thermoplastic materials which can easily be made into cones by vacuum forming. For this process changes in mould shape and even new moulds can be made quite cheaply and easily; furthermore, as the raw cone material is made in the form of flat sheets, it should be very uniform and repeatable.

* By colouration is meant a characteristic timbre imparted to the reproduced sound by the loudspeaker; it is believed to arise from excitation of mechanical resonances.

† The LS3/1A is used for outside broadcast monitoring and has a small lightweight cabinet. The design is intended to provide the best compromise between quality and portability.

‡ These are the BBC's current high-quality monitoring loudspeakers. The LS5/1A is the normal floor-standing version, while the LS5/2A is designed to hang above picture monitors in television control rooms.

## 8. Scope of Design

It was explained earlier that the existing low-frequency units were chosen on the basis that they were relatively free from colouration although in fact they were unnecessarily large. It was therefore decided that the new units should be of 12 in. (305 mm) diameter as this size should afford adequate power-handling capacity to meet all requirements. In order to restrict the investigation as much as possible, it was decided to use commercially available chassis and magnet systems, leaving open the choice of voice coil diameter and length, spider constants, and the design of the cone and surround; for the latter two items, the influence of shape, thickness, and material were to be examined.

## 9. Experimental Details

During the period of roughly forty years in which moving-coil loudspeakers have been under development, very little has been published on the various factors which influence the frequency characteristics. One factor which is known,[a] however, is that cones with straight sides are much more likely to generate subharmonics than those which have curved sides and it was therefore decided to start with a cone shape having slightly curved sides, as shown in Fig. 10; the voice coil diameter was 2 in. (50·8 mm).

The primary criterion which was applied to the choice of material was that it should possess a high degree of mechanical damping, for it was argued that since resonance modes were almost certain to occur in the frequency range of interest it was essential that they should be well damped if a uniform frequency characteristic was to be obtained.

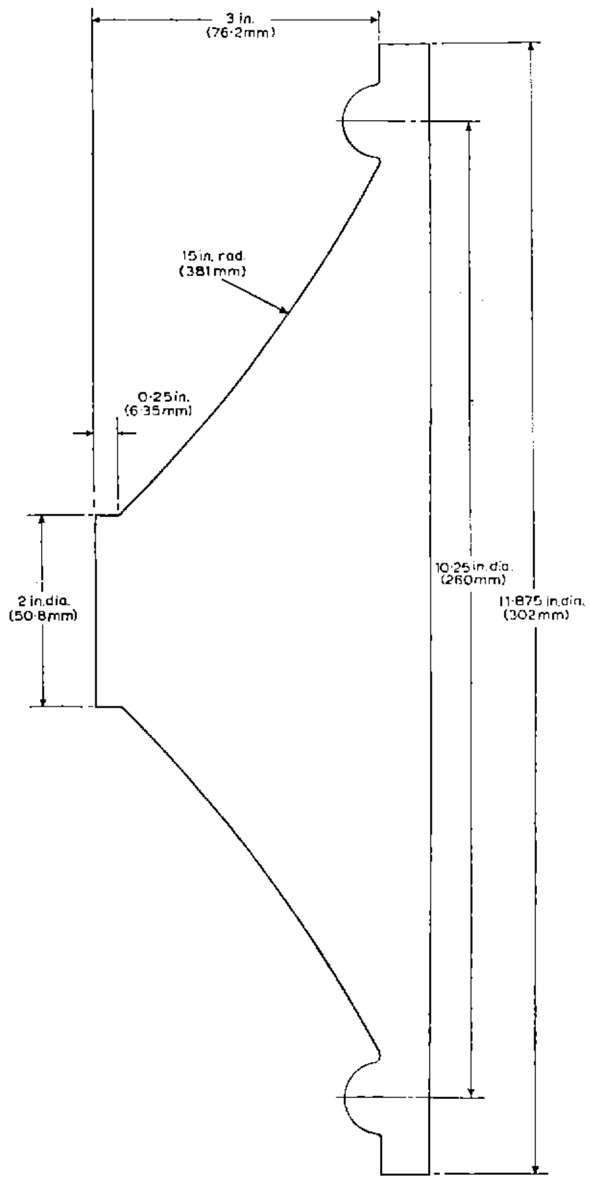


*Fig.* 10 — *Shape of first mould*

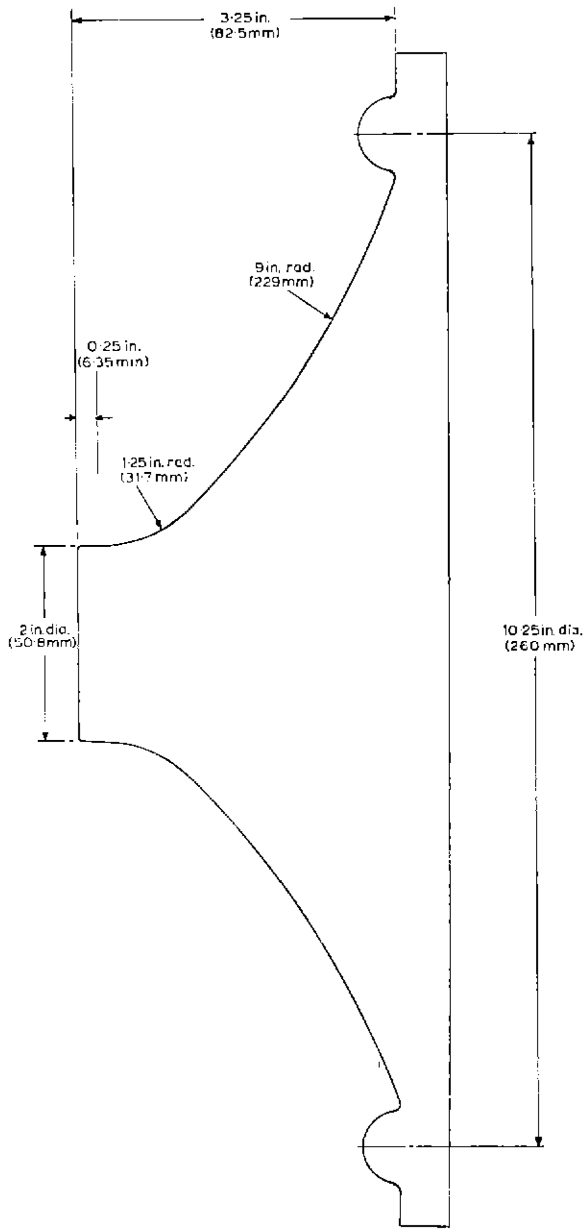


*Fig.* 11 — *Shape of second mould*

The first material to be tried was expanded polythene which is available in sheet form in various thicknesses from $\frac{1}{16}$ in. (1·6 mm) upwards. This material is very light and is characterized by an extremely high damping coefficient. The first experimental models showed axial frequency characteristics which fell off above 500 c/s owing to insufficient stiffness of the material; this result was not altogether unexpected and steps were taken to stiffen the cone. A coat of polyurethane varnish was applied to each side of the material and as a result the frequency characteristic was extended to about 1 kc/s. It will be noted from Fig. 10 that there is a sharp bend in the cone shape near the voice coil, and it was thought likely that flexure was taking place at this point. A further mould was therefore made, of the shape shown in Fig. 11, in which the sharp bend was replaced by a gradual curve, and this resulted in a wider frequency range but the frequency characteristic was rather irregular. Coating the cone again with polyurethane would have improved matters but as more promising results had in the meantime been obtained with other materials, further experiments with this material were abandoned.

Concurrently with the experiments described above, tests were carried out on cones made of 0·02 in. (0·6 mm) thick unplasticized polyvinylchloride (p.v.c.), which is a horny type of material and also with a polystyrene material (Bextrene) of the same thickness which had been toughened by the addition of a synthetic rubber and possessed a higher degree of damping than did the p.v.c. Cones were made with the mould shown in Fig. 10, and the frequency characteristics were measured with the units mounted in an enclosed cabinet similar in volume to that of the type LS5/1A loudspeaker. These characteristics are shown in Figs 12 and 13 respectively. It is evident that the high-frequency range covered was in both cases adequate for the purpose in hand and that the additional damping in the polystyrene was advantageous; further experiments were therefore confined to this material.

All the experiments so far described were made on cones having a surround made of the same material as that of the cone and the irregularities which are seen in Fig. 13 above 500 c/s are due to the presence of resonance modes. The cone can be regarded as a transmission line and resonance modes can occur with the wave motion either in a radial or circumferential direction if it is not properly terminated in a resistive surround; as the required impedance for these two directions is different and the termination must occupy a distance small compared with a wavelength, it will be seen that the problem of designing a good termination is difficult.

The first surround tried was of plasticized p.v.c. 0·02 in. (0·5 mm) thick of the shape shown in Fig. 14, this profile being chosen to allow for fairly large excursions of the cone at low frequencies. The surround was substituted for

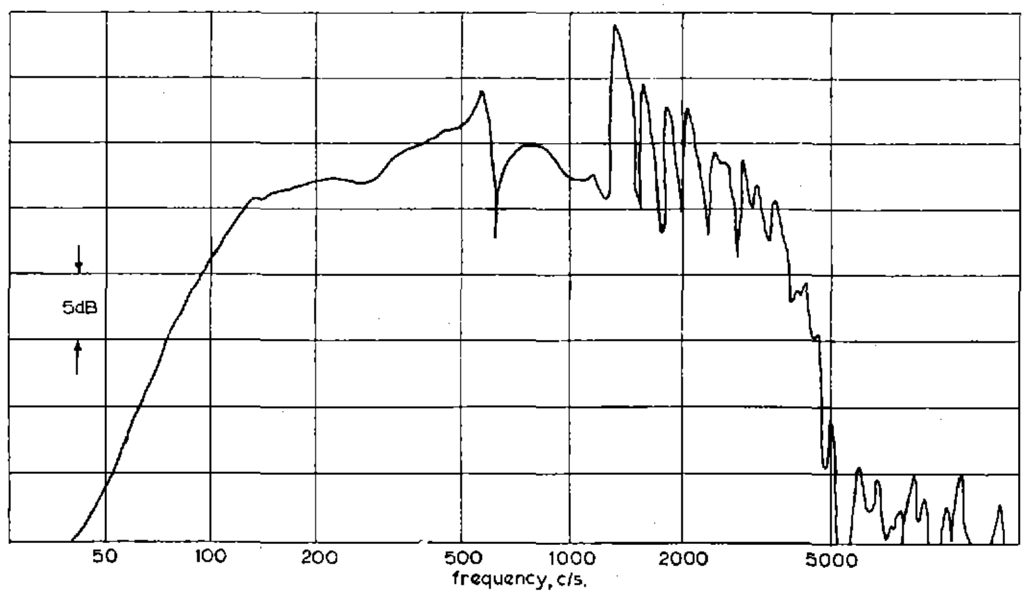


*Fig. 12 — Axial frequency characteristic of unplasticized p.v.c. cone from Mould No. 1*

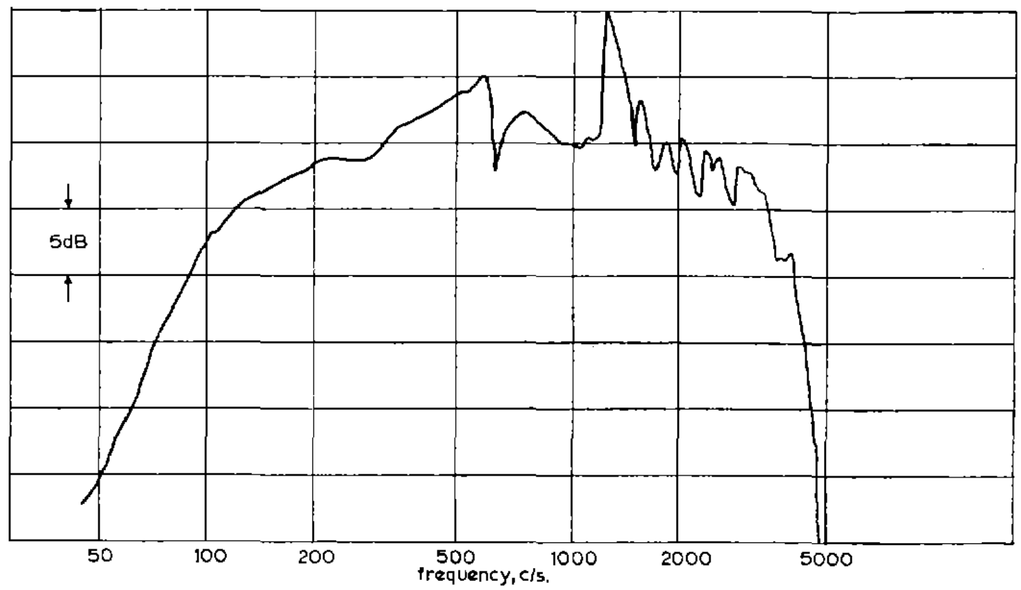


*Fig. 13 — Axial frequency characteristic of Bextrene cone from mould No. 1*

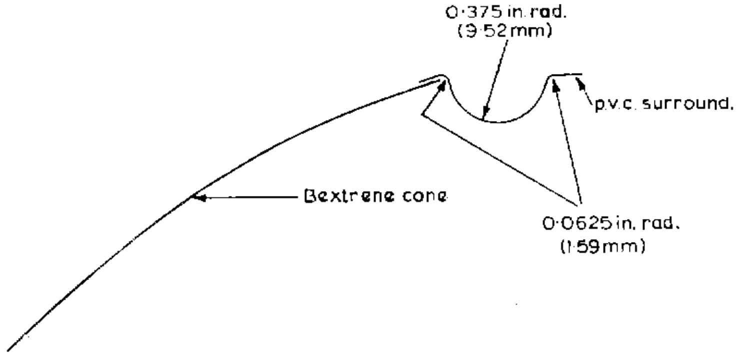


*Fig. 14 — Shape of first p.v.c. surround*

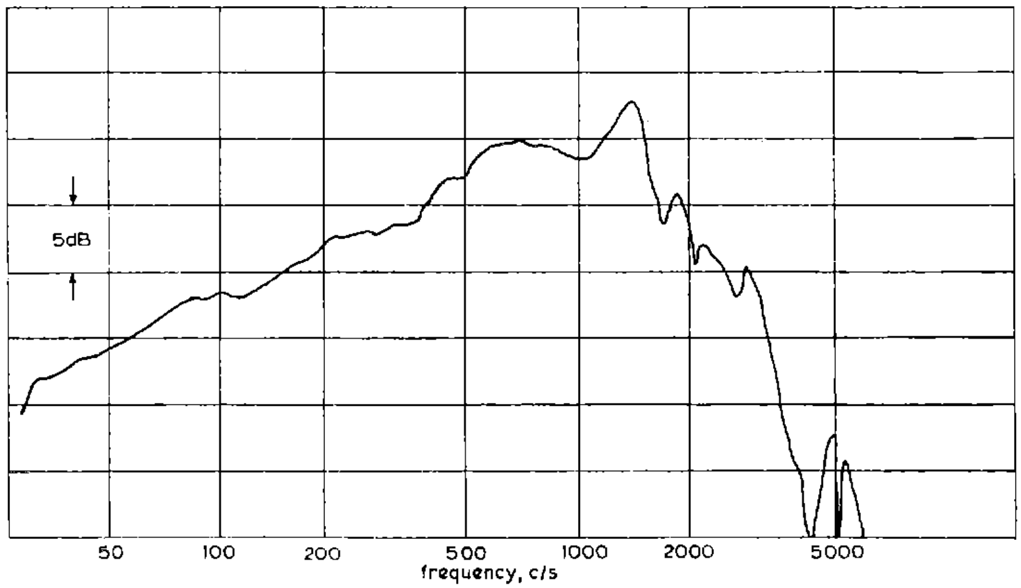


*Fig. 15 — Axial frequency characteristic of Bextrene cone from mould No. 1 fitted with p.v.c. surround of shape shown in Fig. 14*

the integral surround on the polystyrene cone previously used to obtain the curve in Fig. 13 and the resulting axial frequency characteristic is shown in Fig. 15. It will be seen that the curve is considerably smoother than that of Fig. 13 but that the high-frequency response is reduced, probably due to the surround damping out resonance modes; on the other hand, as would be expected, the bass range is extended to lower frequencies. The fact that the axial characteristic rises with frequency is largely due to the directivity increasing with frequency and the concentration of more of the sound energy on the axis. Experiments with a cone material of twice the thickness, i.e. 0·04 in. (1·0 mm), showed that it was possible to recover the high frequency response, but the response was more irregular and the sensitivity lower owing to the greater mass. Cones were then made with 0·02 in. (0·5 mm) material to the second shape mould, shown in Fig. 11; as with the polythene material, the change in shape resulted in an increase in the high frequency response, as shown in Fig. 16. The dip in the curve at 250 c/s was thought to be partly due to a circumferential mode and this was checked by stroboscopic examination. Further evidence was obtained by making a cone with a small turnover at the edge; this had the effect of stiffening the cone edge, thereby increasing the Q and producing an increase in the depth of the dip.

The effects of small changes in the shape of the cone and in the diameter of the voice coil were investigated and it was found that neither of these two factors was critical.

A large number of experiments were then carried out, using surrounds of differing materials, thickness, and pro-

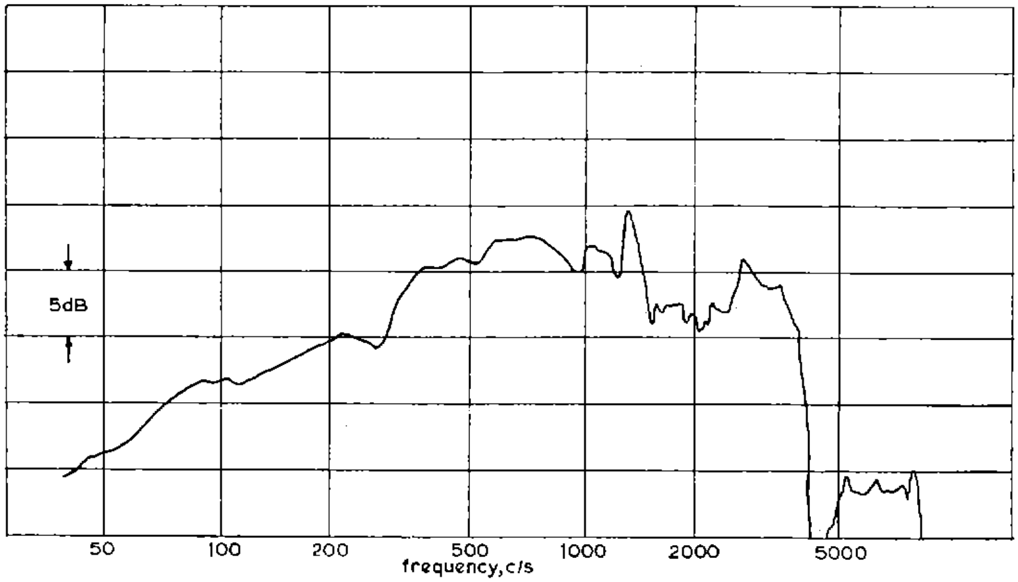


*Fig.* 16 — *Axial frequency characteristic of Bextrene cone from mould No.* 2 *fitted with p.v.c. surround of shape shown in Fig.* 14

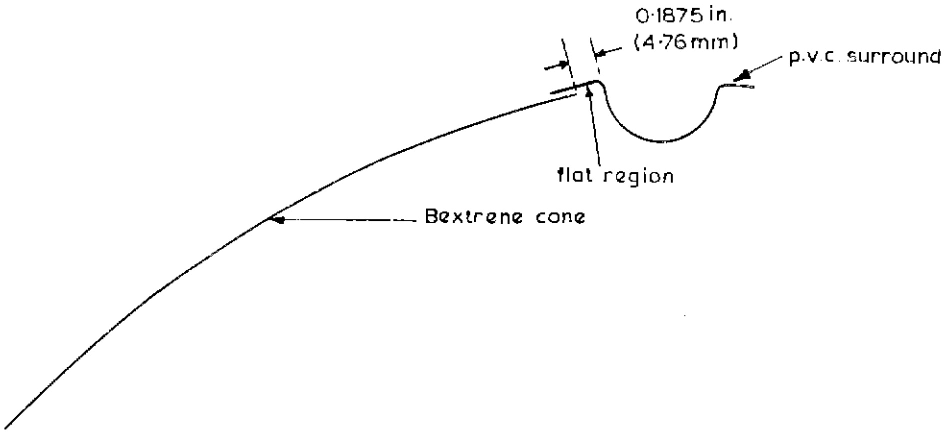


*Fig.* 17 — *Shape of second p.v.c. surround showing flat region*

file in an attempt to damp out the mode at 250 c/s. It was finally discovered that with a suitable surround material better damping could be obtained if, as shown in Fig. 17, a small flat region was left before the turnover of the surround commenced. This flat region has the effect of introducing a shunt arm, as indicated in Fig. 18, consisting of a resistance and compliance, in parallel with the mass, compliance and resistance of the surround proper. The axial characteristic with this surround, shown in Fig. 19, is appreciably smoother than that obtained from commercial 12 in. (305 mm) units, especially in the region above 500 c/s; the sensitivity is about the same as that of the 15 in. (380 mm) unit referred to earlier. The power-handling capacity and transient response were then tested. Mounted in a closed cabinet, the unit was able to take the

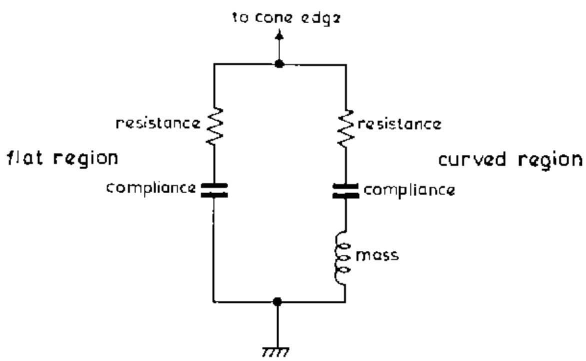


*Fig.* 18 — *Mechanical circuit diagram of surround*

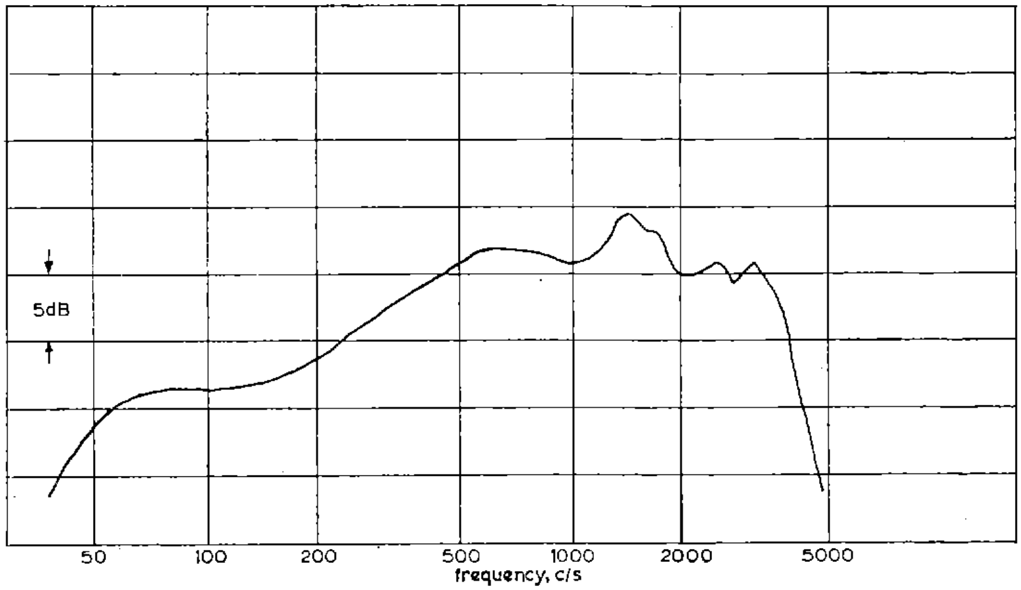


*Fig.* 19 — *Axial frequency characteristic of Bextrene cone fitted with p.v.c. surround of the type shown in Fig.* 17

full output of a 25-watt amplifier down to 70 c/s without obvious amplitude distortion when the waveform was observed on an oscilloscope. Chopped-tone transient response tests[b] showed the unit to be free from serious resonances below 3 kc/s.

Four units were then made to check the reproducibility of this form of construction; the axial frequency characteristics did not differ from one another by more than $\pm\frac{1}{2}$ dB from 75 c/s to 1,250 c/s and $\pm 1$ dB from 30 c/s to 2 kc/s. It was therefore decided to design a complete loudspeaker employing a unit of this type for the low frequencies and to carry out listening tests. Manufacturing details are given in the Appendix.

## 10. Tests in LS5/1 and LS3/1 Cabinets

(*a*) *LS5/1A* (*Studio-type Loudspeaker*)

The 15 in. (380 mm) unit in an LS5/1A loudspeaker was replaced directly by the new 12 in. (305 mm) unit. A slight excess of output in the middle frequencies was corrected by means of a resistor which was originally designed to be adjustable for this purpose. A small dip in the axial response at 1,750 c/s was traced to the effect of the 7 in. (178 mm) wide slot in front of the unit.

(*b*) *LS3/1A* (*Outside-broadcast Loudspeaker*)

When the 15 in. (380 mm) unit in an LS3/1A loudspeaker was replaced by the new 12 in. (305 mm) unit, the response in the region 400 c/s to 800 c/s was found to be somewhat excessive as with the LS5/1A cabinet. To overcome this, it was found necessary to change the values of several components in the crossover network.

## 11. Results of Listening Tests

The two loudspeakers described were given listening tests in Kingswood Warren A.F. Section Listening Room using recordings of speech from dead surroundings and recorded orchestral items; they were judged to be significantly superior to their LS5/1A and LS3/1A counterparts and were therefore offered for an extended field trial. Reports have been very favourable and in particular comments have been made regarding the freedom from colouration of the bass response compared with the corresponding loudspeakers employing the 15 in. (380 mm) unit.

## 12. Cost

The cost of the materials for the cone and surround is only a few shillings, which is a small fraction of that of the complete unit.

## 13. Conclusions

Experiments have been described which have led to the production of a 12 in. (305 mm) low-frequency unit of performance believed to be superior to that of any known commercial product. The cost of production of the cone and surround is only a small fraction of that of the magnet system and the price of the complete unit should be no greater than that of corresponding commercial products.

## 14. References


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b. Shorter, D. E. L., **A Survey of Performance Criteria and Design Considerations for High Quality Monitoring Loudspeakers,** *Proc. I.E.E.*, 105, Pt B, No. 24, Nov. 1958, pp. 607 to 623.

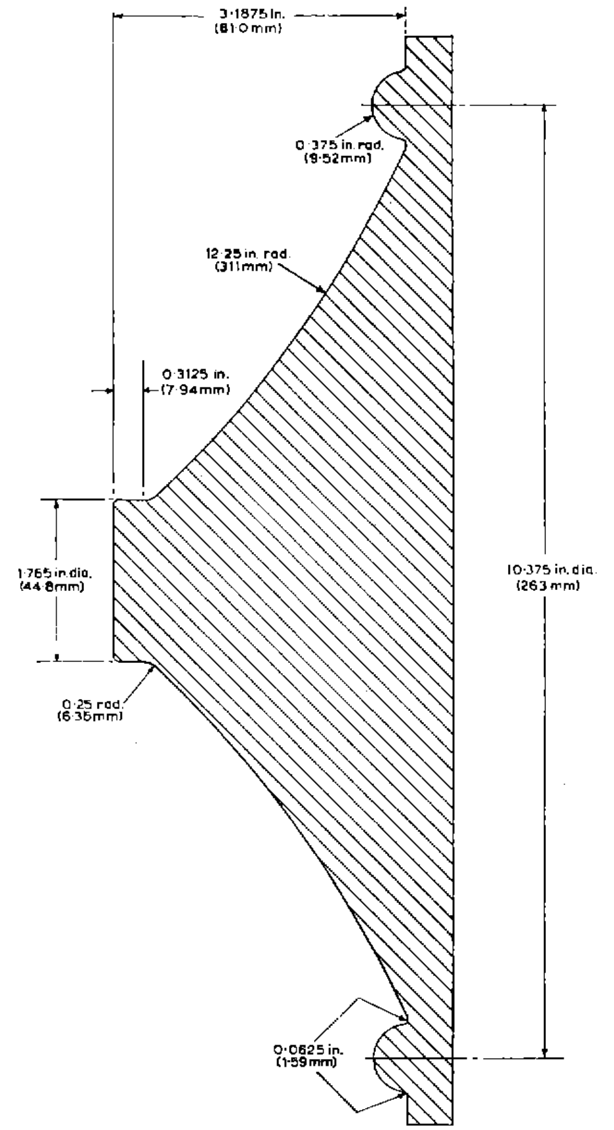


*Fig. 20 — Shape of final mould for cone and surround*

# APPENDIX C

### Materials

The cone is made from Bextrene sheet type 234/2437, 0·02 in. (0·5 mm) thick, obtainable from Messrs BX Plastics Ltd, Higham Station Avenue, Chingford, London, E.4. The surround is made from Nappatex 0·02 in. (0·5 mm) thick, obtainable from Commercial Plastics Ltd, Berkeley Square House, Berkeley Square, London, W.1.

### Components

*Chassis and Magnet System*

The chassis and magnet system is made by Goodmans Industries Ltd, Lancelot Road, Wembley, Middlesex.

*Voice Coil/Spider Sub-assembly*

This also is made by Goodmans Industries Ltd.

*Cone*

The cone is shaped by vacuum forming, employing a drape process to the mould whose shape is given in Fig. 20. Prior to forming, the material is heated for 20 seconds by a radiant heater which, at the working level, gives a temperature of 180°C at the front and 160°C at the rear of the sample. After cooling, the cone is removed and trimmed as shown in Fig. 21(*a*).

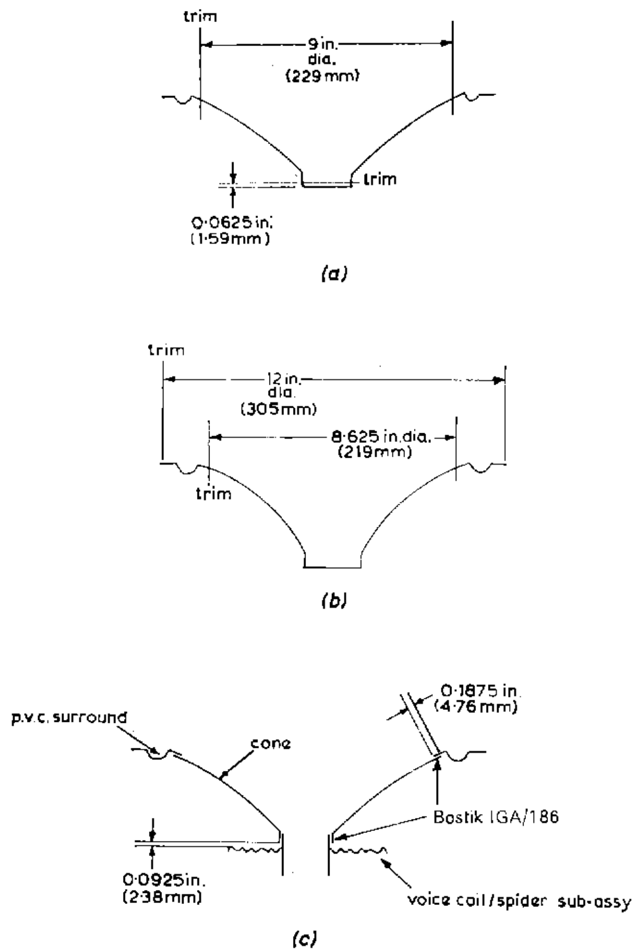


*Fig. 21 — Assembly of cone, surround, and voice coil*

*Surround*

The surround also is shaped by vacuum forming using a mould of the profile given in Fig. 20. The heating time, for the same radiant heater as described above, is 18 seconds. After cooling, the surround is trimmed as shown in Fig. 21(*b*).

### Assembly

*Voice Coil/Spider Sub-assembly to Cone*

These components are mounted on a jig to ensure concentricity and are fixed together with Bostik 1GA/186.

The position of the voice coil former on the cone is indicated in Fig. 21(*c*).

*Cone to Surround*

The position of the cone relative to the surround is also indicated in Fig. 21(*c*); a thin layer of Bostik 1GA/186 is used as the adhesive.

*Cone Assembly to Chassis*

The cone sub-assembly is mounted in the chassis with the voice coil concentric in the magnet air gap. The surround and spider are fixed to the chassis by the Bostik adhesive or by clamps. If all previous assemblies have been correctly carried out, the spider should be undeflected.

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