RADIOTRONICS

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LABORATORY REPORT ON LEAK TL12 MAIN AMPLIFIERS

WITH A DISCUSSION ON STABILITY, OVERSHOOT AND RINGING

by F. Langford-Smith and A. R. Chesterman

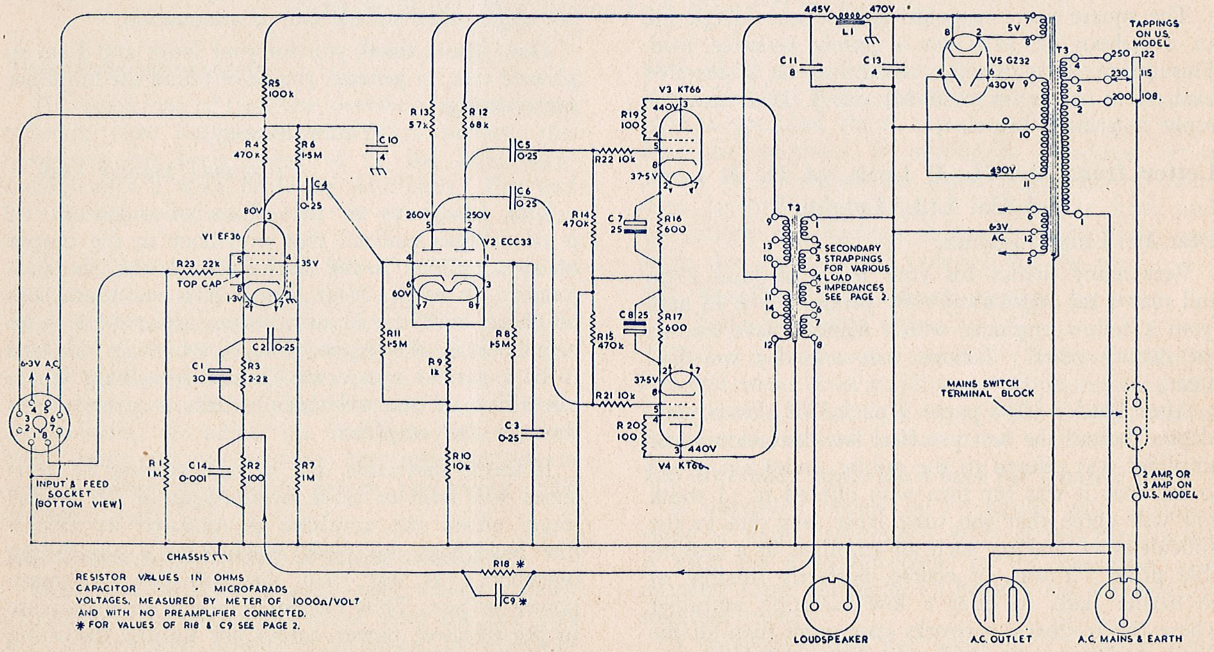
This amplifier has for many years been regarded by the authors as one of the world's best. It has a triode output stage with all the advantages which this confers when driving a loudspeaker load. It has extremely low non-linear distortion — the measured value at 12 watts output was less than the specified figure of 0.1% total harmonic distortion at 1000 c/s.

At low frequencies the performance is very good indeed, the rated output of 12 watts being obtained down to 30 c/s with THD not greater than 0.2%. At 10,000 c/s the total harmonic distortion reaches 3.7% at 12 watts output but, since music would never provide full power at such a high frequency, the THD at half power output, about 0.6% at 6 watts, provides a more realistic figure.

The effect of unbalanced direct currents on the total harmonic distortion was not measurable up to 20 mA at 1000 c/s but it increased the THD from 0.12 to 0.42% at 30 c/s. This performance is good.

The linearity characteristic is almost perfectly straight up to the rated power output, thanks largely to the triode output stage, and the full amount of feedback is therefore sustained up to this level at middle frequencies.

The negative feedback at 1000 c/s is 26 db, and this is maintained very well down to 30 c/s (25 db), but falls of appreciably at 15,000 c/s (17 db). This



RESISTOR VALUES IN OHMS
CAPACITOR " " MICROFARADS
VOLTAGES. MEASURED BY METER OF 1000Ω/VOLT
AND WITH NO PREAMPLIFIER CONNECTED.
* FOR VALUES OF R18 & C9 SEE PAGE 2.

Circuit diagram of Leak TL12 Main Amplifier.

is one of the factors responsible for the increased distortion at high frequencies.

At lower levels the distortion can be expected to fall off in the conventional Class A triode manner. In this, it differs from "Ultra-Linear" amplifiers in which the distortion usually rises somewhat from full power output to some value of reduced output.

The frequency response with and without feedback indicate that, on a purely resistive load, the feedback is negative all the way from 1 c/s to the highest frequencies. The minimum negative feedback at low frequencies is 6 db about 3 c/s, and at high frequencies about 0.5 db at 65,000 c/s. This is a very creditable performance indeed, since the great majority of amplifiers have positive feedback at one or other or both of the extreme frequencies.

However, the amplifier was unstable with our admittedly very severe condition of inductive loading (dummy loudspeaker load). It was also unstable with a shunt capacitance of 0.15 μF across 15 ohms or 0.1 μF when shock excited. Very few amplifiers are absolutely stable, that is, stable under any possible load conditions. The fact that some are absolutely stable indicates that this is an ideal capable of achievement. It is too early for us to attempt to lay down any specific performance on reactive loads; at some later date we hope to publish the measured reactive components of loudspeakers with various types of cross-over networks and from these results to derive a criterion for testing amplifiers for stability. It is also desirable to take into account the capacitive loading of an electrostatic loudspeaker.

With any capacitance shunted across the load resistance, the feedback at very high frequencies becomes positive in this amplifier.

The square wave response is excellent except for an overshoot of 34% on a purely resistive load. This point, and also the instability on a reactive load, were taken up with Mr. H. J. Leak and his reply is printed below.

Letter from Mr. H. J. Leak, of H. J. Leak and Co. Ltd., London

Dear Mr. Langford-Smith,

Very many thanks for your letter of June 27th, and may I say right away how pleasant it is to hear from a fellow engineer whose name I have known for twenty years? I hope that one day we shall meet.

After Black's 1934 paper a period of eleven years elapsed before the first practical low-distortion audio amplifier was offered to the public, and I am proud to say that it was my firm who offered it. I think you will agree that the time lapse was due to the difficulties of making such an amplifier at a reasonable price. It was, of course, perfectly feasible, at an earlier date, to offer a low-distortion amplifier where the feedback networks cost more than all the components in the forward chain! Any design which I have offered has had to fulfil three criteria:—

(1) That it sounds excellent under commonly found working conditions, i.e., with conventional loudspeaker systems connected to the amplifier by short leads.

(2) That it stays that way.

(3) That the amplifier will, on test, meet its published performance figures.

It is quite certain that tests can be applied which the amplifier will not meet perfectly when the gauge of perfection is a theoretical one.

I agree with you that there is some overshoot in the amplifier, but we have been quite unable to detect any difference, on an immediate change-over, between an amplifier with overshoot and one with a flat top, and, in practice, on reasonably-priced amplifiers it appears difficult to get a flat top whilst still maintaining stability in the high frequency region.

I also agree with you that oscillation will occur when a 15 ohm resistive load is shunted by a capacitance of 0.1 mfd. or over. I do not consider this of practical importance for the reason given above, that is, a loudspeaker is normally connected by short leads of low capacitance. I do agree that some dual loudspeakers with quarter-section crossover networks do not look like a pleasant load to some feedback amplifiers! Though we have not had instances of instability with such loudspeaker systems (and we have sold thousands of amplifiers in the States, where there are such loudspeakers), we do actually, in our service sheets, advise people to use constant-resistance half-section dividing networks. Incidentally, have you ever made any voltage/frequency tests on such networks when they have loudspeaker windings connected to them? Resonance commonly occurs within the pass bands unless damping resistors are fitted. This can be done with but slight effect on the rate of attenuation.

Once again, thank you for your letter and I am so pleased that, in general, you have found the amplifier not wanting.

Yours sincerely,

(Signed) Harold Leak.

This brings us to the effects of overshoot. It is not always realized that overshoot in the output of an amplifier is fed back through the feedback loop to an earlier stage where it is combined, out of phase, with the input voltage. Since there is no overshoot in the input voltage, which is assumed to be a perfect square wave, there is nothing which can eliminate the overshoot, which is passed right through the amplifier.

It seems inevitable that a large amount of overshoot will tend to cause overloading in the output stage, unless the amplifier is operated at such a low level that the peak input voltage (including overshoot) is less than the amplifier maximum power output. Thus overshoot results in a decrease in the effective power output for limited distortion when reproducing sharp transients, and is therefore undesirable.

There seems to be no doubt that, with amplifiers having no positive feedback at any frequency, there are only two possible causes of overshoot.

1. The time delay between the application of a pulse to the input terminals and the time when the fed-back voltage reaches the same point. This time delay will vary from almost zero at mid-frequencies to that occurring with the highest significant frequency component of the pulse which completes the feedback loop.

2. The output transformer, which we are inclined to blame for most of the overshoot.

On the other hand there is no doubt whatever that all of the ringing in an amplifier, with no positive feedback at any frequency, is due to the transformer. We stress the importance of distinguishing between overshoot and ringing. If there is no overshoot there is normally no ringing (although we have known cases where the overshoot was suppressed by some network in the amplifier, leaving an irregular "wiggle"). However, there is no direct connection between the amount of the overshoot and the amount of the ringing — for example, with different output transformers having approximately the same overshoot there may be quite marked differences in the amount of ringing. It appears that both overshoot and ringing can be reduced to a considerable extent by careful transformer design. Of course, with any one transformer and fixed arrangement of the windings, reducing the overshoot must result in some increase in rise time*, and the designer in this case is forced to adopt some compromise. However, it appears to be possible, by suitable internal arrangement of the windings, to achieve the optimum condition for both small and overshoot and rapid rise time. This is a point which would repay careful investigation by transformer designers.

We would be pleased to receive comments from our readers on this subject, which has not been adequately treated in the literature.

The mechanical design and finish of the Leak TL12 amplifier are quite outstanding.

* See Ruben Lee "Electronic Transformers and Circuits", John Wiley and Sons, New York, 1947.

Details of electrical performance are given in our standard test manner, and comments on these tests are given below.

See June '56 issue, P. 69 for results with a loud speaker load.

COMMENTS ON TESTS USED IN THE RADIOTRONICS LABORATORY ON MAIN AMPLIFIERS

By F. Langford-Smith and A. R. Chesterman

The following remarks refer to the amplifier test form used elsewhere in this issue for the Leak Model TL12 Amplifier.

1. Square wave tests

The usual tests of rise time, overshoot and transient recovery time are made at 5 Kc/s because this frequency has been found to be the most satisfactory over a wide range of amplifiers. Top and bottom tilt are measured at 50 c/s for a similar reason.

An article entitled "Square Wave Testing" appears in Radiotronics 20.6 (June, 1955), page 65, giving detailed information on this test. The generator used for these tests is noteworthy because it has a very rapid rise time (0.05 μ sec.).

This test is carried out first because, in our circuit development, we adjust the feedback network and some other circuit constants for optimum square wave response at 5 Kc/s before proceeding with the other tests.

1.2. Shunt capacitance to cause oscillation

This test is first carried out without shock excitation. The largest capacitor used for this test is 1 μF shunted across 12-16 ohms, or inversely proportional to this value for lower impedances. This gives, in our opinion, the highest phase angle ever likely to be reached under any condition of load. The fact that a particular amplifier is unstable with a specified shunt capacitance does not mean that the amplifier is necessarily defective. It is hoped to investigate the input impedance of cross-over networks, supplying a loudspeaker load, and to publish the findings in some future issue, and from this to develop a criterion for the test.

1.3. Stability when shock excited by a 5 Kc/s square wave

This is a more severe test than 1.2 above. Stability is noted under three conditions — short-circuited and open-circuited load, and capacitance shunted across the normal resistive load to cause oscillation.

1.4. Partially capacitive load for further tests

If instability occurs in 1.3 above with a stated value of shunt capacitance, 80% of this capacitance is used for a measurement of the overshoot and recovery time, and later (2 below) for a frequency response curve.

If instability does not occur in 1.3 above, then the shunt capacitance giving the greatest overshoot is selected for these same tests.

1.5. Purely capacitive load

If stable, the amplifier is tested for overshoot. The result is only recorded if the overshoot is worse than that with the partially capacitive load (1.4 above).

Absolute stability

An amplifier which is stable under all load conditions covered by 1.2, 1.3, 1.4 and 1.5 above, together with the highly inductive load (9 below) is regarded as being absolutely stable.

2. Frequency response

The frequency response from 1.1 c/s up to several hundred kilocycles is plotted in Fig. 1 with and without feedback for both resistive load and partially capacitive load (as 1.4 above). In each case the difference curve (response with feedback minus response without feedback) gives the actual feedback when a single feedback loop is used.

If multiple feedback loops are used, the curve "without feedback" is for the condition with the main feedback loop from the secondary open-circuited, and also all other feedback loops rendered ineffective by by-passing or other convenient means, unless otherwise stated.

When the response with feedback is greater than that without feedback, the feedback is positive.

The feedback is tabulated at 30, 1000 and 15,000 c/s, and sufficient negative feedback should be sustained out to the limits of the audible band to keep the distortion low.

3. Phase shift versus frequency

This is quite conventional, with two curves in Fig. 1 giving phase shift with and without feedback.

4. Linearity (or transfer) characteristic

The output voltage versus input voltage is shown in Fig. 2. The shape of the curve as it approaches or exceeds the overload point is a function of the type of voltmeter used to measure the output voltage. The authors specify a peak reading voltmeter to read the distorted output voltage because in their opinion it gives a more significant result. As would be expected, a rectifier type instrument gives greater readings on a distorted waveform than a peak reading one, because the distortion products add to the fundamental and hence sometimes result in readings above the straight line in the vicinity of maximum power output. An article on this subject will appear in a future issue of Radiotronics.

If a linearity characteristic of the form adopted by us (using a peak reading voltmeter for reading the output voltage) is straight up to maximum power output, then the full amount of feedback is applied at 1000 c/s at all levels up to maximum power output. This statement does not necessarily apply in other cases.

The usual test by radio engineers is to show the linearity (or transfer) curve on the oscilloscope. This also is a peak-reading device.

5. Total harmonic distortion versus power output

The curve for 1000 c/s is shown in Fig. 3.

Before plotting the total harmonic distortion in Figs. 3 and 4, the oscillator THD was subtracted from the readings. This leads to some inaccuracy at very low distortion readings which will be found to differ from the results using a Wave Analyser given in Fig. 6*. There is a further source of difference in that Figs. 3 and 4 include hum and noise, whereas Fig. 6 does not.

6. Total harmonic distortion versus frequency (with curves of constant power output)

The curves are shown in Fig. 4, and are quite conventional. A choice had to be made between curves of constant distortion and curves of constant power output. The pros and cons were very carefully considered, and we believe that the one adopted has distinct advantages because, amongst other reasons, an amplifier is rated at an output of so many watts. It is quite logical to expect the amplifier to give this output over the whole audio range, unless a more limited frequency range is specified. In either case, the amplifier is expected to deliver its rated output over its rated frequency range. A quite secondary effect is the increase in distortion which occurs at low and high frequencies compared with that at 1000 c/s.

Curves have been drawn for a number of output levels below that of maximum power output, and they can therefore be applied very readily to any commercial application.

7. Intermodulation distortion

These readings from an Altec-Lansing Intermodulation Tester are included because they are very widely used, particularly in U.S.A., largely because they can be made on quite inexpensive equipment. See our comments on 8 below.

8. Ratio of intermodulation distortion (IMD) to total harmonic distortion (THD)

This ratio curve is being plotted for every amplifier we test, whether published or not. In every case tested, this ratio falls from a maximum at some medium level down towards unity, or in some cases even below unity, as maximum power output is approached or slightly exceeded. It is well known that the audible (subjective) distortion in both triodes and pentodes operating in Class A_1 increases rapidly as the overload point is approached.

Every known authority agrees that, with a kink in the linearity characteristic, the THD does not increase sufficiently rapidly to give a true subjective relationship — hence the attempts at "weighted distortion" measurements (Ref. 1).

What we are looking for is some method of indicating distortion which rises more rapidly than THD as the overload point is approached. .That is to say, the ratio of this imaginary new method of measuring distortion to THD should increase as the overload point is approached. Now the measurements which we have made all indicate that IMD does just the opposite — the ratio falls as the overload point is approached. Hence we are driven to the conclusion that IMD as measured on a conventional IM tester is a less reliable indication of subjective distortion than THD. No criticism is

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* This figure will appear in the next issue.

made of Intermodulation Testing as such, but only of a type of instrument which produces results which are far from proportional to the actual distortion.

Further information will appear from time to time. See also 15 below.

9. Effect of dummy loudspeaker load

The purpose of this load is to simulate the effect on distortion of the varying impedance and phase angle of a loudspeaker load. Some measurements were made of typical loudspeakers, and the following was taken as a guide:

Impedance at bass resonance $= 10Z_{400}$.
where $Z_{400} =$ impedance at 400 c/s.
Phase angle in vicinity of bass resonance: from 60° inductive through 0° to 58° capacitive.
Impedance at 10,000 c/s $= 4Z_{400}$.
Phase angle at 10,000 c/s = 42° inductive.

Since the distortion caused by an elliptical load is exactly the same for inductive and capacitive loads provided that they have the same phase angle, it was decided to adopt an inductive load in the dummy loudspeaker load (R and L in series) since a capacitive load tends to cause instability in many amplifiers.

It was finally decided that all the desired conditions could be simulated by values of Z_L, $4Z_L$, and $10Z_L$ with choice of phase angles 0° and 45°, Z_L being numerically equal to the normal resistive load R_L. The test is made at a single frequency only (1000 c/s). It was noticed that in some cases there was distinct flat-topping with $10Z_L$, but the total harmonic distortion was not very much greater than that with the normal load resistance. Hence the introduction of weighted methods of distortion as described in 15 below.

10. Effect of unmatched output valves

Tests for total harmonic distortion are made at maximum rated power output, at frequencies of 30 and 1000 c/s, for out of balance d.c. currents of 5, 10, 15 and 20 mA. The lower frequency of 30 c/s was selected as the usual limit for high-fidelity amplifiers. It was felt that a test at this low frequency would be more significant than one at higher frequencies alone, and tests at both low and high frequencies were not necessary.

11. Hum and noise

Being a main amplifier, it was regarded as quite sufficient to measure the total hum plus noise, expressed in decibels below rated power output and below 1 watt.

12. Output resistance, damping factor and damping ratio

The output resistance recorded is that referred to the secondary. The formulae used for calculating damping factor and damping ratio are given in the amplifier test form. The use of the newer term damping ratio in place of the older term damping factor is set out in an article which has recently been published (Ref. 2).

13. Regulation

Some considerable thought was given to the subject of regulation of the output voltage as being of significance with a loudspeaker load with an impedance variation of the order of 10 to 1. It is true that much the same information may be obtained from the output resistance but the two are not precisely the same since the output resistance is not constant but a function of the output power.

Tests were made on two extreme types of amplifiers, on the one hand the Leak TL12 as having a triode output stage, high feedback and very low output resistance (Amplifier A) and on the other hand a pentode output stage with a rather low amount of feedback (Amplifier B (Ref. 3). Readings were made with a normal load resistance (R_L), $10R_L$ and infinity (open-circuited load), and are tabulated below. It will be seen that the difference between the output voltage with $10R_L$ and open-circuited load is small even with Amplifier B. Consequently it was decided to adopt measurements of output voltage with normal R_L and open-circuited load as being simpler and readily performed by anyone. These were put in the form of regulation, following the British definition, expressed as a percentage.

Amplifier	A			B		
Load resistance	R_L	$10R_L$	∞	R_L	$10R_L$	∞
Output voltage	100%	102.5%	102.7%	100%	188%	200%

The form used by some American authorities, expressing the regulation in terms of decibels, was not favoured.

14. Individual harmonics

Harmonics up to the thirteenth are measured and recorded at various output levels.

In this test, the particular harmonic being measured is attenuated by a parallel-T network, tuned to the harmonic, between the oscillator and the input terminals to the amplifier. By this means, the effect of oscillator distortion is made so low

1. Radiotron Designer's Handbook, 4th ed. pp. 610-611.
2. Langford-Smith, F. "Damping factor—a new approach". * Radiotronics (July, 1955). This is also being published in the Wireless World as a letter to the editor.
3. Hansen, I. C. "High Quality L-P Amplifier". Radiotronics, February, 1952, p. 23. Converted to pentode operation for this test.

Note

Comments and queries from radio engineers are specially requested while our test methods are somewhat fluid, during the development of a standardized procedure.

as to be unmeasurable. In the oscillator used for these tests, the only measurable harmonics are the second and third, so that this precaution is not required for higher order harmonics.

15. Distortion using harmonics up to thirteenth

Three methods of indicating distortion are used here, and shown as curves in Fig. 6.* The formulae are given in the Amplifier Test Form:

A. Normal unweighted total harmonic distortion (THD).

B. Normal weighted (WHD) see Ref. 1.

C. Special weighted (SWHD). This follows the weighting arrangement suggested by Shorter (Ref. 1) using the square of the harmonic power, with the multiplying factor adjusted, as for the normal weighting method, so that all three methods give the same result if all the distortion is second harmonic.

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* This figure will appear in the next issue of Radiotronics.

15. Total harmonic distortion using harmonics up to thirteenth

(a) Unweighted

$$\text{THD} = \frac{\sqrt{E_2^2 + E_3^2 + E_4^2 + \cdots}}{\sqrt{E_1^2 + E_2^2 + E_3^2 + E_4^2 + \cdots}} \times 100 \qquad (1)$$

This is plotted as curve A in Fig. 6

(b) Normal weighted (W)

$$\text{WHD} = \frac{\sqrt{(2E_2)^2 + (3E_3)^2 + \cdots}}{\sqrt{E_1^2 + E_2^2 + E_3^2 + \cdots}} \times 50 \qquad (2)$$

This is plotted as curve B in Fig. 6

(c) Special weighting method (W^2)

$$\text{SWHD} = \frac{\sqrt{(4E_2)^2 + (9E_3)^2 + \cdots}}{\sqrt{E_1^2 + E_2^2 + E_3^2 + \cdots}} \times 25 \qquad (3)$$

This is plotted as curve C in Fig. 6

Amplifier Test Form

(For use with main amplifiers)

Matched valves and resistive loads used unless otherwise indicated. All a.c. voltages recorded as r.m.s. readings. Output valves in amplifier as supplied were replaced by a pair of bogie matched valves where available. If not available, rating characteristics of both output valves have been measured and tabulated below.

Amplifier—Make: Leak.
Model No.: TL12.
Serial No.:
Rated power output: 12W.
Supplied by: Simon Gray, Radio Division.
Output Transformer: Leak.
Output valves: Bogie matched pair (supplied by Radiotronics Laboratory).

1. Square wave test (at 5 Kc/s unless otherwise indicated).

Measured at 5 watts output.

1.1. Resistive load

Rise time (10% to 90% of peak-peak voltage)	5 μ secs.
Overshoot (percentage of peak-peak voltage)	34%
Average of positive and negative half-cycles:	
Transient recovery time (ringing time)	50 μ secs.
Top tilt* at 50 c/s (percentage of peak-peak voltage)	2-3%
Bottom tilt* at 50 c/s (percentage of peak-peak voltage)	2-3%

* After subtracting any tilt in the generator.

1.2. Capacitance shunt across 15 ohms load to cause oscillation: 0.15 μF

Frequency of oscillation .... 46 Kc/s

1.3. Stability when shock excited by a 5 Kc/s square wave

1.3.1. Load short-circuited: stable, but overshoot much worse.

1.3.2. Load open-circuited: stable; overshoot decreases.

1.3.3. Load shunted by a capacitance: unstable with capacitance of 0.1 μF shunted across 15 ohms. Frequencies of oscillation: 25 and 110 Kc/s.

1.4. Partially capacitive load for further tests

1.4.1. 50% of capacitance to give oscillation when shock existed as 1.3.3. above: 0.05 μF.

Overshoot under these conditions: 55%.

Transient recovery time: 100 μ secs.

1.5. Purely capacitive load: Oscillates.

2. Frequency response 1.1. c/s to 500 Kc/s

Measured with constant input voltage to give 50% of rated power at 1000 c/s down to 20 db attenuation; input increased 10 db for higher values of attenuation.

2.1. Resistive load

(A) Without feedback
(B) With feedback
(C) Difference curve (feedback)

Curves A, B and C are plotted in Fig. 1.

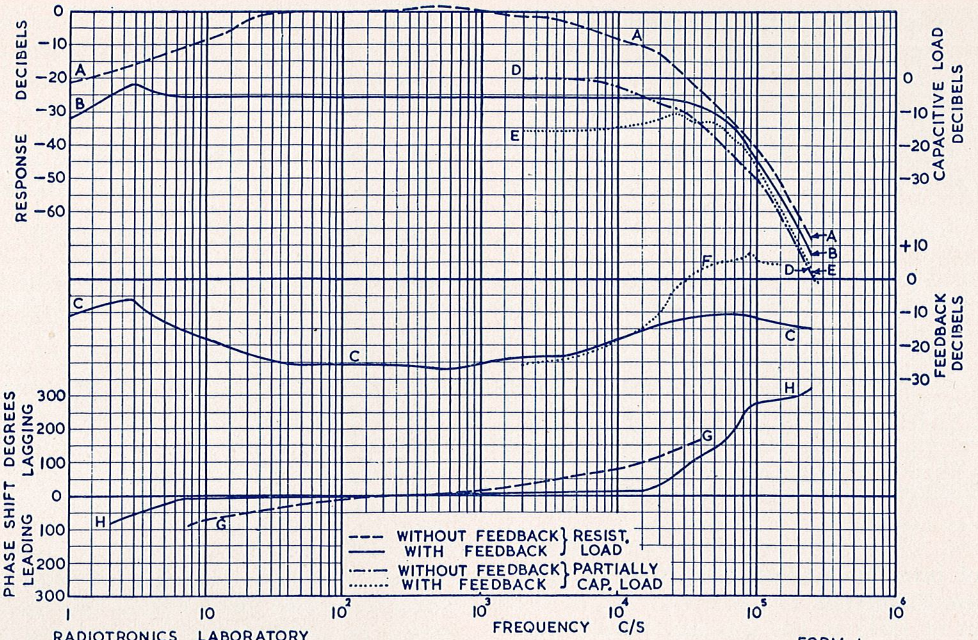
Frequency	30	1000	15000	c/s
Feedback	—25	—26	—17	db

2.2. Partially capacitive load from 1000 c/s to 500 Kc/s

Shunt Capacitance: 0.08 μF.

(D) Without feedback
(E) With feedback
(F) Difference curve (feedback)

Curves D, E and F are plotted in Fig. 1.



RADIOTRONICS LABORATORY AMPLIFIER LEAK TL 12
FIG. 1
FORM 1

3. **Phase shift versus frequency** (from 1.1. c/s to 500 Kc/s)

Resistive load

(G) Without feedback

(H) With feedback

Curves G and H are plotted in Fig. 1.

4. **Linearity characteristics** (output volts versus input volts with power output marked)

At 1000 c/s; up to overload. Output voltage measured with peak-reading voltmeter. The curve is plotted in Fig. 2. Input voltage for rated max. power output (12W) 0.096V.

5. **Total harmonic distortion versus power output**

A curve was plotted, from 1 watt to overload, at each of the frequencies 30, 50, 100, 1000, 5000, 10,000 and 15,000 c/s. The tests were made using a Total Distortion and Noise Meter. The oscillator THD was subtracted from the readings for each frequency before plotting, the values being:

Frequency	30	50	100	1000	5000	10000	15000 c/s
Oscillator THD	0.18	0.14	0.14	0.11	0.11	0.125	0.12 %

The curve for 1000 c/s is shown in Fig. 3, the other curves being used in the preparation of Fig. 4.

6. **Total harmonic distortion versus frequency**

THD versus frequency courves for 2, 10 and 15 watts power output, also for rated max. power output, from 30 to 15,000 c/s, are plotted in Fig. 4.

7. **Intermodulation distortion versus single frequency equivalent power output**

(power output = meter reading × 25/17)

Tests made using Altec-Lansing Intermodulation Tester.

Three curves are plotted in Fig. 5. (1) 40 c/s and 7 Kc/s; (2) 60 c/s and 7 Kc/s; (3) 100 c/s and 7 Kc/s.

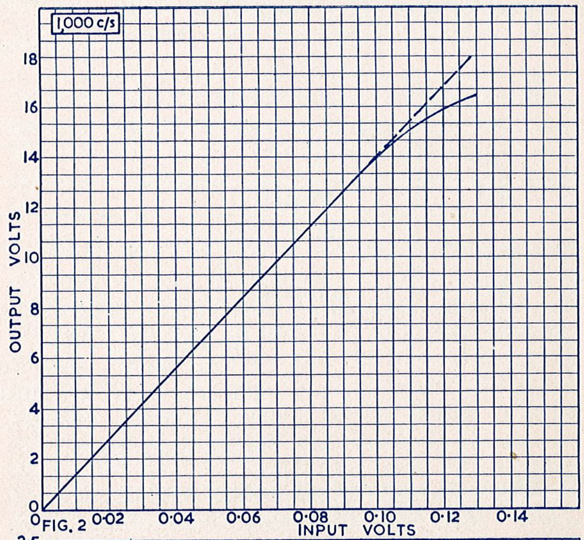
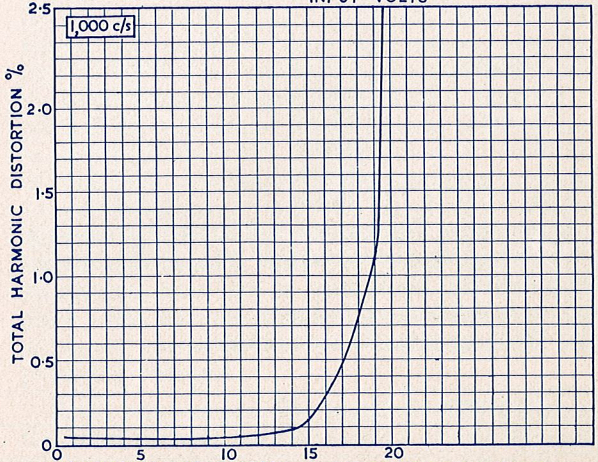
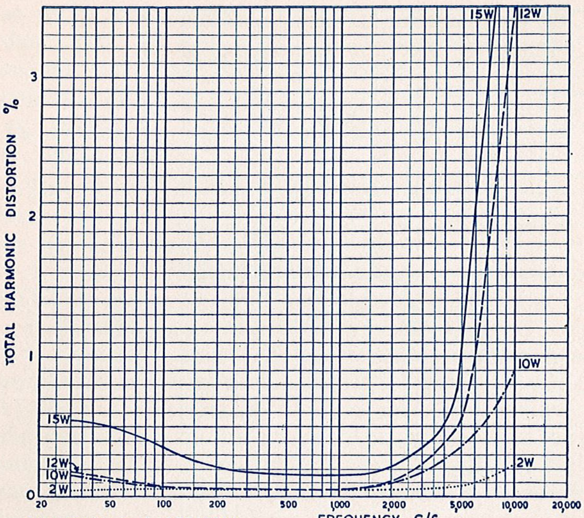


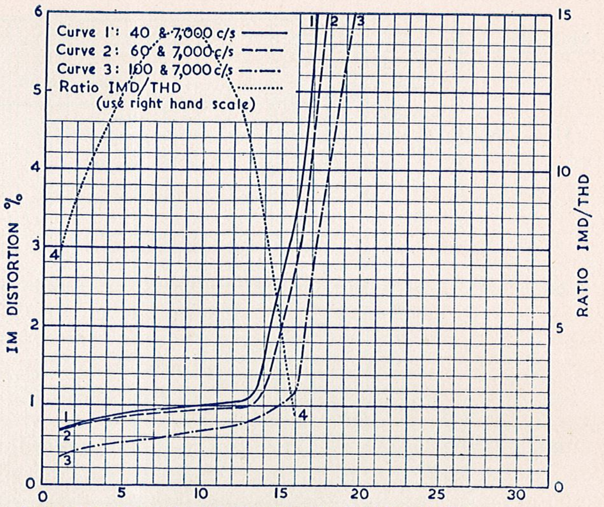
FIG. 2



RADIOTRONICS LABORATORY AMPLIFIER LEAK TL 12
FIG. 3
FORM 2



RADIOTRONICS LABORATORY
AMPLIFIER LEAK TL 12
FIG. 4
FORM 3



RADIOTRONICS LABORATORY
AMPLIFIER LEAK TL 12
FIG. 5
FORM 4

8. Ratio of intermodulation distortion to total harmonic distortion

The ratio of IMD at 100 c/s and 7 Kc/s (see 7.3.) to THD at 1000 c/s (see 5), is plotted as a curve on Fig. 5.

9. Effect of dummy loudspeaker load

The dummy loudspeaker load gives a choice between a resistive load and one with a 45° phase angle, consisting of a resistor and an inductor in series. In each case the impedance is varied from normal, to four times and ten times normal.

Test conditions: Frequency 1000 c/s; amplifier adjusted to give rated power output with normal resistive load.

Phase angle	THD			WHD*			SWHD*		
	Z_L	$4Z_L$	$10Z_L$	Z_L	$4Z_L$	$10Z_L$	Z_L	$4Z_L$	$10Z_L$
0°									
45°	unstable								
	WHD/THD			SWHD/THD					
0°									
45°	unstable								

* See Item 15.

Tests on 0° phase angle were not completed in time for going to press owning to the breakdown of the Wave Analyser. The result will be given in the next issue.

10. Effect of unmatched output valves

Total harmonic distortion at maximum rated power output:

Mismatch	THD 30 c/s	THD 1000 c/s
0	0.12%	0.06%
5 mA	0.17%	0.06%
10	0.20%	0.06%
15	0.29%	0.06%
20	0.42%	0.06%

In amplifiers (such as the Williamson) possessing a bias balancing control, each of these is taken under the alternative conditions:

(a) with Adjustment in centre.
(b) With optimum bias adjustment.

11. Hum and noise

Total hum plus noise:

db below rated power output (12 W)	75 db
db below 1 watt	64 db

12. Output resistance, damping factor and damping ratio

The output resistance (R_{os}) is referred to the secondary.

Nominal load resistance (secondary) $R_{Ls} = 15$ ohms.

Damping Factor (D.F.) is defined as R_{LS}/R_{os}.

Damping ratio (D.R.) is defined as

$$R_{LS}/(R_{LS}+R_{os}).$$

(Note: Damping Ratio is preferred to the older term Damping Factor, since it avoids going through infinity to negative values.)

Frequency	30	50	100	1000	10,000 c/s
R_{os}	0.27	0.27	0.36	0.41	0.24 ohms
D.F.	56	56	41.5	36.5	62.5
D.R.	0.98	0.98	0.98	0.97	0.98

13. **Regulation** is here defined as the difference between the output voltage unloaded and that with normal load, divided by the unloaded voltage, expressed as a percentage (British definition):

Regulation at 1000 c/s 2.7%

14. **Individual harmonics using Wave Analyser**

These tests were not completed in time for going to press owing to the breakdown of the Wave Analyser. The results will be given in the next issue.

The ratios of these two weighing methods to THD are plotted in the upper portion of Fig. 6. Fig. 6 will appear in the next issue of Radiotronics.

RECENT DEVELOPMENTS IN ELECTRO STATIC LOUDSPEAKERS

Most readers of Radiotronics will have read the series of articles by P. J. Walker entitled "Wide Range Electrostatic Loudspeakers", published in the Wireless World, May and June, 1955. Very few, however, would have read the interesting article on a similar subject by H. J. Leak which appeared in "The Gramophone" (May, 1955), which is reprinted below by special permission from Mr. H. J. Leak.

It seems clear that both these two English companies have made an outstanding step forward in the development of electrostatic loudspeakers — one which will put all older types of electrostatic loudspeakers completely in the shade. The distortion is extraordinarily low — only 0.1% for a volume level sufficient for a small hall; this is far lower than that of any competitive type of tweeter. In addition, the frequency response is remarkably smooth and uniform from 2000-16,000 c/s, and only 2 db down at 20,000 c/s on the axis.

We stress the fact that these new loudspeakers are still in the development stage and production is not expected until some time in 1956.

We reprint below the second part of Mr. Leak's article in full (the first part is a general introduction not covering electrostatic loudspeakers).

WHY ELECTROSTATIC Loudspeakers ?

By H. J. Leak, M.Brit., I.R.E.

Electrostatic loudspeakers have been under development for some 30 years, but have not been generally acceptable because of their performance limitations. Comparatively recently these limitations have been largely removed by the development of new materials and techniques, coupled with the conception of ideas. It will greatly help us to grasp the significance of these new developments if we consider the basic form of the earlier electrostatic loudspeakers, pictured typically in Fig. 5.

The isolating capacitor merely serves to prevent the transformer short-circuiting the polarising potential applied across the rigid plate and the moving foil which comprise the actual electrostatic transducer. The high resistance may be several megohms in value because no current is drawn from the polarising source by the loudspeaker, which can be seen to be a capacitor ("condenser"). This resistor also prevents the transformer being loaded by the source of the polarising voltage. This voltage will be several hundred volts or more, and in practice will be derived from the supply mains, but for simplicity a battery is shown in Fig. 5. The air-gap between the rigid plate and the diaphragm will be of the order of a few hundredths of an inch. The area of each plate will be related to the lowest frequency which the loudspeaker is expected to reproduce efficiently; a few square inches will suffice to cover the range from, say, 8 kc/s upwards, but to extend the range downwards to, say, 1,000 c/s will require something more than a square foot. Whatever may be the dimensions and spacing of the plates, we can calculate or measure the capacitance between them, and in practice it will range between a few hundreds and a few thousands of pF. This value will give us the impedance range of the loudspeaker, which behaves as a capacitive reactance. We can now design our step-up transformer to give optimum matching between amplifier and loudspeaker.

We should now have a fair idea of the circuitry, construction and dimensions of what is called a single-sided electrostatic loudspeaker, and we can proceed to examine its modes of behaviour, referring again to Fig. 5. Assume that the high-ratio step-up transformer is temporarily disconnected from the amplifier. If the polarising voltage is now switched into circuit a potential will build up across the rigid plate and the diaphragm, and the resulting electrostatic force of attraction will cause the thin diaphragm to move towards the rigid plate. If this flexible diaphragm is not constrained, as by stretching, it will obviously move into contact with the rigid plate. If the diaphragm is tensioned sufficiently to prevent this collapse, then it will take up a position of equilibrium whose location with respect to the rigid plate will be determined by the ratio of the forces contributed by the polarising potential (towards collapse) and the diaphragm tension (against collapse). It can be shown, experimentally and mathematically, that to ensure stability the diaphragm must not be pulled towards the fixed plate more than one quarter of the distance which separated them before the application of the polarising voltage.[3]

If we now connect the high-ratio step-up transformer to the amplifier the electrical signals from the

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[3] "Eletroacoustics", F. V. Hunt, Harvard University Press, 1954.

latter will cause the diaphragm to move back and forth about the equilibrium position, so producing a sound output. Our immediate interest is the degree of faithfulness of this sound output, which depends on how accurately these backward and forward movements duplicate, mechanically, the positive and negative half-cycles of the electrical signals which cause them. It must suffice to say that it can be shown, experimentally and theoretically, that the degree of duplication is poor (i.e., the distortion in the sound output is high) unless the amplitude of movement of the diaphragm is kept very small.[3] This means that the sound output is small, and the loudspeaker is therefore *effectively* too inefficient to be of practical interest.

There are also other disadvantages arising from our stipulated construction:

(*a*) The layer of air trapped between the diaphragm and the rigid plate adds to the non-linearity of the system.

(*b*) The foil diaphragm will be too heavy to follow quickly the electrical signals if it is made thick enough to obviate extreme fragility, and

(*c*) temperature changes will affect the tensioning of the thin foil diaphragm; a drop in temperature will stiffen it, and a rise may expand it sufficiently to cause the polarising potential to arc across the reduced air-gap.

Therefore, our basic single-sided electrostatic loudspeaker does not appear practical as a high-fidelity reproducer, and this conclusion is confirmed by every engineer who has laboured on this project. But engineers are apt to think deeply and work hard on those problems which are theoretically attractive, and as the result of many years' development there has been evolved a form of modern electrostatic loudspeaker whose performance is markedly superior to that of other types. We will jump the slow progressive stages of its evolution and proceed to examine the basic form of the balanced-push-pull electrostatic loudspeakers which have recently been developed.

It will be seen that Fig. 6 bears *some* resemblances to Fig. 5. We still have the high-ratio step-up transformer, the high polarising voltage and the high resistance, but the actual loudspeaker elements are quite different, and we can state their basic features as under:

(1) The thin, flexible diaphragm is a sheet of extremely tough plastic material, having a negligible co-efficient of expansion as regards temperature, and coated with a conducting material which is so thin that it does not materially add to the weight of the diaphragm. The thickness of the diaphragm is a fraction of one thousandth of an inch.

(2) The thin diaphragm is held by a system of insulating spacers equidistant between two rigid plates, these being acoustically transparent (i.e., they allow sound waves to pass through them unimpeded).

(3) The whole assembly is formed into an arc in the horizontal plate. (See Fig. 7.)

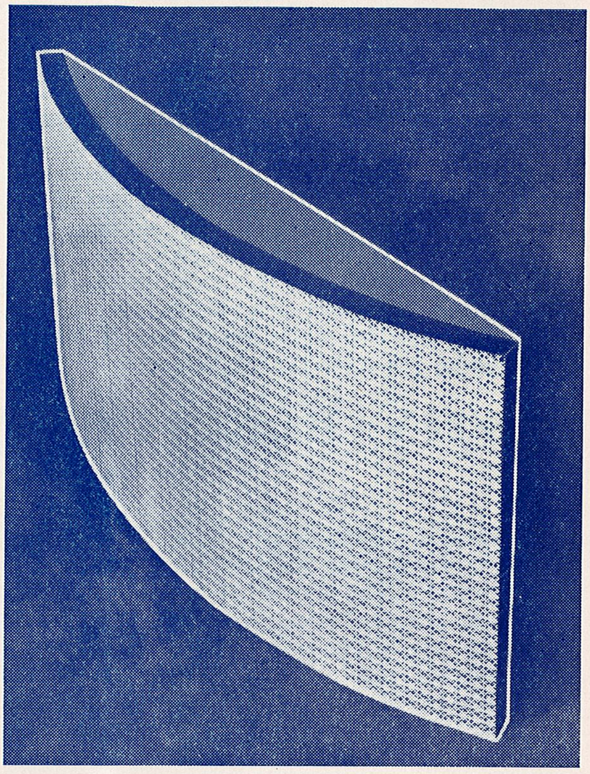

Fig. 7. A developed balanced-push-pull electrostatic loudspeaker.

We will now examine the behaviour of this push-pull loudspeaker. If one changes from a single-sided amplifier to a push-pull amplifier there are appreciable improvements in distortion and power output, but when one changes from a single-sided electrostatic loudspeaker to the balanced-push-pull type it would be an understatement to say that the improvements are appreciable: they are indeed spectacular, as can be shown mathematically and experimentally.[3]

If, in the absence of a signal from the amplifier we switch the polarising voltage into circuit, the diaphragm will *not* move towards either plate, because it is subjected to equal and opposite electrostatic forces from each plate. This means that the diaphragm need not be stretched to resist the static forces, thus removing one cause of the non-linearities inherent in the single-sided loudspeaker previously discussed. Another important feature of the push-pull assembly is this: if the diaphragm is moved

4. H. J. Leak & Co. Ltd. First "Point One" announcement. Journal Brit. I.R.E., October, 1945.
5. "Acoustics". L. L. Beranek. McGraw-Hill Book Co. Inc., 1954.
6. D. E. L. Shorter. Brit. Pat. No. 537,931.

towards one plate it does not upset the condition of equal and opposite forces acting on it, provided that the charge is maintained, and this can easily be ensured by making the resistance in series with the diaphragm of sufficient magnitude to give a long time-constant.

Under the above conditions the loudspeaker is an almost linear device, and harmonic distortion is extremely low. An unusual feature of this push-pull device is that the 2nd harmonic will always be greater than any other; furthermore, it can be shown that if the 2nd harmonic is reduced all the higher harmonics are reduced simultaneously!

At volume levels sufficient for a small hall, the particular type of loudspeaker illustrated in Fig. 7 has a measured distortion content over its working range of approximately 0.1 per cent! This result may be considered incredible, and it is therefore worth recalling that incredulity was also expressed when the author introduced the very first low-distortion amplifier (the original "Point One") in 1945.[4] Strangely enough, there is often resistance to progressive developments, both in the arts and the sciences.

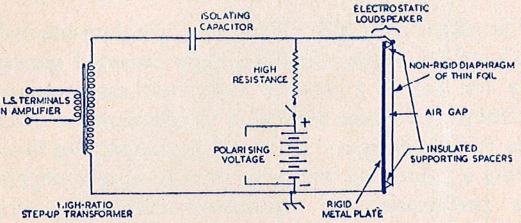

Fig. 5. Schematic drawing of single-sided electrostatic loudspeaker.

Fig. 8 shows that the frequency response of the loudspeaker in the horizontal plane is excellent, and the high frequency response is maintained off the axis because of the curved construction. However, in the vertical plane the response will be more directional if the total area of the diaphragm is used as the radiator for high frequencies.[5] Broader directivity can be obtained by subdividing the diaphragm and/or fixed plates, and feeding these separate areas through electrical dividing networks connected to tappings on the transformer. A further advantage can be obtained from this expedient because it tends to minimise the variation of load impedance with frequency.[6] A neat solution of these directivity/impedance problems is offered by Janszen, who uses a diaphragm coated with resistive material.[7]

The absence of rapid changes in the frequency characteristic is indicative of a transient response superior to any other form of loudspeaker (excepting the Ionophone,[8] a gaseous device previously investigated by the author). Corrington confirms that a similar type of balanced-push-pull electrostatic loudspeaker gives transient decay measurements greatly superior to those of any other loudspeaker tested in the R.C.A. acoustics laboratories.[2]

The acoustic output from this type of balanced-push-pull electrostatic loudspeaker is of the same order as from conventional cone loudspeakers. Its sensitivity is therefore satisfactory, in direct contrast with the single-sided system.

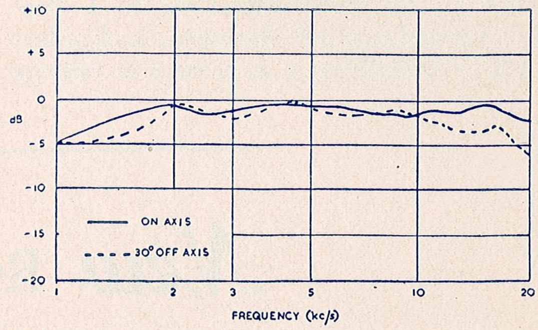

Fig. 8. Frequency response curve of the balanced-push-pull electrostatic loudspeaker illustrated in Fig. 7.

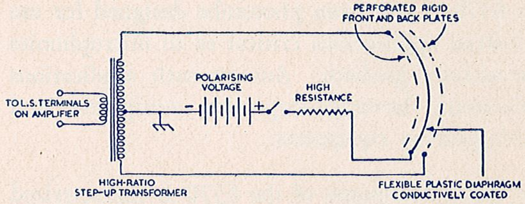

Fig 6. Schematic drawing of balanced-push-pull electrostatic loudspeaker.

From the above performance details the reader may deduce that in this particular case it is possible to disagree for the first time with the dictum that "the loudspeaker is the weakest link in the chain". Any record/pickup combination and any transmitter/receiver combination (F.M. included) will have greater distortions than this particular loudspeaker. This is, of course, a revolutionary engineering situation, but the reader may ask: "Does this loudspeaker *sound* revolutionary?". The short answer is: "It most certainly *can* do so, but much depends on the goodness of the bass woofer which must of necessity be heard simultaneously". Now, there is little to choose between the better few available conventional 15-inch woofers, and when the balanced-push-pull electrostatic tweeter of Fig. 7 is

7. A. A. Janszen. U.S. Pat. No. 2,631,196.
8. S. Klein. "Un nouveau transducleur electroacoustique: l'ionophone". Proc. of First I.C.A. Congress: Electro-acoustics. W. D. Meinema, Delft, 1953.

properly married to such a woofer the overall quality of reproduction is voted a notable advance by the majority of listeners. A further noticeable improvement in sound quality can be effected by using novel constructions and materials for the woofer, and it has thereby been found possible to eradicate or ameliorate three significant distortions common to all the contemporary woofers investigated by the author. However, these developments make another story, and it must suffice to say here that a greatly improved tweeter needs and deserves a greatly improved woofer.

To sum up: the author believes that the development of balanced-push-pull electrostatic loudspeakers will rank in importance, as an advance in listening quality, with the advent of the Rice-Kellogg moving-coil loudspeaker in 1925 and with the introduction of very low-distortion amplifiers in 1945.

RADIOTRON DESIGNER'S HANDBOOK MAKES ADVANCE

The fourth edition of the Radiotron Designer's Handbook is now being translated into Spanish and Japanese, while a request has been received for translation rights into Italian. The Handbook is now being separately published, or preparing for publication, in a total of six countries (including England, U.S.A. and Australia).

In addition, the third edition was also translated into Polish.

New RCA Releases

RCA-6570 VACUUM PHOTOTUBE

The 6570 is a vacuum phototube designed for use in industrial applications critical as to microphonics and sensitivity gradient. Among such applications are electronic beverage-inspection equipment and ampul-inspection equipment.

The spectral response of the 6570 is characterized by high sensitivity to red and near-infrared radiant energy. Because of its spectral response, the 6570 is especially suitable for use with an incandescent light source.

The 6570 has a maximum anode-supply voltage rating of 500 volts, a maximum average cathode-current rating of 5 microamperes, and an average luminous sensitivity of 30 microamperes per lumen.

MEDIUM-MU TWIN TRIODE RCA-6CG7

The 6CG7 is a general-purpose, medium-mu twin triode of the 9-pin miniature type intended particularly for use as a vertical deflection oscillator and horizontal deflection oscillator in television receivers. This type is designed with a 600-milliampere heater having a controlled warm-up time to ensure dependable performance in equipment employing series heater-string arrangement.

Design features of the 6CG7 include an internal shield which provides effective shielding between the triode units to prevent electrical coupling between them.

The 6CG7 may also be used as a phase inverter, multivibrator, synchronizing separator and amplifier, and resistance-coupled amplifier in electronic equipment.

Editor .... D. Cunliffe-Jones

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