# Wide Range Electrostatic Loudspeakers

By P. J. WALKER*

## 2—*Problems of Air Loading : Different Requirements of Moving-coil and Electrostatic Drive Units*

In the first part of this article we showed that it was possible to design and construct electrostatic driving units which were capable of applying a force which virtually acted directly on to the air, and we showed that this force was linear. This state of affairs applied over a bandwidth of several octaves for any single unit, depending upon the efficiency required from that unit, and it was further shown that that bandwidth could be placed anywhere in the audio range.

The only mechanical impedance likely to affect performance is the suspension compliance of the diaphragm, necessary to offset the negative compliance due to electrical attraction. We can therefore begin to draw an electrical analogue circuit of the mechanical elements of the loudspeaker as in Fig. 1, showing the force fed in series with a capacitance. In practice the compliance will considerably exceed the electrical negative compliance, so that this capacitance $C_d$ is almost solely due to the diaphragm compliance.

For simplicity we will restrict consideration to units driven from constant-voltage sources, so that no elements need be included to indicate amplifier source impedance.

Since the loudspeaker will be coupled to the air, we can now add the front air load radiation resistance $R_f$ and the front air load mass, $M_f$ and we can include the impedance Z which represents the impedance presented to the back of the diaphragm.

The impedance Z may include dissipative terms in the form of absorption and/or acoustic radiation resistance. With most acoustic devices the analogy elements change with frequency and the problem, as with all loudspeaker design, is to arrange matters so that the power developed in the radiation resistance(s) is independent of frequency.

The electrostatic unit differs from the moving coil in that there is no large mass component (cone and speech coil) which normally appears as a large inductance in series with $C_d$. The absence of this inductance profoundly alters the requirements for Z, and since Z is the cabinet or back enclosure it is to be expected that the form of cabinet for electrostatic units will follow trends entirely different from those that have been evolved for moving-coil units. A further difference is that the shape of the diaphragm area is more versatile, so that $R_f$ and $M_f$ may be independently varied over reasonable limits.

Due to the absence of large mass we can, if we wish, arrange the constants so that $R_f$ is large compared with the other elements, and therefore becomes the controlling factor for the equivalent current in the circuit, i.e., the velocity of motion of the diaphragm. This means that the impedance looking back into the loudspeaker can be very low. When this is so, any increase in the acoustic resistance on the front of the diaphragm will result in *reduced* power output. If, on the other hand, the impedance of the loudspeaker is made to appear high by arranging that the total impedance is

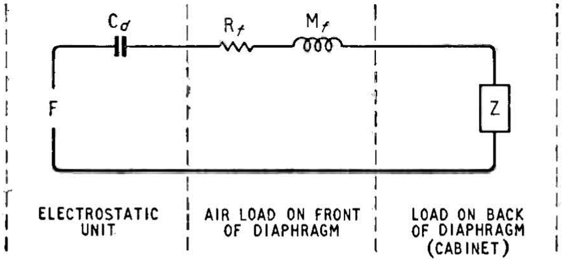

*Fig. 1. Elementary equivalent circuit of mechanical and acoustical parameters of an electrostatic loudspeaker.*

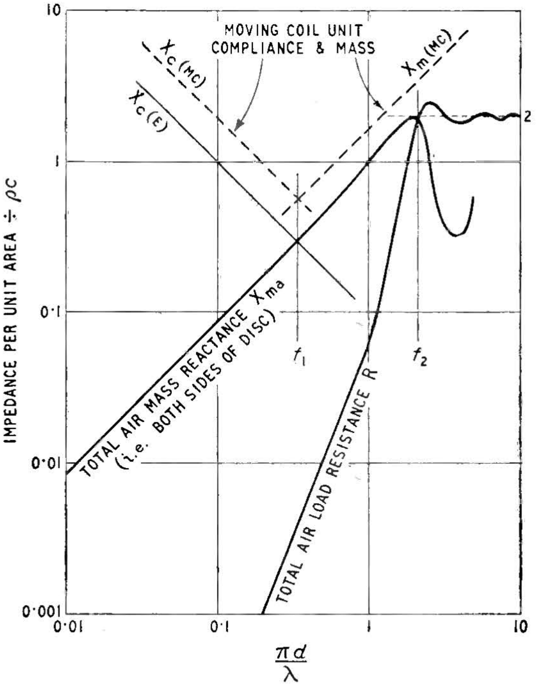

*Fig. 2. Mass and radiation resistance loads on circular diaphragm in free air. The normalized frequency scale is in terms of the relationship of diaphragm size to wavelength.*

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* Acoustical Manufacturing Co. Ltd.

large compared with $R_f$ then an increase in acoustic resistance on the front of the diaphragm will result in *increased* power output. This ability to control the impedance looking back into the diaphragm is a useful feature in designs where $R_f$ is subject to fluctuations due to surroundings, horn reflections, etc., and, in particular, where one loudspeaker unit is influenced by another unit at cross-over frequencies.

In order to show the action of an electrostatic unit which is small compared to the wavelength of the radiated sound it is convenient to commence with a circular shape, because impedance information is readily available for such a shape. Load impedance for other shapes is best obtained by considering the diaphragm as a number of unit areas of equal size and calculating the impedance of each unit area, taking into account the mutual radiation due to the presence of all other unit areas.

Fig. 2 shows the load on a piston operated in an unlimited atmosphere without a baffle. The diaphragm compliance reactance $X_c(E)$ is also drawn. Between $f_1$ and $f_2$ the controlling factor is the air mass, and the velocity of motion will vary directly with frequency until resonance between $X_c(E)$ and $X_{ma}$ is approached. R, however, falls rapidly with frequency, and the power output will fall at approximately 6db per octave with declining frequency. (Exactly the same would occur with a moving coil unit, control this time being the mass of cone and speech coil designated $X_m(MC)$. $X_c(MC)$ is the moving-coil suspension compliance.)

Multiple diaphragms without baffles, having the above characteristics, form the basis of design for loudspeakers to provide the directivity of a doublet. Such a system has useful attributes in relation to the listening rooms, a subject to be dealt with in a later article.

Above $f_2$ the velocity of the moving-coil unit would still be controlled by $X_m(MC)$ (except for cone "break-up") and, since the resistance becomes constant, the response will fall with increasing frequency. In the electrostatic case above $f_2$ the velocity will be controlled by the air load resistance, and the response will be independent of frequency.

Extending this comparison to units in very large baffles we have the curves of Fig. 3. Here the radiation resistance varies with the square of the frequency below $f_2$. With a moving coil the response will be level below $f_2$ and will fall with frequency above $f_2$. With the electrostatic the response will be level below $f_2$ and also level above $f_2$, but there will be a step in response so that the output level above $f_2$ will be 3db higher than that below $f_2$.

A simple arithmetical example will make clear the reason for this step. With constant force F applied to the diaphragm, the velocity of movement will be $\frac{F}{\sqrt{R^2 + X^2}}$ and the power expended usefully in the radiation resistance will be $P = \left(\frac{F}{\sqrt{R^2 + X^2}}\right)^2 \times R$

At $f_B$ in Fig. 3, neglecting Z due to the declining air mass reactance, we have for a constant force F = 1, $P = \frac{R}{R^2} = \frac{2}{4} = \frac{1}{2}$. At $f_A$, on the other hand, the air mass predominates and, if R can be neglected in calculating the velocity of motion, $P = \frac{R}{X^2} = \frac{0.01}{(0.2)^2} = \frac{0.01}{0.04} = \frac{1}{4}$, or half the power at $f_B$. A similar relationship will be found for any other pair of values of R and X at points below $f_2$.

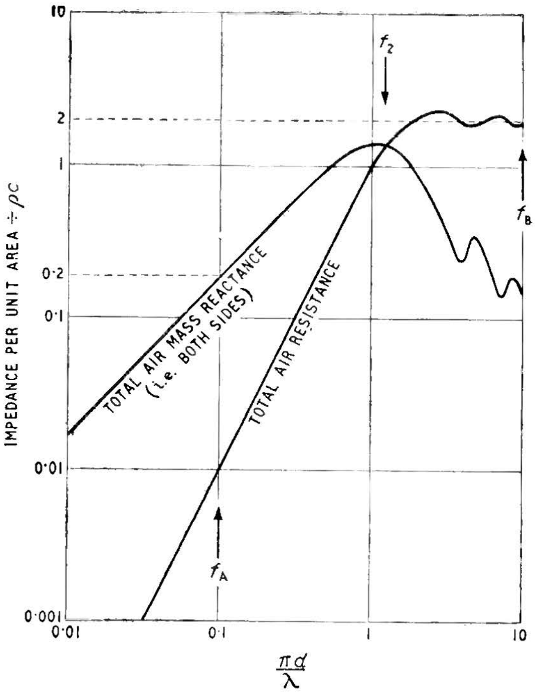


*Fig. 3. Mass and radiation resistance curves for a circular diaphragm in a large baffle. The power radiated at any frequency $f_A$ well below $f_2$ is half that radiated at frequencies $f_B$ well above $f_2$ (see text).*

This change in level can be overcome by deviating from the circular piston shape. For wavelengths large compared to the diaphragm size the resistance per unit area is dependent upon the new area and not upon the shape, whereas the mass is mainly dependent upon the smaller dimension. By elongating the diaphragm shape the output level below $f_2$ can be made equal to that above $f_2$.

We have so far been considering a comparatively small diaphragm in a flat baffle, the latter being very much larger than the piston, and the size of the complete system is obviously that of the baffle. The reason that the piston has been kept small is purely for the convenience of the moving-coil unit, because its diaphragm is driven at only one point. In the electrostatic case we no longer have this restriction, and it will always be preferable to increase the size of the piston (without increasing the total size of the complete system). This will usually be necessary because there is a limit to the available amplitude of movement, and thus, for a given power output per unit area, we have a minimum limit to the radiation resistance in order that the diaphragm excursions may be attainable. Increasing the size of the piston for a given power output has the double advantage of reducing power requirements per unit area, and, where the loading is below $2\rho c$, of increasing the radiation resistance per unit area, and therefore reducing the amplitude required to provide that power output. For reasons of efficiency we shall in any case limit the high-frequency response of the unit so that optimum design is obtained by increasing the area of the diaphragm to the point where the piston just begins to become directional at the frequency which we have chosen for cross-over (set by the efficiency laid down in the design requirements).

Continuing the consideration of the air load on diaphragms, reference should be made to horn loading. Here we have large resistive and mass components due to the horn. Fig. 4 shows the load of an idealized horn to which has been added $X_m$(MC), the cone mass of a typical moving-coil loudspeaker which might be used with such a horn. It will be seen that at low frequencies the cone mass is largely swamped by the horn impedance, so that the design of horns for electrostatic units differs very little from the design for moving-coil units. Although we can now have the advantages of a virtually distortionless driving unit, we are still left with the disadvantages of practical horns, which are present independently of the drive units. Horns are normally used to match the high impedance of moving-coil diaphragms to the low impedance of the air. Since we have no such fundamental mismatch with the electrostatic loudspeaker, and since diaphragm shape and size are not fundamentally restricted, we shall not normally have to resort to the use of horns to the same degree. It should be remembered, however, that any back enclosed volume is a direct function of throat area, so that in some applications it is possible to use space for providing a length of horn in exchange for saving in size of capacitive enclosure. Again, we may wish to restrict the front-wave expansion in order to maintain a reasonable resistance per unit area at low frequencies (utilizing the corner of a room, for example).

One of the most desirable diaphragm shapes for electrostatic designs is that of a strip having a length (together with floor or wall image) large compared to $\lambda/3$ at the lowest frequency of interest, and a width small compared to wavelength at the highest frequency of interest. The strip may be curved along its length if desired, provided the radius of curvature is not less than $\lambda/3$ at the lowest frequency.

To consider the load on such a strip it is convenient to assume the strip as being infinite in length (legitimate provided it is at least $\lambda/3$ in length). With such a diaphragm there will be no expansion of sound in the direction of the length since all pressures along the length of the strip will be equal. Expansion from any given element of the diaphragm takes place in one plane only and will therefore take the form $S = S_0x$. This is the expansion of a parabolic horn. At low frequencies the front air load resistance is falling directly with frequency (instead of $f_2$ as with the circular piston shape). The advantages of the strip shape may now be enumerated:—

(a) The air resistance even at low frequencies (since $R \propto f$) is sufficient to develop adequate power with reasonable diaphragm amplitude.
(b) The narrow diaphragm gives good dispersion for several octaves (up to the frequency at which width $\approx\lambda/3$).
(c) The narrow diaphragm enables other units to be placed close to it, thus being less than $\frac{1}{4}$ wavelength apart at cross-over frequency.
(d) The frequency limitations, amplitude at the low end, and directional problems at the high end, fit in nicely with the 4-5 octave range which we established in Part I of this article for satisfactory efficiency. Thus a strip shape can form one basis of design for our ideal—the perfect loudspeaker.

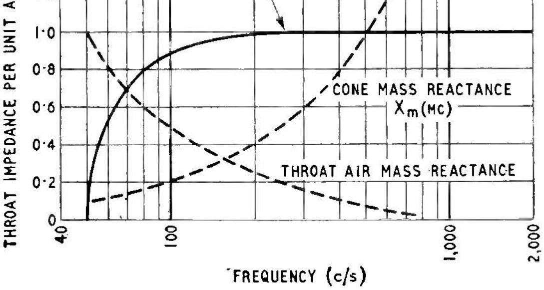


*Fig. 4. Throat air resistance and reactance curves of idealized horn with moving-coil mass reactance superimposed.*

It will be obvious that a curved front source similar to that illustrated in the photograph of Fig. 5 in Part I of this article will give similar distribution to a strip, and, due to the larger surface, smaller spacing may be used and higher efficiency may thus be achieved. In such a case however, the diaphragm must be large compared to wavelength in both dimensions, because it is the nature of curved surfaces to become directional when the radius of curvature is comparable with the wavelength. When the diaphragm is large compared to $\lambda$ it is impossible to design an intimate acoustic cross-over. This small inherent imperfection would appear to preclude its use in a " perfect " loudspeaker design, although its " efficiency " advantages will have obvious applications in some practical compromise designs.

Although designs free to the air on both sides have useful attributes, it is obviously desirable also to produce loudspeakers in cabinet form, enclosing the rear. This rear enclosure, if it is to be of reasonable size, will be the controlling factor for the diaphragm velocity, at least at low frequencies.

With any unit, the high-frequency limit will be set by efficiency requirements, and the low-frequency limit by amplitude limitation or by the compliance of the enclosure in series with the diaphragm compliance. This compliance will resonate with the air mass on the front and back of the diaphragm (unless the diaphragm is so large that the loading is $\rho c$—for example, as in the curved diaphragms previously mentioned). Since the total mass is small, this resonance will usually occur above the lowest frequency of interest. It may be dealt with in two ways, (1) by adding acoustic mass within the cabinet to reduce the resonant frequency to the lowest required frequency, or (2) critically damping the resonant frequency and maintaining response below this frequency either by re-matching or by a secondary acoustic resonant circuit, or both.

There are innumerable ways in which either of these alternatives may be achieved. Consider the first alternative. Suppose that the enclosure is made deep and narrow (or fitted with partitions so that it appears deep and narrow to the loudspeaker): then, at wavelengths just under four times the depth, the reaction on the diaphragm will be positive. This will effectively force the resonance to the $\frac{1}{4}$ wavelength reasonance of the depth of the enclosure. Absorbent wedges may now be fitted to control the resonance and to present

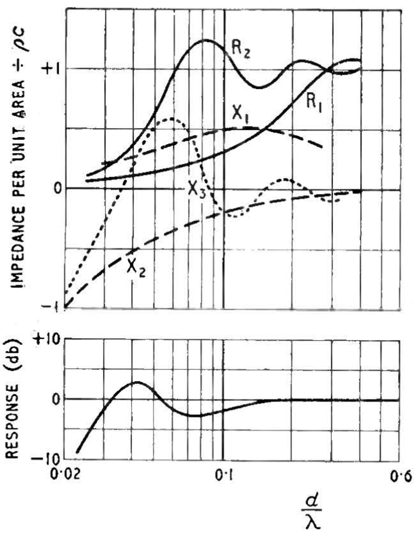
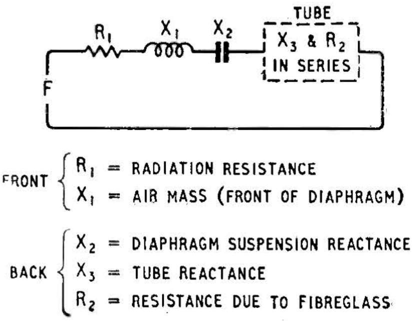


*Fig. 5. Strip loudspeaker, long compared with wavelength, and of width d, mounted in a wall, with the back of the diaphragm loaded by a tube with cross-sectional area equal to that of the diaphragm and of a length 5d, blocked at the far end. Resistance (fibre-glass wedge) included in tube to control impedance.*



a purely resistive load at all higher frequencies. Sound compression within the wedges becomes isothermal, decreasing the speed of sound, so that the depth of the enclosure can be reduced accordingly.

Fig. 5 shows the impedances of a strip unit loaded on this principle together with a curve showing the power output radiated as sound for constant applied voltage. The output is extended by more than an octave over that which would be obtained if the same volume of enclosure were allowed to act as a lumped capacitance.

Turning now to the second method of extending the low frequency range, Fig. 6 shows a diaphragm loaded by a capacitance leading through resistance and inductance into a larger capacitance. Both volumes have dimensions many times less than the wavelength in the ranges where they are operative.

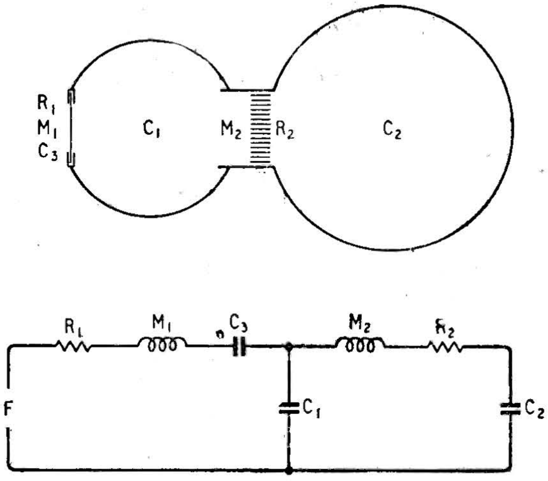
If the constants are adjusted to give a step in response as the frequency is lowered, then the total volume of the enclosure is reduced accordingly and the response restored to level by re-matching at the step frequency.

Fig. 7 shows a strip diaphragm loaded by a capacitance with series resistance, all elements continuing along the whole length of the structure. With this assumption there will be no waves in the enclosure along its length so that the constants can be calculated on a sectional element of thickness *t*. If the cross section of $C_2$ has dimensions which are many times smaller than the wavelength, then $C_2$ will behave as a capacitance (independent of length). If this proviso is not met then $R_2$ must be distributed to avoid $C_2$ appearing as a multi-resonant circuit.

Where the unit crosses over to another unit for low frequencies then $R_2$ may be adjusted to give a Q of 0.7 so that the cross-over components are already present in the acoustic circuit.

When the lower-frequency unit is arranged so that the two diaphragms are close and intimately coupled, then $R_1$ will be increased in value by the mutual radiation of the low-frequency unit. $R_2$ is then reduced to restore Q and we find that if $R_1$ is larger

*Fig. 6. Diaphragm loaded by an equivalent capacitance $C_1$ leading through an acoustic mass and resistance $M_2$ and $R_2$ into a larger capacitance $C_2$.*



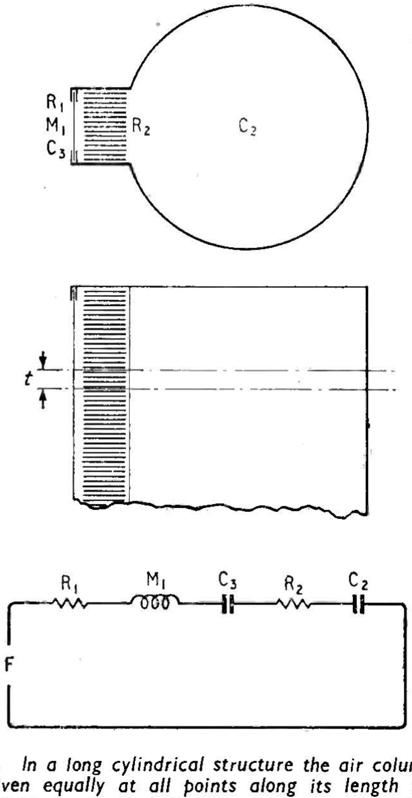


*Fig. 7. In a long cylindrical structure the air column will be driven equally at all points along its length and no appreciable longitudinal standing waves can be established, at frequencies other than that corresponding to λ/4.*

than $R_2$ a useful self-compensating effect takes place.

If the voltage applied to the low-frequency unit is reduced at cross-over due to tolerance in its cross-over components then $R_1$ is automatically reduced and the output of the higher-frequency unit increases at cross-over. At cross-over $P_{out} \propto \frac{R_1}{(R_1+R_2)^2}$

Where the enclosure of Fig. 7 is used for the unit covering the lowest part of the audio range, bass response may be extended by rematching or by introducing a secondary resonant circuit and utilizing back radiation from the diaphragm. If an aperture is provided at one end of the enclosure, opening to the air, then, when the enclosure length is ¼ wavelength, resonance will occur along its length, and there will be radiation from the aperture. 3/4, 5/4 resonances, etc., will not arise, because the enclosure is excited by a force distributed along its length. At frequencies above the ¼ wavelength, the enclosure will behave approximately as a capacitance, as if the aperture were not present.

The next part of this article will deal with electrostatic units as part of delay lines, and the application of various complete designs, " built in," " boxed in " and " doublet " in relation to the listening-room. Complete electrostatic loudspeakers can take several different forms, each of which in terms of frequency response, distortion and sound dispersion can meet a specification virtually to perfection. When the listening-room and subjective factors are considered it becomes impossible to lay down a rigid specification. To adopt a quotation " Each design is perfect, but some designs are more perfect than others "!

**Acknowledgement.** Fig. 2 is based on Fig. 5. 9, p. 127 of " Acoustics " by Leo. L. Beranek (McGraw Hill).

*(To be continued)*

# LETTERS TO THE EDITOR

*The Editor does not necessarily endorse the opinions expressed by his correspondents*

## *Situations Vacant*

WITH the present state of full employment in the electronic profession, the competition amongst employers to find suitable men is fierce. This is shown by the numerous posts advertised in technical journals. The time has come, however, for employers to pay a little more attention to the " Sits. Vac." replies.

Three members of my laboratory have, over a period of the last six months, written to a dozen advertisers. The results have been very disheartening; only 40 per cent of the applications were acknowledged. The applicants were qualified men: A.M.I.E.E., A.M.Brit.I.R.E., Higher National, National and City and Guilds certificates. In good faith they have taken some trouble to apply for positions, expecting that they would be treated with good manners by the advertiser, and have been embittered by the callous manner in which their applications were treated.

I would ask " Sits. Vac." advertisers to read page 498 of *Electronics* for March, 1955, and then to make moves at least to treat engineers with the courtesy their professional status deserves.
J. GILBERT.

Biophysics Dept.,
Postgraduate Medical School of London.

## *Transistor Symbols*

IT would seem that an over-riding factor when assessing the desirability of a logical system of transistor symbols is whether the advantages of the system are more important than international standardization. It is impossible to ignore the fact that there is a well-established convention at present widely used in both Europe and the U.S.A., and it is, to say the least of it, unlikely that any alternative suggestions at this late stage will replace the accepted practice. I would suggest that it is better to follow the generally accepted convention and concentrate on clearing up minor differences about points such as the thickness of base line and the presence of a circle to isolate the transistor from the rest of the circuit.

Leaving on one side the question of standardization, there is still a doubt whether your suggested symbols (April and May, Editorial Comment) do in fact add to an understanding of the devices. The symbol you suggest is particularly undesirable since it is very misleading to regard a transistor as a back-to-back arrangement of two diodes.

Finally, the point raised about the abbreviation to use in circuit diagrams can be met without causing confusion by using the same " V " for the crystal valve as for the thermionic version.
B. R. BETTRIDGE.

General Electric Company,
London, W.C.2.

BOTH D. Nappin and W. E. Thompson (your May issue) regard the transistor as a new device needing a new symbol, but surely this problem arose as the normal valve developed.

It was no doubt thought that gas triodes and neon stabilizers were separate devices, that each needed a new letter symbol, but in fact they are both given the letter V, and no confusion is caused by this. The type of device is made clear by the circuit symbol.

I suggest, therefore, that the letter V be kept to include the transistor.

London, N.1.
M. LEVY.

WHILST in full agreement with the general scheme of transistor symbols proposed in your April and May Editorials, I should like to plead for the symbol originally shown for the *n-p-n* junction transistor in *Wireless World*, July, 1954, p. 325, Fig. 2(c), rather than the new version in Fig. (f) of the May Editorial. This later version is likely to cause error, particularly when pencil sketches are copied in the drawing office or print room. Furthermore, the original version appears more logical and distinct, being characterized by a black and white triangle like the symbol for the *p-n-p* transistors.

London, N.W.3.
FRANCIS OAKES.

## *Electronics on the Farm*

R. S. DRAKE'S letter (your May issue) is very interesting and certainly very pertinent. Within limits one must admit that a manufacturer should know! However, I beg leave to suggest that there is justification for some comment, if not criticism.

Popularity obviously justifies manufacture and sale, but it does not follow that it confirms excellence of design and practical value. Established habits die hard.

It may be true that there is no serviceable electronic " switch " or " trigger," but I feel that there is no valid objection to a glass-enveloped tube in a fencer unit. These units must in practice be effectively boxed and weather-proofed, and in any case we have electric lights all over the place on farms these days.

I still hope to find an electronic dry battery unit on sale in the not-too-distant future; a unit which is neatly boxed