Permanent Magnets

Fundamental properties, and the quantities used to measure them

by "Cathode Ray"

My last treatise, on magnetism*, though it went to a length that no doubt you thought was excessive enough, said no more about permanent magnetism or magnets than a half-promise to deal with the matter later. The Editor having made some encouraging noises with reference to that proposition, here we are. Some justification for giving it special attention can be found in the odd fact that although permanent magnets are nowadays encountered by readers of *Wireless World* much more than electromagnets, in such things as loudspeakers, pickups, microphones, meters and recorder tape, most of the books that explain the principles of electromagnets are much less forthcoming on permanent magnets.

All magnetic effects are due to electric currents. Electric currents are movements of electric charges. We are familiar with electric currents flowing around circuits, but every atom and molecule of every substance is made up largely of electric charges (electrons and protons) which are continually moving. In gases and liquids and the great majority of solids the molecular structure is such that these tiny currents normally cancel out. If a magnetic field is brought to bear on them, very complicated things happen†. For practical purposes the net magnetic results in most materials are negligible, and we are going to neglect them and consider only the small group of materials classed as ferro-magnetic. This word comes from *ferrum*, Latin for iron, because iron was the first and still is an important substance found to respond very strongly to a magnetic field. But many modern permanent magnets are made of alloys of such metals as aluminium and copper and contain no iron, and others (ferrites) are not even metallic.

The molecules of ferromagnetic substances form groups, known as domains, but unlike the proud kingly ones in history they are microscopically small. In each domain the molecules are so aligned that as a whole it is a tiny magnet. In the natural state of the material the domains are randomly aligned, so their magnetic effects tend to cancel out and there is little or no external magnetism. But when placed in a gradually increasing magnetic field more and more domains come into line with that field, in effect multiplying its strength. The multiplying factor is relative permeability, μ_r. (In SI units the permeability of empty space, μ_0, is not 1 but $4\pi \times 10^{-7}$. The multiplying value of ferromagnetic materials, μ_r, is therefore μ/μ_0.)

This μ_r is a very valuable property, for such things as transformers. At audio and power frequencies, at least, the strength of magnetic field needed to generate the required voltage in the secondary winding would call for an excessively large magnetizing current in the primary if a ferromagnetic core were not used. Ideally the core material would provide a large and constant value of μ_r. This would be shown as a steep linear slope of a graph of magnetic flux density (B) against magnetizing force (H), as in Fig. 1. But the domain-aligning process is far from linear. Very small values of H have a comparatively small effect, yielding only moderate μ_r. As H is increased, domains swing into line faster, and μ_r increases. When most of them have already responded, large increases of H are needed to persuade the remainder; and finally there are none left, so the curve levels off at what is called saturation value, Fig. 2. For such purposes as transformer cores the working H has to be limited to the steep (high-μ_r) part.

You may be wondering why in Fig. 2 I have shown only the $+H+B$ quarter (or quadrant) and in particular not the $-H-B$ quadrant that is equally important in a.c. applications, where there are negative as well as positive half-cycles. The reason is that there is a second departure from the ideal. Fig. 1 implies that after the first positive half-cycle has reached its peak and is declining, the domains get jumbled up again exactly in proportion to the decline in current, so that the magnetization continues to be proportional to the current, throughout the cycle. This is shown by the graph passing through the origin O on its way to and from the negative quadrant.

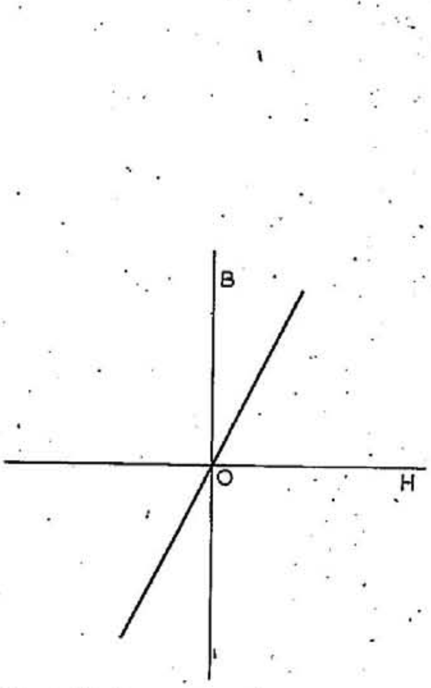

Fig. 1. Ideal magnetization curve for transformer core material, one of its advantages being complete absence of permanent magnetism.

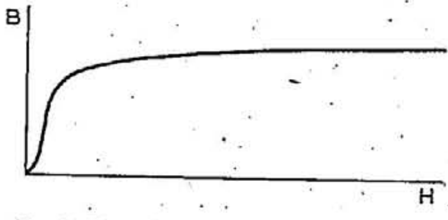

Fig. 2. Typical actual magnetization curve of ferromagnetic material, with H held at its maximum value.

No ferromagnetic material behaves in this way. Soft annealed iron, usually improved by a small proportion of silicon to increase its resistance to eddy currents, is about the best that can be found, and transformer core stampings are commonly made of some such material. But just as it is usually easier to get people into a pub than to get them out again, there is a tendency for the domains to stay put until H has been reduced well below the level that was needed to bring the material up to that B in the first place. If H is carried through a complete cycle from zero, the first positive magnetization curve is as in the steep part of Fig. 2, shown dotted in Fig. 3. During the falling phase of the positive half-cycle, the fall in B lags behind that of H, so by the time H is back to zero B still has a positive value, represented by OR. B reaches zero only when H is appreciably negative, by the amount OC. The negative half-cycle is of course similar.

For many years I have raised my feeble protest against the many unsatisfactory technical terms in our art. Here we have another example. In the old days, when electric bells, relays, etc. began to be used, it was soon found that there was a tendency for the armature to remain stuck to the pole

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*January 1973 issue, p. 23.

†See. *The Electron in Electronics*, M. G. Scroggie, Chapter 9.

of the electromagnet after the current had been cut off—as one would expect from consideration of Fig. 3. This effect became known as *residual magnetism*, and as far as I know it still is. At a rather more sophisticated stage, when BH curves came into vogue, the value of B represented in Fig. 3 by OR was called *residual magnetization* or *residual flux density* or *residual induction*. In some books this is alternatively called *remanence*. In other books this term is reserved for the highest possible value of residual magnetization, which is obtained after the material has been magnetized to saturation. In yet another book, *remanence* is defined for a magnetic *circuit*, whereas it is normally applied to magnetic *materials*, explicitly or (more usually) implicitly in the form of a continuous ring, with no gap or variation in cross-sectional area. In view of this ambiguity I propose that *remanence* be abolished. There is yet another word, *retentivity*. A word ending in *-ivity* signifies a property of a material under standard conditions. The value of residual magnetization in general depends on the amplitude of H if less than saturation, but if the material has been taken to saturation it should be the same every time. So retentivity figures enable materials to be compared. On the same principle OC is called (in general) *coercive force*, and its highest possible value, following saturation, has the special name *coercivity*.

The one-way traffic circulation system shown in Fig. 3 is an example of the well-known hysteresis curve. The fact that the 'up and down' lines are comparatively close together shows that it refers to a fairly low-hysteresis material such as could be used for transformer cores. The reason it is important to use a material in which the area enclosed by the hysteresis loop is as small as possible is that this area represents power lost due to hysteresis. If you insist on a proof of this statement you can find it in textbooks on electrical engineering.

The usefulness of a magnet, electro or permanent, usually depends on its forming part of a magnetic circuit. It may be needed to set up a certain flux density (B) in an air gap, as in loudspeakers and meters, in order to make a coil therein move in accord with the current it carries. Or it may be needed to magnetize a piece of iron, to produce an attractive force governed by the principle that opposite poles attract and like poles repel. Pieces of high-μ_r material, called polepieces, are often used to serve the same sort of purpose as connecting wires in electric circuits, to connect the magnet to its "load" with the least possible reluctance.

Last time we saw (I hope) that magnetic circuits can be calculated in the same way as electric circuits with their Ohm's law. But Ohm's law is based on the discovery by Dr. Ohm that the resistance of ordinary circuit materials does not depend on the current flowing (if heating effects are disregarded). Electronics deals with circuit components that are not ordinary in this sense; their ratios of V to I are not constant, so Ohm's law cannot be applied. Instead, I is plotted against V as a characteristic curve. Suppose we have a diode, complete with characteristic curve (Fig. 4), and want to find the resistance (R) is series with it which will pass a certain current (I_0) through both when the voltage applied is V_T. All we have to do is mark V_T on the V scale of the graph, and point P on the curve, level with I_0, and join the two points by a straight line. The slope of this line is equal to I_0/V_R, which is the conductance of the resistor in series with the diode, so V_R/I_0 is its resistance. Which is what we wanted. The same thing can be done in reverse, to find I_0 or V_T, given R. If R is zero its line is vertically upwards from V_T, so I_0 is large; if R is infinite (open circuit) its line is horizontal, so I_0 is nil.

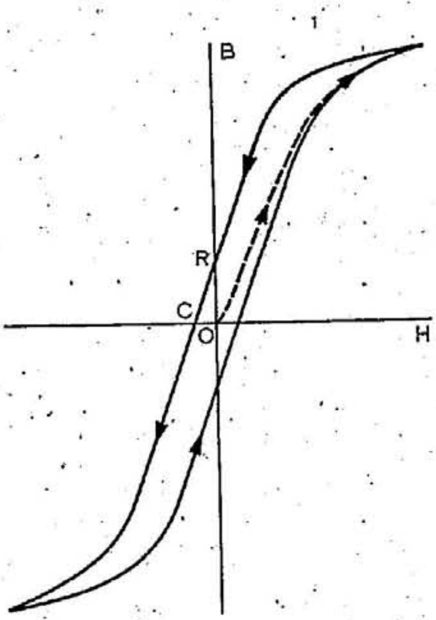

Fig. 3. For comparison with Fig. 1, a typical magnetization curve of transformer core material, taken from zero to maximum (dotted) and then over a complete cycle.

Fig. 4. Example of a load-line diagram for an electric circuit consisting of a diode in series with a linear resistor.

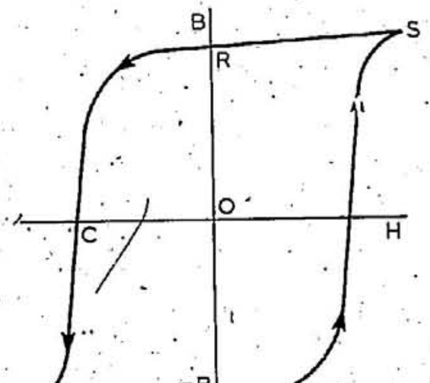

Fig. 5. For comparison with Fig. 3, a typical magnetization curve of a permanent magnet material.

Precisely the same method is used for magnetic circuits containing ferromagnetic and therefore non-linear material (call it "iron" for short). Corresponding to V_T is the total magnetomotive force (call it F_T), and corresponding to I_0 is Φ. F_D is the m.m.f. needed for the iron and F_R the m.m.f. needed for an air gap in series.

In an electromagnet circuit F_T is provided by the current in the coil, and in SI units is equal to it (every turn of the coil being counted as a separate current). It is obvious that with a diode having a curve as in Fig. 4, typical of semiconductors, if V_T were zero there would be no current, no matter what R was. Readers in the higher age groups and with good memories will recall that there used to be such things as thermionic diodes, whose curves began to the left of O, so current flowed through a resistance even if it was connected straight across the diode, with no V_T. We have just noted that ferromagnetic characteristic curves always extend to the left of O, as in Fig. 3, provided that the material has been magnetized. So if we use an electric current to raise H to a high value, and then switch the current off, we still have some B (and therefore Φ). (Our curves are B against H, but B is simply Φ per square metre and H if F per metre.) If the iron having the curve shown in Fig. 3 was a completely closed circuit, without even the smallest gap in series, then the value of B would be represented by R. There is no such thing as a perfect magnetic open circuit, but if the air gap was large its reluctance line would be nearly horizontal and the working point close to C, so almost no flux. This would obviously not be useful, neither for most purposes would the largest possible flux density (R) because it would all be inside the iron and so not directly available. As with the diode, practical "load" lines come somewhere between these extremes. Where?

Now that we have at last got on to permanent magnets it is time we took leave of Fig. 3, which illustrates a type of material in which permanent magnetism has been deliberately minimized, and looked at Fig. 5, typical of permanent magnet materials and obviously far more rewarding for that purpose. Having taken in the contrast between it and Fig. 3, we move rather swiftly to Fig. 6, in which the only quadrant that now matters has been repeated in the left-hand half, leaving the other half free for answering the question that has just been posed.

We shall take as a typical permanent magnet circuit the magnet itself in series with an air gap. Loudspeakers and meter magnet circuits are of this type. The magnets employed to hold papers on boards or keep the fridge door shut may appear not to be, but in one there is a paper gap and in the other probably a rubber gap, and even when there is no intentional gap there is almost bound to be an unintentional one with appreciable reluctance. Allowance has to be made for polepieces where used, but their reluctance is small compared with a gap even when its length is many times less. The biggest practical departures from theory lie in what is called leakage flux. But theory is enough to be getting on with just now. And to make things as basic and simple as possible we shall assume that a magnet l_m in length and A_m in constant cross-sectional area is "feeding" a gap l_a long and A_a in area.

Neglecting leakage flux, as we are doing, we must accept that the flux Φ is the same in both:

$$\Phi = B_m A_m = B_a A_a$$

Therefore $$A_m = A_a \frac{B_a}{B_m} \qquad (1)$$

And the magnetic "potential drop" must be the same across both, being equal and opposite as in Kirchhoff's voltage law for electric circuits:

$$H_m l_m + H_a l_a = 0$$

Therefore $$l_m = l_a \frac{H_a}{-H_m}$$

and because $H_a = B_a/\mu_r$, and μ_r for air is practically the same as for vacuum, $4\pi/10^7$, this becomes

$$l_m = \frac{B_a \times 10^7}{4\pi(-H_m)} \qquad (2)$$

Multiplying (1) and (2) together we get the volume of the magnet:

$$A_m l_m = A_a l_a \frac{B_a{}^2 \times 10^7}{4\pi(-H_m B_m)} \qquad (3)$$

So the volume of magnet material required is directly proportional to the volume of the gap and to the square of the flux density therein. And for given values of these it is least when $-H_m B_m$ is most. So our question is answered by finding the point on the second quadrant of the demagnetization curve that corresponds to the highest value of $-HB$. This can be found by selecting a number of points on the curve, multiplying their co-ordinates, and plotting these products to a scale of $-HB$ to the right of O, as shown dotted. The maximum value of $-HB$ is of course where the resulting curve sticks out most, and by drawing a horizontal line from here to the magnet curve we find P, the working point for the smallest magnet to do the job. The gap "load" line can be drawn to it from O.

If we are too lazy or short of time to plot the $-HB$ curve we can usually get very near it very quickly by completing the rectangle with ROC as its corners and drawing the diagonal from O to cut the curve at a point that turns out to be a good approximation to P. Even this reduced effort on our part is rendered superfluous by the magnet makers, who thoughtfully mention the optimum B and $-H$ and their product $(-HB)$ among their data. This value of $(-HB)_{max}$, however found, is the one to use in place of $(-H_m B_m)$ in (3) above.

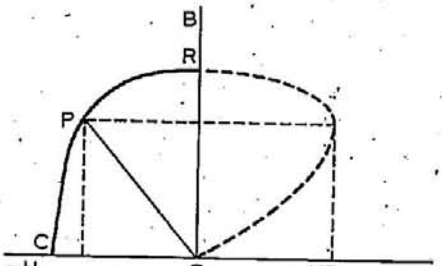

Fig. 6. The left-hand half is a "load-line" diagram for a permanent magnet material in series with an air gap, analogous to Fig. 4; the dotted lines are a construction for finding the best working point, P.

These data figures enable fair comparisons to be made between different materials, and help one to choose the best material for a job. But I hope I've made clear that designing an actual magnetic circuit is not nearly so simple and demands a lot of experience. But again, the makers are ready to put their experience at your command, if an order is likely to be forthcoming.

There are however some points to be remembered when *using* magnets. Sometimes permanent magnet circuits are exposed to intentional or unintentional magnetic fields. These shift the working point to right or left from the original point, P in Fig. 6. If it is to the left (a demagnetizing field) the working point continues along the demagnetization curve from P to say X in Fig. 7. If now this external field is withdrawn, the working point finds itself in a one-way street (remember the arrows in Fig. 5?) and is bound by hysteresis to follow another track, to Y say. The strength of the magnet has been reduced. In a meter this would definitely be a bad thing. So such magnets are aged by submitting them in advance to fields stronger than they are likely to experience after calibration.

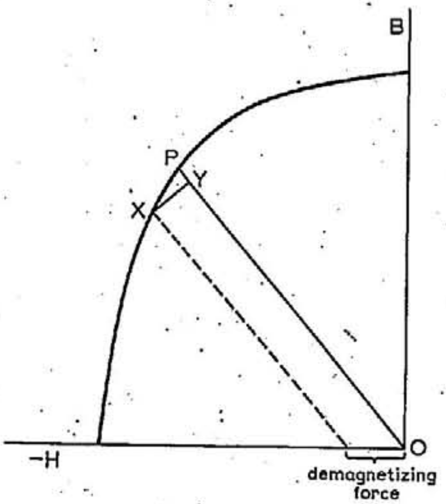

Fig. 7. What happens when a permanent magnet originally working at point P is demagnetized to point X. The recovery is to point Y.

This also shows why it is not a good idea to take a permanent magnet circuit to pieces. Doing so generally introduces a relatively large reluctance in series, which makes the gap line move close to the horizontal, bringing the working point low down so that the value of B is much reduced. When the system is reassembled, much of the original magnetism is likely to have been lost. If possible, the magnet should first be short-circuited, but that needs care, for if the iron shorting piece is drawn against the magnet violently the resulting shake-up is likely to demagnetize it considerably.

Ceramic magnets, although short on retentivity, have exceptionally large values of coercivity. So they are relatively immune to external fields, and because of the shapes of their curves they are especially suitable for high-reluctance circuits.

An application of permanent magnetism not yet mentioned is in computer memories —the ferrite-core store. Here the permanent magnets are small (down to 0.35mm) closed rings, as in Fig. 8, and they are magnetized by current passed through straight wires threading the cores and acting thereon as one-turn coils. There are large numbers of X and Y wires forming a network or matrix, with a core around each point where they cross. Because there are no gaps in the cores, only a moderate current is needed even through the single turn to reverse the magnetization, from R to $-S$ in Fig. 5. After the current ceases the core is then at $-R$ instead of R. This large change of flux induces a pulse in a third wire (not shown in Fig. 8). If the core had been at $-R$ before the current, there would have been only a small change, from $-R$ to $-S$ and back, insufficient to induce an effective signal. The currents actually passed through the X and Y wires are made only half as much as needed to reverse the magnetization, so the

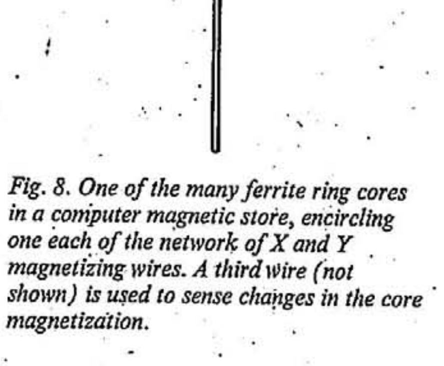

Fig. 8. One of the many ferrite ring cores in a computer magnetic store, encircling one each of the network of X and Y magnetizing wires. A third wire (not shown) is used to sense changes in the core magnetization.

only core to be reversed is the one encircling the particular X and Y wires selected, where the currents add up. So any core in the whole matrix can be selected for storing a 1 digit, corresponding to state $-R$, all in state R being 0 digits. That core can be interrogated by $+H$ currents in that particular pair of X and Y wires; if the encircling core was previously in the $-R$ state a signal is induced in the third wire; if in the R state, it is not.

Some of the newer ferrites have such enormous coercivities (such as 10 times greater than for the most effective magnet alloys) that even when powdered and embedded in rubber they are still strongly magnetic, with the added attraction of being able to surprise the uninitiated by their flexibility.

The principles we have been studying apply also to recorder tape in spite of the fact that the signals to be recorded are usually a.c. Because the tape is being drawn past the recorder head, any one line of magnetic material coating across the tape (call it L) is exposed to only one phase of one cycle of the signal; so as far as L is concerned the magnetizing force begins at zero, before L reaches the head, rises to a certain amount depending on the phase of the signal in the head coil at the moment L crosses the head gap, and then declines to zero again.

Good retentivity is needed to ensure that the coating retains enough magnetism to provide the playback head with an adequate signal. And coercivity should be enough to resist stray fields but not enough to necessitate an unreasonable erasing current. In connection with Fig. 3 I mentioned that the area inside the loop was a measure of the power loss in the core. To be more precise, it indicates the energy loss per unit volume per cycle. Now that we are thinking about materials for permanent magnets we look on this area from quite a different point of view and want it to be as large as possible. It still represents energy, but now it is the energy usefully stored in the material. Some recorder tape is described as "high-energy" tape, which one can correctly guess is tape coated with material having higher retentivity or coercivity or both compared with the usual sort which consists of ferric oxide. By treating this oxide with cobalt the retentivity and coercivity can be about doubled. This permits better signal/noise ratio (largely because of a small improvement at the high-frequency end) and signal level. Somewhat similar results are obtainable using chromium dioxide instead of ferric oxide. But unless the recording signal current and erase current are increased to the right extent, not only will benefits not appear but previous recordings will not be completely erased.

Of course the whole thing is complicated in ways we cannot go into here by h.f. "bias". Incidentally, have you ever considered that the magnetic detector used in the early days of wireless was a magnetic recorder in reverse, the incoming signals playing the part of what is now known as bias?

Letters to the Editor

The Editor does not necessarily endorse opinions expressed by his correspondents

Seeing in the dark

Though neither broadcaster nor camera manufacturer, may I be allowed to jump on the coat which Mr R. C. Whitehead trailed in your January issue?

He makes statements about the operating range of a television camera and the acuity of the human eye with which I, for one, will not quibble.

He goes on to suggest that modification should be made to camera channel characteristics when the camera is allowed to view scenes of low luminance in order, as he says, that the viewer should not be presented with information which a direct viewer of the scene would not perceive.

No doubt, as an engineer, Mr Whitehead resents the idea of unnatural reproduction but he must surely realize that the whole art of television broadcasting is the portrayal of an illusion, and I suggest that in his more relaxed moments he would find little to enjoy if he were presented with a truly accurate rendering of the scene in front of the camera.

The dark alleyway he mentions was probably anything but dark in the studio and it would have been inconvenient for it to be so. However, careful adjustment of the amount of light available to the camera tube together with adjustment of black level by the vision operator ensured that the illusion of gloom was successfully portrayed.

If a sports fan, would Mr Whitehead relish a true and accurate reproduction of the murky visibility of a football field or the low colour perception of a November handicap?

Some broadcasts from stately homes and gardens have inevitably been recorded under less than good lighting conditions. Should we not be grateful for the ability of the broadcaster to paint the lily and let us see something better than nature would have it be?

Mr Whitehead has not been fallacious but merely forgetful that there is more to broadcasting than the engineer's need to be faithful.

Gwilym Dann,
Chipstead,
Surrey.

If one is viewing under average ambient light, i.e. in the home, the "d.c." level about which the eye will operate on the 10-10 range will be different to that when the eye is subjected to low ambient conditions.

Thus when the broadcaster wishes to present to the viewer a scene shot under low luminance conditions he knows that his pictures are not going to contribute much to setting the "d.c." level about which the eye is operating at the time. The eye will probably be set at a much higher level than that coming off the screen.

Therefore some of the realism must be sacrificed for the sake of clarity, otherwise we would have to turn down the ambient lighting every time a night scene came up so that the eye could shift its "d.c." level down to that point which it would be if it were actually viewing the scene.

This brings me to the role of the programme director. It is his job to present via the TV medium a programme that the viewer can watch satisfactorily and understand. If he wishes to shoot some night scenes he must ensure that the viewer will understand the action or detail in that scene immediately because the viewer cannot get up out of his chair and inspect the scene more closely or at a different angle as one would if one were actually in the situation depicted.

This is the situation at the moment and if one were to degrade the pictures to the extent that Mr Whitehead suggests for the sake of more realism I'm sure that the viewer would find it very difficult to follow the action.

I cannot see why Mr Whitehead only picks on these points to say that the reproduction is unnatural because until we get 3D television of lifelike dimensions it will always appear unreal to the realist.

Stephen Waring,
Worcester Park,
Surrey.

Doppler effect in loudspeakers

In his letter in the January 1973 issue Mr Harwood draws attention to the large difference between my figure of 0.001% for the "just audible" Doppler distortion and the B.B.C. figure of 0.2% derived from the Stott and Axon investigations in the B.B.C. Research Dept in 1955.

He rightly points out that the two values cannot be compared because mine were obtained using pure tones, whereas the B.B.C. data was the result of group listening tests using ordinary programme material. This is an explanation with which I would entirely agree. In fact the