A Valve Amplifier for Ionisation Currents. By C. E. WYNN-WILLIAMS, Trinity College. (Communicated by Prof. Sir E. RUTHERFORD.)

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Attempts have often been made, by means of valve amplifiers, to magnify small ionisation currents so that they can be measured by galvanometers of comparatively low sensitivity. The instabilities in the amplifying system, generally due to fluctuations in the voltage of the batteries supplying the valve currents, cause erratic changes in the position of the zero of the galvanometer, rendering accurate working impossible. Consequently such methods have not come into general use. But yet the advantages arising from the substitution of a low sensitivity, short period galvanometer for a high sensitivity electrometer having a long time of swing, or a high sensitivity galvanometer, are so self-evident that any method of making a valve amplifier more reliable from the point of view of a steady zero is of interest.

In the present paper, a system of "compensation," involving the use of only two valves, is described, by which the trouble of an unsteady zero is overcome to such an extent that it is possible to measure ionisation currents of the order of 10^{-12} to 10^{-13} amperes by means of a galvanometer of low sensitivity. If desired, a table or recording instrument may be used for special work. The current amplification factor for the apparatus is of the order of 10^5.

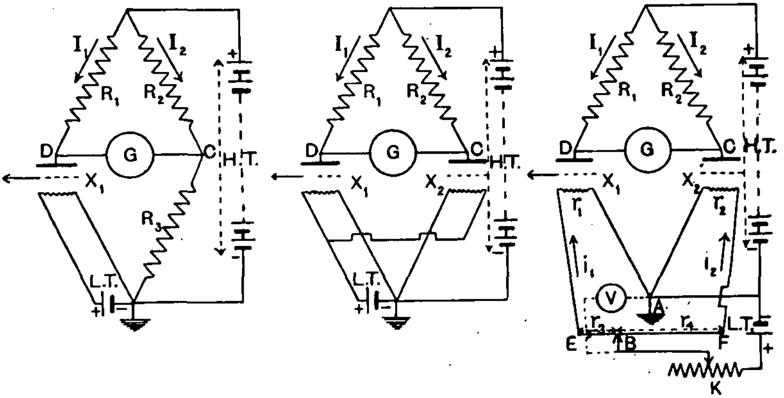
While the advantages of the system are discussed later, it may here be said that besides enabling a high sensitivity instrument to be replaced by a more robust and easily adjusted low sensitivity galvanometer, the compactness of the apparatus enables it to be moved from place to place, and quickly set up when required. It is thus specially suitable for lecture demonstrations, it being easily possible to illustrate with it such phenomena as the relative degrees of ionisation produced by α, β and γ rays, stopping powers, Bragg curves, decay curves, etc. The principle of compensation can also be applied to other valve apparatus where great steadiness of zero is required.

In addition to describing the actual methods of obtaining a steady zero, the characteristics of the apparatus are included in the account as a guide to any who desire to use this method for measuring ionisation currents.

Old Methods.

Valve methods of measuring ionisation currents generally depend upon the relaying action of the thermionic valve. The small current to be measured is sent through a high resistance, and the difference of potential set up across the latter is applied to the grid and earth terminals of a voltage amplifier. Alternatively, the ionisation current may be driven on to the insulated grid of a three-electrode valve, gradually raising its potential (in virtue of its small capacity) until the ionisation current is in equilibrium with the leakage current from the grid. In either case, the final result is the same—the change in grid potential causes the plate current in the valve to change, the increase or decrease (read by means of a galvanometer) being used to measure the ionisation current. A change of one volt in the grid potential usually results in a change in the plate current of the order of a milli-ampere.

The alternative method (in which the insulated grid is used) is the more sensitive, although this is only a particular case of the other method, for a certain amount of "grid-leakage" is always present, and may be regarded as the high resistance through which the ionisation current is being driven when a state of equilibrium has been established between the ionisation current and the leakage current.



(*a*) (uncompensated) (*b*) (uncompensated) (*c*) (compensated)

In each case, the grid of valve *D* is connected to the ionisation chamber, while that of *C* is free.

Fig. 1.

The usual circuit employed is shown in Fig. 1(*a*). In series with the plate *D* of a valve is placed a resistance R_1, of the order of 10,000 ohms, while two other variable resistances, R_2 and R_3, are connected in series across the high tension battery H.T., supplying the plate current. The ionisation chamber is connected to the grid, and the negative pole of the low tension battery L.T., supplying the filament heating current, is usually connected to earth. The galvanometer, *G*, is connected between the anode and the junction of R_2 and R_3.

Denoting the currents in R_1 and R_2 by I_1 and I_2, the galvanometer will be undeflected if the relation $R_1I_1 = R_3I_2$ is satisfied. Alternatively, denoting the impedance of the valve to the plate current by X_1, and regarding the system as a Wheatstone bridge, balance will be obtained when $R_1/R_2 = X_1/R_3 = I_2/I_1$. Any change in the potential of the grid (produced by the ionisation current) alters the value of I_1 (or of X_1) and so throws the system out of balance, giving rise to a galvanometer deflection which, it can be shown, is proportional to the change of grid potential*.

While such a system may have a large current amplification factor, an early limit is set to the minimum current that can be measured by it *by the unsteadiness of the zero*, and no advantage is to be gained by using an extremely sensitive galvanometer unless the system can be stabilised.

The unsteadiness of the zero is mainly due to the small changes of the plate current I_1 produced by small fluctuations of the voltage of the L.T. or H.T. batteries. In other words, the impedance X_1 of the valve is not constant, but a function of the L.T. and H.T. battery voltages. Hence, if R_1, R_2 and R_3 [Fig. 1(*a*)] are constant, any change in X_1, produced by battery voltage fluctuations, will result in the system becoming unbalanced.

This unsteadiness can be overcome to a certain extent by using another valve [Fig. 1(*b*)] similar to the first, and of impedance X_2, to replace R_3 [of Fig. 1(*a*)]. The first valve only is used as an amplifier, the second being idle. With two perfectly matched valves, the debalancing effects produced by battery voltage fluctuations would cancel out. No two valves, however, have characteristics sufficiently similar to give perfect compensation in this manner, although this circuit is an improvement on the one shown in Fig. 1 (*a*).

Compensated System.

The foregoing will have made it clear why valve methods of measurement, while they have been regarded with great interest as laboratory experiments, have not seriously been considered as possible rivals to the quadrant electrometer or high sensitivity galvanometer.

By means of the method described in subsequent pages, a valve bridge similar to the type shown in Fig. 1(*b*) can be changed from what might perhaps be regarded as a wireless toy, whose action was always accompanied by a considerable degree of uncertainty, to a physical measuring instrument, capable of giving useful and consistent results for a variety of purposes where an electrometer would normally be used.

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* Provided that the valve is operated on a suitable portion of its triode characteristic.

The necessary modification seems at first sight to be so superficial as to render such a claim absurd, it consisting of merely 30 cm. of Eureka wire, *EF*, connected to the filaments of the valves [see Fig. 1(*c*)]. But a consideration of the theoretical side of the question shows that this is not the case, the inclusion of the slide wire *EF* being the most natural and simplest way of enabling certain theoretical conditions to be realised experimentally, and not a haphazard addition to an existing older circuit.

It may be wondered why, if the circuit is so simple, it has not been already tried in the past. But again, even if it had been tried, the full advantages of it are only realised when it is properly adjusted in accordance with theoretical considerations. In other circumstances, little or no advantage will be gained over the older circuit of Fig. 1 (*b*).

Fortunately, these adjustments, while very necessary, are extremely simple to carry out, and when once made, do not have to be altered except on rare occasions. As in the older circuit of Fig. 1 (*b*), one valve only is used to amplify, the other being employed to make the system symmetrical. Any slight differences in the characteristics of the two valves are compensated for over a small, though sufficient range of working voltages, so enabling the advantages of a pair of perfectly matched valves to be realised experimentally.

As so much depends upon the theoretical considerations, a full discussion is given in the next sections. Meanwhile, in passing, attention is directed to the curves of Figs. 4(*b*), 4(*c*) and 4(*d*). These are records showing the degree of steadiness of zero attained for three systems; Fig. 4 (*b*), a *compensated* system as described here [Fig. 1(*c*)], and Figs. 4(*c*) and 4(*d*), *uncompensated* systems similar to those shown in Figs. 1(*a*) and 1(*b*). The advantage of this method of using valves is well brought out by a comparison of the curves.

Compensation for Low-tension Battery Voltage Fluctuations.

Assuming that the H.T. voltage is constant, the effects of small changes produced in the filament currents by a change in the low tension battery voltage is to alter the electronic emission of the filaments, and thus give rise to changes in the plate currents (I_1 and I_2). If the filament circuit can be so arranged that while I_1 and I_2 vary, their ratio is always kept constant during these changes, the galvanometer deflection will remain undisturbed by small L.T. battery voltage fluctuations.

For I_1/I_2 to be constant, we have

$$\frac{1}{I_1}\frac{dI_1}{dv}=\frac{1}{I_2}\frac{dI_2}{dv},$$

where v is the L.T. battery voltage. That is, the *percentage changes* in the plate currents must be equal. The two filament currents being denoted by i_1 and i_2, the above condition may be written:

$$\frac{1}{I_1}\frac{dI_1}{di_1}\frac{di_1}{dv}=\frac{1}{I_2}\frac{dI_2}{di_2}\frac{di_2}{dv}.$$

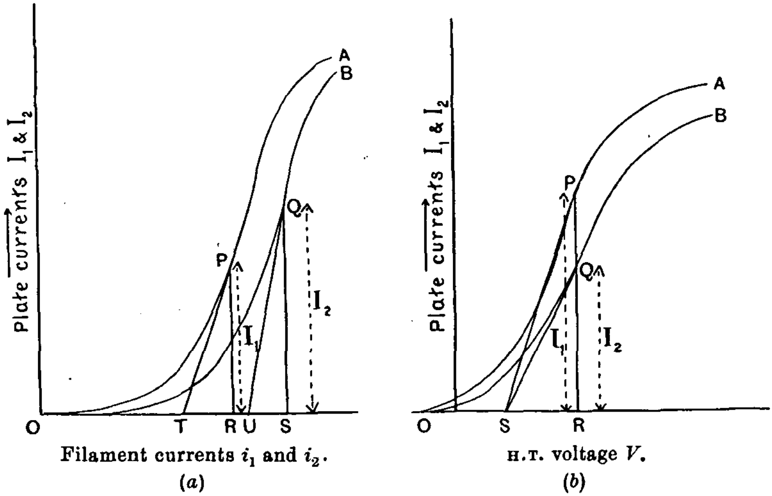
While the first two factors of each side of the equation

$$(dI_1/I_1 di_1 \text{ or } dI_2/I_2 di_2)$$

depend upon the characteristics of the valves, and the experimental conditions, the last (di_1/dv or di_2/dv) can be varied at will by a suitable adjustment of resistance in series* with the filaments (i.e. the slide wire EF).

For any given experimental conditions, $dI_1/I_1 di_1$ and $dI_2/I_2 di_2$ will have definite values. If, therefore, the values of di_1/dv and di_2/dv can be adjusted by means of the slide wire, until the ratio $\frac{di_1}{dv}\Big/\frac{di_2}{dv}$ is equal to the ratio $\frac{1}{I_2}\frac{dI_2}{di_2}\Big/\frac{1}{I_1}\frac{dI_1}{di_1}$, compensation will be effected, and L.T. battery voltage fluctuations will not upset the balance.

That this adjustment of the ratio of $\frac{di_1}{dv}\Big/\frac{di_2}{dv}$ is possible may be



Filament currents i_1 and i_2. (*a*)

H.T. voltage V. (*b*)

Note. These curves are illustrative only, and do not refer to specific conditions.

Fig. 2.

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* In this paper the filaments are assumed to be connected in parallel. By using *shunt* resistances, compensation can also be effected when the filaments are connected in series.

seen by considering the form of the emission curves for the valves. Fig. 2(*a*) shows the general form of the curves for two valves of the type employed in this apparatus, the plate current being plotted as a function of the filament current, and the H.T. voltage being assumed constant.

The shapes of the curves depend upon the type of valve employed, and the value of the H.T. voltage, etc. If two precisely similar valves were employed, the curves AO and BO would be coincident. Actually, they lie very close together, but are shown well separated in the figure to avoid confusion.

Let P and Q be two points on the curves, corresponding to the values of the filament current and plate current of the two valves under a given set of conditions. The perpendiculars PR, QS represent I_1 and I_2, while the slopes of the tangents PT, QU to the curves at P and Q will be measures of dI_1/di_1 and dI_2/di_2 (i.e. $dI_1/di_1 = PR/TR$ and $dI_2/di_2 = QS/US$). Hence

$$\frac{1}{I_1}\frac{dI_1}{di_1} = \frac{1}{PR}\frac{PR}{TR} = \frac{1}{TR}$$

and

$$\frac{1}{I_2}\frac{dI_2}{di_2} = \frac{1}{QS}\frac{QS}{US} = \frac{1}{US},$$

so that the ratio $\frac{1}{I_2}\frac{dI_2}{di_2}\Big/\frac{1}{I_1}\frac{dI_1}{di_1}$ (to which $\frac{di_1}{dv}\Big/\frac{di_2}{dv}$ must be made equal for compensation to be effected) is represented in the figure by the ratio TR/US.

This fraction, TR/US, can obviously have values ranging from zero to infinity, depending upon the positions of P and Q. In practice, it is endeavoured to operate the valves at points situated on fairly straight portions of their respective emission curves, as the compensation then holds over a greater range of L.T. voltage fluctuation. For a pair of similar valves the straight portions of the curves will lie close together, so that P and Q occupy approximately similar positions on their respective curves. Under these conditions, the value of the ratio TR/US is usually very close to unity.

The adjustment of $\frac{di_1}{dv}\Big/\frac{di_2}{dv}$ to this value is effected—as described in the next section—by altering the position of the slider B on the slide wire EF [see Fig. 1(*c*)]. Assuming the resistances of the filaments to be constant, and equal to r_1 and r_2, and of the portions of the slide wire in series with each to be respectively r_3 and r_4, it is clear that

$$i_1 = \frac{v}{r_1 + r_3}, \quad i_2 = \frac{v}{r_2 + r_4}$$

(v being the L.T. battery voltage), so that

$$\frac{di_1}{dv}\bigg/\frac{di_2}{dv}=\frac{r_2+r_4}{r_1+r_3}=\frac{r_2}{r_1}\left(\frac{1+\dfrac{r_4}{r_2}}{1+\dfrac{r_3}{r_1}}\right).$$

Thus, by altering the position of the slider on the wire, the ratio of r_3 to r_4 may be varied until $\dfrac{di_1}{dv}\bigg/\dfrac{di_2}{dv}$ is of the value required for compensation to be effected.

Practical Method of Compensating.

In effecting compensation it is not necessary to draw the characteristic curves for the valves and to determine from them the most suitable position of the slider B on the wire, and the value of the filament voltage, etc. A simple method of trial and error suffices, and is more convenient. In the first experiments, however, in order to investigate the matter properly, the characteristic curves were obtained.

Referring to the diagram of Fig. 1(c), the procedure of compensating is as follows*. The slider B (which divides the wire into the two resistances r_3 and r_4) is placed at the centre of the wire, and the voltage across AB is raised, by cutting out some of the resistance K, until it is near the normal working voltage of the valves (i.e. about 1·8 volts for dull-emitter valves). R_1 and R_2 are then adjusted until the system is balanced (i.e. until $R_1/R_2=I_2/I_1$), as shown by zero deflection of the galvanometer. (For this part of the work a table galvanometer, of sensitivity about 1 or 2 divisions per micro-ampere, is preferable to a reflecting galvanometer.) A small definite change of a few per cent. is then made in the voltage across AB, and the amount of debalancing, i.e. the number of divisions of the galvanometer deflection, observed. B is then moved to one end of the wire, and the operation of balancing and observing the galvanometer deflection for a given change in the

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* While in this method, the value of $\dfrac{di_1}{dv}\bigg/\dfrac{di_2}{dv}$ is adjusted to equal the existing value of $\dfrac{1}{I_2}\dfrac{dI_2}{di_2}\bigg/\dfrac{1}{I_1}\dfrac{dI_1}{di_1}$, the converse method is also possible, and sometimes more convenient. The ratio of $\dfrac{di_1}{dv}\bigg/\dfrac{di_2}{dv}$ is fixed by clamping down the slider B in one position, and the characteristic curves are searched by raising the voltage across AB until a pair of points P and Q are found for which the ratio $\dfrac{1}{I_2}\dfrac{dI_2}{di_2}\bigg/\dfrac{1}{I_1}\dfrac{dI_1}{di_1}$ is equal to the predetermined ratio $\dfrac{di_1}{dv}\bigg/\dfrac{di_2}{dv}$, indicated by a reversal in the galvanometer deflection.

voltage across AB is repeated. The same procedure is followed with B at the other end of the wire.

It may be found that at one end of the wire the galvanometer deflection for a given change in voltage across AB is *increased*, while at the other end it is either *decreased* or *reversed*. Should a reversal be obtained at one end, a point may be found (by trial and error) between that end and the centre of the wire, at which no debalancing occurs for a small change in the voltage across AB (i.e. at which the system is compensated). Should a reversal not be obtained at either end of the wire, the operation should be repeated with values of the filament voltage above or below the normal one.

Degree of Compensation Obtainable.

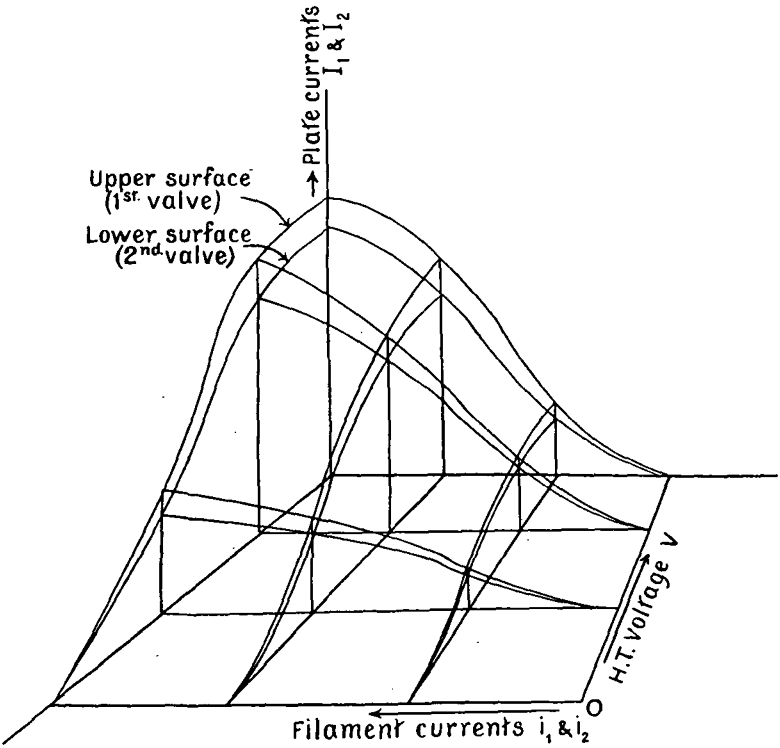
The degree of compensation obtainable, that is, the range of L.T. voltage fluctuation which produces no appreciable debalancing, depends on what portions of the emission curves P and Q lie upon. It is clear that if they lie on comparatively straight portions of the curves, for which dI_1/di_1 and dI_2/di_2 are constant, a larger L.T. voltage fluctuation can be compensated for than otherwise. By a suitable manipulation of the slider B and the rheostat K, it is possible to move P and Q along their respective curves, while still keeping the system compensated, until the optimum position is found, the relative degree of compensation in each case being measured by the ratio of the change in voltage applied to AB, to the amount of debalancing it produces.

To convey some idea of the results obtainable, it may be said that with the valves used in this apparatus, no difficulty should be experienced in compensating the system so that a change of about 0·05 volt across AB, in a mean value of between 1·60 and 1·90 volts, produces a change of less than 0·25 micro-ampere in the galvanometer current. This means that the ratio of I_1/I_2 is kept constant to about one part in ten thousand for a 2·5 per cent. change in the voltage of the low tension battery.

Compensation for H.T. Battery Voltage Fluctuations.

An investigation of the conditions for compensation for small fluctuations of the H.T. battery voltage results in a similar expression to the one relating to the L.T. battery voltage, i.e. $\frac{1}{I_1}\frac{dI_1}{dv}=\frac{1}{I_2}\frac{dI_2}{dv}$, v being now the H.T. voltage, the L.T. voltage being assumed constant.

On plotting the relation between I_1 or I_2 and v under normal working conditions, curves of the form shown in Fig. 2(*b*), similar to the well-known diode emission curves, are obtained. Since both valves are operated at the same H.T. voltage, the two points P and Q on the curves, at which the valves are operated, must lie on the same perpendicular PQR. Subject to this condition, it may be shown that the relation $\frac{1}{I_1}\frac{dI_1}{dv} = \frac{1}{I_2}\frac{dI_2}{dv}$ only holds if the two tangents PS, QS, to the curves at the points P and Q intersect at some point S on the axis of v. Whether such a pair of points P and Q, having a common point of intersection of their tangents on the axis of v, exists depends upon the shapes of the curves. If it does, H.T. battery voltage compensation is theoretically possible, although the value of v in such a case may not be suitable for practical purposes. The shape of the curves can be modified to some extent by altering the values of R_1 and R_2 while still



Note. The surfaces may or may not intersect. Here, for clearness, they are shown separate. Fig. 2 (*a*) represents a section perpendicular to the axis of V, and Fig. 2 (*b*) one perpendicular to the axis of i_1 and i_2.

Fig. 3.

keeping their ratio R_1/R_2 constant, which may or may not so alter the positions of P and Q as to make the corresponding value of v a suitable one for practical purposes.

Since the plate currents I_1 and I_2 are functions of both the H.T. and L.T. battery voltages, the curves shown in Figs. 2(*a*) and 2(*b*) must be regarded as perpendicular sections of two surfaces in three dimensions—one surface relating to each valve—similar to those shown in Fig. 3. While therefore individual compensation for either L.T. or H.T. voltage fluctuations may be separately effected, simultaneous compensation* for both these effects, which would mean exploring the surfaces of Fig. 3 for suitable working points, would be a very difficult and tedious process.

In practice, the debalancing produced by H.T. battery voltage fluctuation is not so serious as that produced by fluctuations in the L.T. voltage, and may generally be ignored if a rather larger capacity accumulator than is usual is employed for the H.T. battery. Under such conditions, low tension battery voltage compensation alone renders the zero sufficiently steady for currents of the order of 10^{-12} or 10^{-13} amperes to be dealt with.

Choice of Valves.

The first consideration in the choice of valves is the degree of amplification obtainable. It is assumed for simplicity that the total capacity and insulation of the ionisation chamber and grid is approximately the same whatever type of valve is employed, so that a given ionisation current causes the same change of grid potential in various cases. It may be shown that a change of grid potential E produces a change of galvanometer current equal to

$$E\frac{\mu}{2X+G\left(1+\dfrac{X}{R}\right)},$$

μ, X, R, and G being respectively the voltage amplification factor and impedance of the valves, the anode resistances, and the galvanometer resistance. (For simplicity, the system is assumed symmetrical.) If, as is usually the case, G is small compared with

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* Where great steadiness of zero is required, and a large capacity H.T. battery is available, *simultaneous* compensation may be effected by using a common L.T. and H.T. battery. The slider B [Fig. 1 (*c*)] should be connected through a resistance of about 150 to 300 ohms to the positive pole of the H.T. battery. As before, compensation is effected by varying the position of the slider B on EF until a small change in the voltage of the battery produces no debalancing. In this case, the characteristic curves on which P and Q lie are represented by a diagonal section of the surfaces of Fig. 3, the L.T. and H.T. being both represented proportionally on the horizontal axis. With this system, the size of the common 60 volt battery required to supply a filament current about a hundred times the value of the plate current is rather a drawback.

X, this may be written $E\mu/2X$. The greatest current magnification will therefore be given by a valve having a large value of μ/X, or mutual conductance: a power valve.

Another consideration is the type of filament employed. Dull emitter valves, operating at comparatively low filament temperatures, are obviously more suitable than the old bright emitter valves, not only on account of the smaller heating current required, but also owing to the fact that the smaller changes in the temperature produced by changes of filament current give rise to much smaller changes in the resistance of the filament, thus approximating more nearly to the assumption made on p. 816 that the resistance was constant.

Valves which give good results are the "Marconi 215" and "Osram 215," which normally require a filament voltage of 1·8, and a filament current of 0·15 ampere per valve. A two-volt accumulator of at least 30 ampere-hours capacity should be used for the L.T. battery. For the H.T. battery, a 60 volt 2·5 ampere-hour accumulator, preferably of the "block" type, is suitable. While the H.T. voltage may be increased to 120 with these valves, no advantage is gained unless large changes of grid potential, of the order of volts, have to be dealt with.

The average values of μ and X for the valves are 6·25 and 6·250 ohms. When a galvanometer of 50 ohms resistance, and 10,000 ohms anode resistances were employed, a milli-volt change in the grid potential gave rise to a galvanometer current of 1/3·15 micro-ampere, a good agreement with the value of approximately $\frac{1}{2}$ micro-ampere as calculated from the makers' average data.

Arrangement of Apparatus.

It is found convenient to have as much as possible of the apparatus mounted on a baseboard. Compensation then being once effected, the apparatus will remain in that state, and can be conveniently carried from place to place and quickly connected up as required.

The two valves fit into holders on an ebonite panel in an earthed metal box, screened leads to the grids of either valve being brought into the box by metal tubes. Connections to the anode resistances, batteries, etc. which are situated outside the box, are made with ordinary insulated wire. While such a high degree of insulation as is usual with electrometers is not required in this case, care should be taken that the insulation of the grid is not unduly lowered by poor quality ebonite, etc.

The slide wire EF consists of about 30 cms. of Eureka wire No. 28, having a resistance of between 1 and 1·5 ohms, and the sliding contact B is so arranged that it can be secured to the baseboard with wax when compensation has been effected. A scale under the wire is a convenience.

The anode resistances consist of two resistance boxes, each of 10,000 ohms, and a 500 ohm variable rheostat. The sliding contact of the latter serves as the common junction of the anode resistances, connected to the positive pole of the H.T. battery, while the two ends of the resistance are connected, through the 10,000 ohm boxes, to the anode terminals of the valves. By this means, the boxes being adjusted to the nearest 500 ohms, the system may be rapidly balanced by moving the sliding contact on the variable rheostat. This gives a convenient method of controlling the position of the zero of the galvanometer.

Most of the loose components (i.e. resistance boxes, voltmeters, etc.) can be conveniently situated on the baseboard and connected to appropriate terminals on the latter. The earth terminal should be connected to the point A [Fig. 1(c)] and also to the metal box surrounding the valves.

Precautions to be observed.

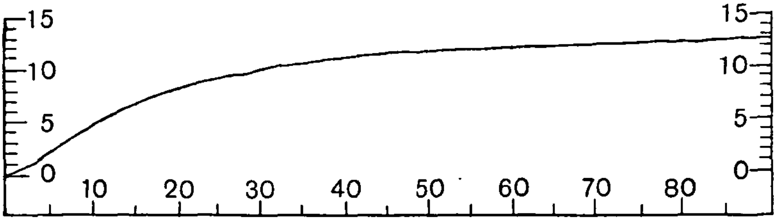
The zero of a new pair of valves, even after compensation has been effected, is very unsteady for some time. This is due to the fact that, the filaments being "thoriated," a state of equilibrium has to be established at their surfaces. After the system has been in operation for about 50 hours under normal conditions, the zero will be found to be very much steadier. A slight change in the position of the slider B on EF may be necessary during the first 50 or 100 hours, but finally it may be secured to the baseboard, and need only be altered if other valves are used, etc.

The valves should not be interchanged, used alone or together for any other purpose, or operated at values of the H.T. voltage other than the normal one employed during compensation, or the state of equilibrium will be disturbed. The L.T. battery should therefore be *connected last* and *disconnected first*, and the apparatus not operated if the H.T. circuit is broken by the omission of one or both of the anode resistances.

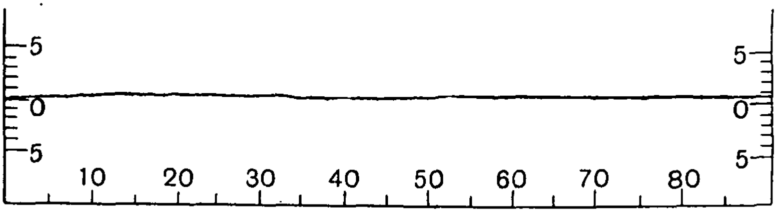
Trouble arising from electrostatic effects can be largely eliminated if it is observed that, as far as possible, the earth terminal of the apparatus is connected to the *same* earth wire as any other apparatus (i.e. ionisation chamber, battery, etc.) employed with it, and that if water, or other safety resistances are employed, they are placed near the ionisation chamber, and *not* in the earth lead.

Steadiness of the Zero.

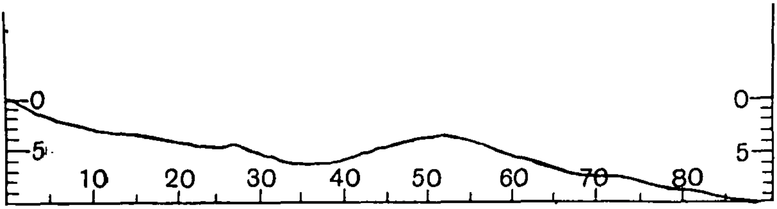
In order to investigate the steadiness of the zero of the system, and to compare it with those of other systems, a recording galvanometer, kindly lent by Dr C. D. Ellis, was used in place of the ordinary one. This instrument, which gave a full scale deflection for 25 micro-amperes, enabled a great deal of information to be



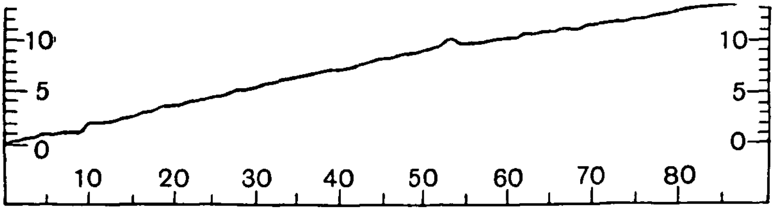
(*a*) Curve for compensated system [Fig. 1 (*c*)] before temperature equilibrium has been established.



(*b*) Curve for compensated system [Fig. 1 (*c*)] under normal conditions.



(*c*) Curve for uncompensated system [Fig. 1 (*a*)] under normal conditions. [Compare with (*b*) above.]



(*d*) Curve for uncompensated system [Fig. 1 (*b*)] under normal conditions. [Compare with (*b*) above.]

Fig. 4.

obtained which might otherwise have been overlooked, and greatly facilitated the investigation.

The recorder, arranged to take readings every half minute, was started immediately after the valves had been switched on and the system balanced, the grids being left unconnected. Except during the first few days, during which the system was establishing its state of equilibrium as previously explained, the curve traced by the recorder was of the form shown in Fig. 4(*a*), the same form being obtained on repetition. For the first half hour or hour, the zero drifts to a new position, the amount of drift in this case being about 12 micro-amperes. This drift is due to the fact that a temperature equilibrium has to be established between the various electrodes within the valve. If the system be re-balanced at the end of an hour after switching on, the zero is very steady, though a very small drift is almost always present, even after the system has been in operation for several hours. Generally, this does not exceed ½ to 1 micro-ampere per hour, and takes place at a *steady rate*, so that allowance may be made for it by taking the initial and final zero positions during an experiment.

This residual drift is probably due, not to imperfect compensation, but to the fact that the physical conditions of the two filaments change slowly when in use, at slightly different rates. The drift is shown in the record of Fig. 4(*b*), taken several hours after first switching on. It will be observed how regular this effect is, there being little trace of any other disturbance present.

For comparison, two curves, Figs. 4(*c*) and 4(*d*), were obtained, when the recorder was connected to a single valve uncompensated system [Fig. 1(*a*)] and a double valve uncompensated system [Fig. 1(*b*)]. These curves were taken under the same conditions as the curve of Fig. 4(*b*), with which they should be compared. The superiority of the compensated system as a physical instrument is self-evident.

Characteristics of the System.

The behaviour of the instrument is very similar to that of a quadrant electrometer used in conjunction with a leak across the quadrants, the ionisation current in both cases being measured by the steady deflection it gives rise to, the leak in the case of the valve system being the natural grid leakage*. It will therefore be convenient and useful to effect a comparison between the two types of instruments, and to refer to the characteristics of the system (e.g. capacity, insulation, etc.) as if it were an electrometer used with a leak.

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* The similarity is carried further by the fact that the perfectly insulated grid of a hard valve would retain a negative charge indefinitely. In such a case, a negative ionisation current to the grid would result in a steady increase in the potential of the latter, giving rise to a regular movement of the galvanometer. The current could, in this way, be measured in a similar manner to that employed for an electrometer without a leak. Such a system might, however, be unstable without a leak to earth of some sort.

Capacity. The electrostatic capacity of the grid on open circuit is usually of the order of a few centimetres, the system in this respect corresponding to an electrometer of low capacity.

Voltage sensitivity and uniformity of scale. By applying various potentials to the grid by means of a potentiometer connected to the negative end of the filament (and hence, to earth), and observing the galvanometer deflections, it was established that the deflection was proportional to the change in grid potential*. A change of grid potential of one milli-volt gave rise to a galvanometer current of 1/3·15 micro-ampere. Used in conjunction with a galvanometer of sensitivity 200 mm. per micro-ampere, the system has therefore a voltage sensitivity of 6350 mm. per volt. The normal "floating" potential of the grid was found to be slightly negative. This corresponds to contact potential in the electrometer.

Current sensitivity and uniformity of scale. For the purpose of determining the current sensitivity of the system, a direct comparison was made with a quadrant electrometer and leak. Various positive and negative ionisation currents were driven, in turn, to the electrometer, and on to one of the grids, and the deflections of the two instruments were compared. The deflections caused by currents up to $3·5 \times 10^{-12}$ amperes were measured quantitatively, while the effect on the system of currents greater than these was determined qualitatively.

It was found that, in general, a given negative ionisation current produced a slightly larger deflection than a positive one of equal amount. The current amplification factor *increases with increasing negative grid potential, and decreases with increasing positive grid potential.* The increase in magnification becomes very large for large negative ionisation currents—a fact which can be utilised to exaggerate phenomena in lecture demonstrations. With the particular valves used, the current amplification factor for positive ionisation currents up to $3·5 \times 10^{-12}$ amperes was found to be almost constant, and of the order of $1·13 \times 10^{5}$†.

The reason for the variation of the current amplification factor for positive and negative currents lies in the difference in the rate of leakage from the grid of positive and negative charges. Grid leakage is due to (1) imperfect insulation of the grid, and (2) the emission current between the grid and the filament. While the grid current due to the former is a linear function of the grid potential—the insulation resistance of the grid being constant—

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* This shows that the valve is operated on a suitable portion of its triode characteristic curve.

† As one of the two valves employed is sometimes found to be more sensitive than the other for current amplification, it is advisable to try both in turn and observe which is the better. The small differences in grid current characteristics and hardness, which affect the sensitivity, are not usually apparent in the tests to which valves are subjected by the makers.

the emission current increases with increasing positive grid potential, and decreases, tending to zero, with increasing negative grid potential. The grid leakage is therefore greater for a positive charge on the grid than for a negative, so that a given negative ionisation current raises the grid to a numerically higher potential than does a positive one of equal amount. The presence of a trace of gas in the valve, i.e. the valve not being perfectly hard, results in an increase of both positive and negative leakage currents, which tends to make the current amplification factor more nearly uniform for positive and negative ionisation currents.

Leak. A distinction must be made between the insulation resistance of the grid when the filament is cold, and the resistance between the grid and filament when the latter is emitting electrons.

The former, determined in the usual way for high resistances, i.e. condenser discharge, was found to be of the order of 70,000 to 85,000 megohms*.

The latter, which corresponds to the leak used with an electrometer to obtain steady deflections, was estimated by calculating, from the results of the two preceding sections, the rise of grid potential produced by unit ionisation current. This gave a value of 360 megohms, very much smaller than the cold insulation resistance. While therefore good insulation of the ionisation chamber is desirable, it is evidently not necessary to have such a high degree of insulation as when working with an electrometer, a very important advantage.

The Apparatus considered as an Electrometer.

Collecting the data given in the preceding section, it may be said that, in conjunction with a galvanometer of sensitivity 200 mm. per micro-ampere, the system can be regarded as equivalent to an electrometer of small capacity, having a voltage sensitivity of 6350 mm. per volt, and shunted by a leak of 360 megohms. The resistance of the leak increases with increasing negative current, and decreases with increasing positive current. In addition, it has the advantages of portability, compactness, and ease of erection and operation. The lower time of swing, dependent only upon the type of galvanometer employed, is also an advantage.

The lower limit to the minimum current that can be measured by the apparatus is governed by the steadiness of the zero. In spite of careful screening, it is almost impossible to eliminate completely small fluctuations of the galvanometer zero, due, not to imperfect compensation, but to electrical disturbances from induction coils, etc., which are picked up by the apparatus. For this particular apparatus, the lower limit appeared to lie between

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* This includes leakage of the valve cap and valve holder, etc.

10^{-13} and 10^{-12} amperes, the deflections produced by currents less than 10^{-13} amperes being of the same order as the galvanometer zero fluctuations. Increasing the sensitivity of the galvanometer beyond a certain limit does not therefore extend the range. The current amplification factor could, of course, be increased, by giving to the grid a suitable negative bias through an ionisation leak* but this would probably result in increased unsteadiness of the zero also.

The explanation of the unsteadiness caused by electrical disturbances is interesting. When an inductive circuit is broken, as when an induction coil is operated near the apparatus, an electric wave is set up, which induces an electric oscillation in the leads connected to the grid. The alternations of potential on the grid are rectified, in virtue of the dissymmetry of the grid leakage for positive and negative grid potentials, so that the grid acquires a mean negative potential, causing a reduction of the plate current. The characteristics of the two valves being different, a nett change takes place in the galvanometer current, resulting in a kick for each wave train picked up by the apparatus. Balance is restored as the grids recover their normal floating potential.

The similarity between this effect and the grid condenser and leak method of rectification suggests the possibility of using the apparatus as a sensitive wireless detector†.

The use of the instrument is not confined to the measurement of ionisation currents. By connecting a high resistance between the grid and earth, it can be used in the usual way for amplifying other small currents, *provided that the circuit contains sufficient potential to drive the current through the high resistance.* This will be the case when the other resistances in the circuit are large compared to the auxiliary resistance connected between the grid and earth. The current amplification factor for such a system is given by

$$\frac{\mu S}{2X + G\left(1 + \frac{X}{R}\right)},$$

S being the auxiliary resistance. When used for measuring ionisation currents, S takes the form of the natural grid leakage, viz. 360 megohms, corresponding to a value for the factor equal to $1{\cdot}15 \times 10^5$.

With a comparatively low value of S, which might have to be

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* An ionisation or other saturation leak would have to be used to smooth out fluctuations of the bias battery voltage.

† This type of apparatus has been tried by Mr J. A. Ratcliffe for signal-strength measurements, and found to be very useful for this type of work, being superior to an ordinary valve detector on account of its steady zero, and less troublesome than a crystal rectifier.

used in certain circumstances, the value of the factor would be considerably reduced, a large current magnification only being obtained with an insulated grid.

In conclusion, it may be said that the method of compensation can be applied to other valve apparatus where a steady zero is required. By omitting the galvanometer G [Fig. 1 (c)] the system becomes a voltage amplifier. A change E in the grid potential gives rise to a potential difference equal to $E\mu R/(X+R)$ between the two anodes, the value of the factor being as large as 30 or 40 when suitable "resistance-capacity" valves, having a large value of μ, are used in conjunction with anode resistances of the order of 10^6 ohms.

If either or both of the grids are to be earthed, through tuning coils, transformers, etc., *compensation should be effected under the conditions under which the apparatus will be operated*, and not with the grids insulated, as the characteristic curves (Fig. 2) are different in the two cases.

Summary.

A method of using a valve for amplifying ionisation currents 100,000 times is described, which avoids the instabilities usually associated with such apparatus. The necessary conditions to be satisfied, while extremely simple, are based on theoretical conditions which are discussed in full. Used in conjunction with a galvanometer of sensitivity 200 mm. per micro-ampere, the system behaves in a similar manner to a low capacity quadrant electrometer of sensitivity 6350 mm. per volt, shunted by a leak of 360 megohms, the value of the latter being slightly greater for negative currents than for positive. In addition, it has the advantages of portability, compactness, and ease and rapidity of erection and operation, being specially suitable for lecture demonstrations.

The method of compensation can also be applied to other valve circuits, resulting in a much steadier zero.

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