A DIRECT-READING DYNAMIC ELECTROMETER

by J. van HENGEL and W. J. OOSTERKAMP. 621.317.723.082.742:621.386.82

A description is given of a direct reading d.c. electrometer. It is based on the dynamic principle, the direct voltage being converted into an alternating voltage with the aid of a parallel-plate capacitor, the capacitance of which changes periodically as one plate is kept stationary while the other is kept in vibration. The alternating voltage is applied to an amplifier with conventional valves; the output voltage is rectified and the conducted direct voltage measured with a moving-coil meter. In order to keep the amplification constant, a high degree of negative feedback is applied by connecting the output d.c. voltage wholly or partly in opposition to the voltage to be measured. This makes it necessary to use a special rectifying circuit which is sensitive to the polarity of the a.c. input voltage. Due in part to the direct-voltage feedback, the (apparent) input resistance reaches extremely high values (more than $10^{14}$ Ω). Two instruments are discussed: a millivoltmeter (full deflection at 100 mV) for laboratory measurements, and a dosimeter for X-rays (in combination with an ionization chamber and a measuring resistor). The dosimeter has a scale calibrated in r/min and covers a very wide measuring range, from $4 \times 10^{-7}$ r/sec (fraction of the tolerance dose) to 200 r/sec (contact therapy). For the calibration a standard-current generator has been designed which supplies a calibrated current of $10^{-4}$ A.

In many investigations in the field of physics and of electrical engineering the tension of direct-voltage sources which have a high internal resistance have to be measured. It is then essential that the voltmeter used should draw as little current as possible, so that the difference between the e.m.f. of the voltage source and the measured voltage under load is kept as small as possible.

Sometimes, when small direct currents are to be determined, the voltage produced across a high-ohmic resistor through which the currents flow is measured. Such cases occur not only in physical investigations but also, as will be shown farther on, in the daily routine of X-ray therapy. In these cases, too, one must have a voltmeter with very high resistance, since the meter bridges the measuring resistor and thus sets an upper limit to the resistance formed by the parallel connection of the two, thus limiting the sensitivity of the circuit.

In the cases mentioned one may often advantageously use an electrometer. This is an instrument in which the deflection is brought about by the electrostatic effect of charges and which therefore, in principle, consumes no current at all (apart from the charging current required to give the instrument a deflection, and the leakage current due to the finite insulation resistance).

A special form of electrometer is a triode — or, more generally, an electronic valve with a control grid — so arranged that no grid current flows through it. The word "no" is not to be taken too strictly, since owing to various causes the grid current is not generally absolutely zero; such causes may be imperfect insulation between the grid and other electrodes, ionic current flowing to the grid, or thermionic and photo emission from the grid. The methods applied in the special triode for use as an electrometer (type 4060) have already been described in this journal 1). Within a wide range of conditions the grid current of this triode can be reduced to less than $10^{-14}$ A.

Here an electrometer will be described which, at full deflection, has a current consumption even $10^2$ to $10^3$ times smaller, so that the internal resistance of the source of the voltage to be measured, or the resistor through which the current to be measured flows, may be a corresponding factor larger. Moreover, this instrument has the advantage that, as opposed to some other electrometers, it gives a direct reading, whilst furthermore no special valves are required, only normal pentodes and rectifying valves being employed.

Principle of the dynamic electrometer

Our instrument is a further development of the dynamic electrometer described by Dorsman 2), the principle of which is as follows. The direct voltage to be measured is applied via a high-ohmic resistor to a capacitor one of the plates of which is kept in vibration (for instance, with the aid of a loudspeaker system — see fig. 1 — and a

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1) H. van Suchtelen, The electrometer triode and its applications, Philips Techn. Rev. 5, 54-59, 1940.
valve oscillator), so that the capacitance varies periodically. Just as in the case of a condenser-microphone, an alternating voltage is produced across the capacitor which at a given amplitude of vibration is proportional to the direct voltage applied. This alternating voltage is led via a coupling capacitor \( C_2 \) to a normal a.c. pentode amplifier. The input resistance of the electrometer is mainly governed by the insulation of the coupling capacitor and that of the vibrating capacitor. With amber, polystyrene and similar substances as insulating material (and if desired as dielectric in the coupling capacitor) both capacitors can be given a much higher insulation resistance than is possible with an electrometer triode.

The electrometer described by Dorsman was designed for measuring the potential of a "glass electrode", from which potential the acidity \( (p_H) \) of a solution can be derived. The method of measuring is a zero method: the voltage to be measured is applied to the input of the electrometer in opposition to a reference voltage derived from a compensator, the latter voltage being so adjusted that the alternating voltage at the output of the amplifier is zero; this is observed on a cathode-ray indicator connected to the output. When the output voltage is zero the two d.c. input voltages are equal, so that the unknown potential may be read from the compensator calibrations.

The zero method is suitable for the accurate measurement of very low voltages and has, moreover, the advantage that variations in the amplification or in the amplitude of the vibrating capacitor (due, for instance, to mains voltage fluctuations) only affect the precision of the adjustment and not the reading.

For many purposes, however, a direct-reading instrument is to be preferred, where no adjustments have to be made for every measurement, so that one's hands are left free and, moreover, the work can be done more quickly. It is then obvious that there should be connected to the output of the electrometer amplifier a measuring instrument provided with a scale calibrated in the units of the quantity to be measured, for instance mV.

Of course the favourable features of the zero method were to be retained as far as possible, and therefore the amplifier had to be of such a type that its amplification factor is reasonably constant, both in the event of mains voltage fluctuations and in the case of a variation of the characteristics of the valves. This requirement of constancy in the amplification has made it necessary to introduce drastic modifications of the electrometer amplifier used for \( p_H \)-measuring before it was possible to realize a direct-reading instrument.

Following these lines we have so far made two types of direct-reading dynamic electrometers for laboratory work, one as a mV-meter with very high impedance for general laboratory use, the other provided with a scale in röntgens per minute for measuring X-ray doses (with the aid of an ionization chamber). The circuit arrangements of both these types are mainly the same.

**Direct-voltage feedback**

The desired constancy of the amplifying factor is obtained by applying feedback \(^2\) to a high degree, by returning the output voltage \( E_2 \) (fig. 3) either wholly or in part to the input and there connecting it in opposition to the voltage to be measured, \( E_1 \). The output voltage must therefore be a direct voltage (which can thus be measured with a moving-coil meter); it is obtained with the aid of a rectifier connected to the output of the amplifier. Thus the feedback is a direct-voltage feedback.

Across the vibrating capacitor is the direct voltage \( E_1 - E_2 \). The vibration sets up a proportional alternating voltage \( v_1 \):
\[
v_1 = a_1 (E_1 - E_2),
\]
which is amplified by a factor \( a_2 \) to the a.c. output voltage \( v_2 \):
\[
v_2 = a_2 v_1 = a_1 a_2 (E_1 - E_2).
\]

Fig. 3. Circuit diagram of the direct-voltage negative feedback system applied in our electrometer. \( E_1 \) = direct voltage to be measured; \( E_0 \) = d.c. output voltage; \( v_1 \), \( v_2 \) = a.c. input and output voltage, respectively of the amplifier \( A \); \( T \) = transformer; \( R \) = rectifier with smoothing capacitor \( C_2 \); and \( M \) = moving-coil voltmeter. The other letters have the same meaning as in fig. 2.

From this the rectifier produces the direct voltage \( E_2 \) proportional to the amplitude of \( v_2 \) (proportionality factor \( a_3 \)):
\[
E_2 = a_1 a_2 a_3 (E_1 - E_2).
\]
Thus we have for the ratio \( p \) between the d.c. output voltage \( E_2 \) and the direct voltage to be measured \( E_1 \):
\[
\frac{E_2}{E_1} = p = \frac{a_1 a_2 a_3}{1 + a_1 a_2 a_3} = \frac{A}{1 + A}.
\]
when \( A = a_1 a_2 a_3 \).

The factors \( a_1 \), \( a_2 \) and \( a_3 \) depend more or less upon the properties of the oscillating, amplifying and rectifying valves respectively and upon the supply voltages (and thus the mains voltage). If however, it is arranged that \( a_1 a_2 a_3 \) is always large with respect to unity, then \( p \approx 1 \) and therefore practically constant, in spite of fluctuations in the values of \( a_1 \), \( a_2 \) and \( a_3 \). Now \( a_1 \) and \( a_3 \) are both smaller than unity, but \( a_2 \) can be made so large that in fact \( A = a_1 a_2 a_3 \gg 1 \). This requirement has been met in both forms of construction of our electrometer.

A limit is set to the raising of the value of \( A \) owing to the fact that at a higher amplification the system would become unstable, that is to say it would oscillate at a frequency depending upon the time constants of the circuits contained in the system. The larger the time constants, the more the amplification can be raised, but the adjustment time of the instrument becomes longer.

With the method of feedback applied the direct voltage across the vibrating capacitor is not \( E_1 \) but only \( E_1 - E_2 \), which may well be 30 times smaller than \( E_1 \). This means that the leakage current flowing across the capacitors \( C_1 \) and \( C_2 \) at a given insulation resistance is reduced. It is partly due to this fact that the (apparent) resistance between the input terminals is exceptionally high.

As regards the a.c. losses in the resistors \( R_1 \) and \( R_2 \) (and the resistor \( R \) to be discussed farther on), it must be noted that these are supplied by the oscillator driving the vibrating capacitor. These losses, therefore, do not form any load upon the voltage source to be measured.

Rectification

If the rectifier (\( R \), fig. 3) were arranged according to one of the conventional methods, where the direct voltage obtained depends only upon the amplitude and not upon the phase of the a.c. input voltage, an unstable situation would arise, as may be seen from the following numerical example.

Let \( A = 30 \), thus, according to eq. (1), \( p = \frac{30}{31} \), and let \( E_1 \) be 100 mV, thus \( E_2 = \frac{30}{31} \times 100 = 97 \) mV. (The scale of the moving-coil meter to which \( E_2 \) is applied is such that the instrument indicates \( E_2/p = E_1 \), in this case 100 mV). \( E_1 - E_2 = 3 \) mV.

Let us suppose, further, that \( E_1 \) suddenly drops to 94 mV. Since \( E_2 \) cannot change quickly, \( E_1 - E_2 \) becomes at first \(-3 \) mV, in consequence of which \( v_1 \) and \( v_2 \) maintain the same amplitude but change polarity, which amounts to a phase shift of 180°. An ordinary rectifying system, however, is insensitive to this change and \( E_2 \) is kept at 97 mV. The situation is now unstable: any further drop of \( E_1 \) is accompanied by a rise in the absolute value of \( E_1 - E_2 \), and also in the output voltage \( E_2 \). The negative feedback is turned into a positive feedback.

Besides this hypothetical experiment, any normal switching-on leads to instability, since \( E_2 \) builds up in an oscillatory way, so that there will be moments when \( E_1 - E_2 \) is negative and the pointer of the instrument swings beyond the end of the scale.

To avoid this instability a rectifying system has been designed in which, when \( v_2 \) changes 180° in phase, \( E_2 \) tends to drop and to restore the proper polarity of \( E_1 - E_2 \). When \( E_2 \) has reached \( p \) times the new value \( E_1 \) — in the example just given, therefore, \( \frac{30}{31} \times 94 = 91 \) mV — equilibrium is again obtained, \( E_1 - E_2 \) again having practically its
original value (+3 mV). At this lower value of $E_2$ (91 mV) the meter indicates the exact value of $E_1$ (94 mV).

Fig. 4 represents the rectifying system in question. The polarity of $V_3$ is compared with that of the alternating voltage $V_2$ derived from the oscillator driving the vibrating capacitor. Special measures (to which we shall refer later) have been taken to ensure that the phase difference between $V_2$ and $V_3$ can only be either 0° or 180°.

This systems functions in the following way.

![Fig. 4. Circuit of the phase-sensitive rectifier.](image)

For alternate half cycles $V_2$ causes current to flow through the diodes $D_{III}$ and $D_{IV}$ and the resistors $R_3$ and $R_4$. During these half cycles voltages are developed across these resistors which, apart from voltage losses, are equal to $V_2$. The resistors also form part of the circuits via which the smoothing capacitor $C_3$, across which the output voltage $E_2$ is developed, either receives charge from the transformer $T$ (via the diode $D_I$) or is discharged (via the diode $D_{II}$). When the phase shift between $V_2$ and $V_3$ becomes 180° then — as will be explained below — a change takes place in the ratio of the quantities of the charge fed to and drawn from $C_3$ per cycle, thus changing $E_2$ in the desired direction.

Let us first consider the situation where the direct voltage across the vibrating capacitor has the normal polarity ($E_1 - E_2 > 0$). The system must be then so adjusted that $V_2$ has the polarity at which $A$ is positive with respect to the terminal of $T$ connected to $C_2$ (fig. 4) during the half cycles in which $D_{III}$ and $D_{IV}$ are non-conducting; within these half cycles the capacitor $C_3$ receives a charge via $D_I$ (so long as $V_2 > E_2$) and gives off a charge via $D_{IV}$ (so long as $V_2 < E_2$)

4) For the sake of convenience we speak of "half cycles" although actually the intervals referred to differ slightly from half a cycle. We shall not go into this because it is of no consequence for our arguments.

These valves not being blocked by the voltages $V_2$. During the other half cycles the diodes $D_{III}$ and $D_{IV}$ are conducting and, as we have seen, across each of the resistors $R_3$ and $R_4$ there lies the voltage $V_3$. This voltage is chosen high enough to block the diodes $D_I$ and $D_{II}$; thus the voltage $V_3$ does not cause any current to flow. As a result the voltage $E_2$ adjusts itself in such a way that the capacitor $C_2$ receives (via $D_I$) per cycle just as much charge as it gives off (via $D_{II}$ and via the meter connected to $C_3$).

We shall now consider the case where $E_1 - E_2 < 0$. The polarity of $V_2$ at which $A$ is positive with respect to the terminal of $T$ connected to $C_2$ then occurs during the half cycles in which $D_{III}$ and $D_{IV}$ are conducting, and consequently — just as was the case before — $D_I$ and $D_{II}$ are blocked. During the other half cycles ($D_{III}$ and $D_{IV}$ non-conducting) no charge can flow to $C_3$ via $D_I$ ($V_3$ has the wrong polarity for that) but charge can flow from $C_3$ through $D_{II}$. Thus the case in question ($E_1 - E_2 < 0$) leads to a drop in $E_2$, as was desired.

With this system two valves suffice if double diodes (type EB4) are used as indicated in fig. 4. Any voltage superimposed upon $V_2$ with a frequency different from that of $V_2$ and $V_3$ as a rule contributes little or nothing towards $E_2$. In other words, the rectification is selective, so that an interfering voltage with the mains frequency or resulting from "microphonic effect" will have little influence. The selectivity is still further increased by tuning the transformer $T$ (fig. 4) with a parallel capacitor ($C_4$) to the frequency of vibration (125 c/s, midway between two harmonics of 50 c/s, so chosen as to avoid trouble from these harmonics). Although this circuit has so much damping that the voltage gain is of little significance, harmonics of $V_2$ are effectively suppressed.

**Amplifier**

From the explanation of the functioning of the rectifying system it will be clear that changes in the phase angle between $V_2$ and $V_3$ will affect the amplitude of $E_2$. When, in the amplifier, circuits are used with little damping and tuned to the frequency of the vibration — as is the case in the amplifier designed for $pH$-measurements (see footnote 5) — then the phase of $V_2$ changes considerably with small variations in the frequency of vibration or in the event of a slight detuning. In order to avoid this we have not used any tuned circuits in the amplifier for our electrometer (the circuit $T-C_4$ previously mentioned — fig. 4 — is so strongly damped as not to endanger phase stability).

We employ a resistance-coupled amplifier (fig. 5) with two stages. The value of the coupling capacitors $C_a$ and $C_b$ has been so chosen that, in combination with the resistors $R_5$ and $R_6$ respectively, they bring about an appropriate phase shift such as to bring
Fig. 5. More detailed diagram of the direct-reading electrometer (cf. fig. 3). $R_s$, $C_s$ and $R_o$ = circuits for bringing $v_2$ into phase with $v_0$, $R_p$, $C_p$ = smoothing circuit via which the d.c. output voltage (or a part of it) is returned to the input; $S_1$, $S_2$ = switches for varying the sensitivity: in position 1 the full deflection is at 1000 mV input voltage, in position 2 at 300 mV, in position 3 at 100 mV; $P_1$ = potentiometer for zero point correction; $P_2$ = potentiometer for scale correction; $V_b$ = supply voltage. The other letters have the meaning given in figs 2 and 3.

The dimensions of the circuit $C_2$-$R_2$-$C_5$-$R_s$ are such that voltages having the frequency of vibration are little attenuated in contrast with interference voltages derived from the first or second harmonics of the mains frequency. Thus the overall selectivity is improved. As an illustration of the strong filter action obtained in this manner it can be stated that an interfering voltage of 200 mV r.m.s., 50 c/s, superimposed upon an input direct voltage $E_1 = 10$ mV, does not affect the meter reading.

Fig. 6 shows how little the reading is affected by mains voltage fluctuations, due to the method of negative feedback applied; a variation in the mains voltage from the nominal value (100%) to 90% or 110% gives at most a difference of 1% on the meter.

Further details of the electrometer

The electrometer was designed for 100 mV at full deflection, corresponding to an accuracy within about 1 mV. This relatively low voltage-sensitivity enhances the reliability of the instrument and has, moreover, the advantage that as a rule no trouble is experienced from statistical current fluctuations. With this degree of sensitivity the direct voltage across the vibrating capacitor at the full deflection amounts to about 3 mV.

In cases where voltages higher than 100 mV have to be measured a switching device is used; this will be dealt with presently.

The reading is taken from a moving-coil meter giving full deflection when a current of 50 μA is flowing through the coil.

Zero adjustment is made in the first place, as far as the meter itself is concerned, with the normal zero adjustment of the pointer. In addition there is an electrical correction: by means of the potentiometer $P_1$ (fig. 5), connected to a small auxiliary direct voltage, any changes in the contact potential on the plates of the vibrating capacitor can be compensated.

The calibration of the meter can be corrected with the aid of the potentiometer $P_2$.

In the types already constructed the resistance between the input terminals of the electrometer is more than $10^{15}$ Ω and the input capacitance about 40 pF.

Still more favourable values can be reached by applying the variation of the input circuit illustrated in fig. 7 (so far this has not been normally applied). The insulation of the non-earthed input terminal is screened with a guard ring brought to the potential $E_2$. As we have already seen in the case of the capacitors $C_1$ and $C_2$ owing to this measure the insulation is only loaded with the voltage $E_1 - E_2$ = about $E_1/30$. As a consequence the apparent input resistance is greatly increased and the apparent input capacitance many times reduced.

Fig. 6. Variation of the deflection (nominally, e.g., 55 scale divisions) as a function of the mains voltage fluctuations. If the mains voltage (rated value 220 V) fluctuates between 90% and 110% the variation in deflection is less than 0.5 division.
Fig. 7. Modification of the input part of the system according to fig. 5. In the insulator of the input terminal is a guard ring brought to the potential $E_2'$, as is also the screening of $C_1'$, so that the insulation at that spot is only loaded with the voltage $E_1 - E_2'$. This greatly increases the apparent input impedance and reduces the apparent input capacitance.

**Practical application as laboratory voltmeter**

Fig. 8 gives an illustration of the electrometer developed upon the principle described and intended for use as a laboratory instrument for taking measurements in cases where a very high input resistance is required. The circuit is that represented in fig. 5 (but without the switches $S_1$ and $S_2$) and in fig. 4. After what has already been said, this instrument needs no further explanation.

Fig. 8. Direct-reading dynamic electrometer for laboratory use. Full deflection at 100 mV input voltage. Input impedance $> 10^{15}$ Ω, input capacitance about 40 pF.

**Practical application as dosimeter for X-ray therapy**

The dosage of X-ray or gamma irradiation is expressed in terms of the röntgen unit (r), which is based upon the ionizing action of the rays and is defined as follows (Chicago 1937):

"The roentgen shall be that quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 e.s.u. of quantity of electricity of either sign".

A well-known method of measuring X-ray doses which is of course based on this definition is the following: an ionization chamber — a vessel containing a given quantity of air (or some other gas) and two electrodes between which a direct voltage is applied — is exposed to the rays, which ionize the gas and thus make it partially conducting. A current therefore flows between the electrodes. The potential difference should be large enough to cause the current of ions to reach its saturation value but must remain below the striking voltage. A current intensity of $3.33 \times 10^{-10}$ A per cm$^2$ air (of one atm. and 0°C) in the ionisation chamber corresponds to 1 r/sec.

In order to measure the current it is passed through a high-ohmic resistor ($R_s$, fig. 9) and the voltage developed across it is measured. In view of the very weak current an electrometer is required for this purpose, and, given its exceptionally low current consumption, the electrometer described is particularly suitable.

Since the X-ray tube is fed with a more or less pulsating direct voltage (sometimes even with an alternating voltage) there is a certain "ripple" in the radiation, thus also in the ionization current thereby generated. A capacitor ($C_s$) shunted across the measuring resistor keeps the ripple voltage across the resistor sufficiently small.

**Measuring range**

The measuring range for which the dosimeter had to be designed is very wide: on the one hand it was desired to be able to measure the very large dose rates (doses per unit of time) which occur in contact therapy $^5$ (up to 200 r/sec), while on the other hand it had to be possible to measure also fractions of the very much smaller dose rate corresponding to the amount of radiation that the tissues of the human body can bear without being

damaged (e.g. 0.1 r/day, i.e. about $10^{-3}$ r/sec)\(^6\). These limits thus differ by a factor $10^9$.

We shall now consider in what way the desired range in sensitivity of the instrument can be realized.

1) Volume of the ionization chamber. The current supplied by the ionization chamber is approximately proportional to its volume. A series of ionization chambers differing greatly in size therefore already permit an extensive measuring range to be covered. Of course the dimensions cannot be chosen arbitrarily, since one has to take into account the spatial distribution of the field of radiation in which the measurement is to be taken. For contact therapy we use a chamber of 25 mm\(^3\), for deep therapy one of 6 cm\(^3\) and for measuring tolerance doses one of 35 cm\(^3\) or of 150 cm\(^3\).

2) Gas filling. Usually the ionization chamber is in communication with the outside air and is thus filled with air under atmospheric pressure. Consequently for very accurate measurements corrections have to be applied for temperature and barometric pressure.

If it is decided to use a sealed ionization chamber then this can be filled with some other gas under a different pressure. If high sensitivity is required then a gas is chosen with a high atomic number and not too low pressure. The higher the atomic number of the gas, the greater is the absorption of the X-rays (at least if the rays are not very "hard") and thus also the greater the ionization brought about in the gas. In krypton (atomic number 36), for instance, the ionization current is about 400 times as large as that in air (atomic number of nitrogen 7 and of oxygen 8). An ionization chamber filled with krypton therefore renders good service for measuring very small dose rates. There is the disadvantage, however, that then the meter reading is dependent upon the hardness of the rays, so that a different calibrating constant has to be used for different qualities of radiation.

3) Measuring resistance. The higher the measuring resistance, the greater is the sensitivity. We use measuring resistors having a value between 50 M\(\Omega\) and 2000 M\(\Omega\). Since the resistance between the input terminals of our electrometer is much higher, the measuring resistance can be further increased if required, but it is not easy to make resistors of such a high value which are sufficiently stable.

It is possible to do without the measuring resistor. Then the ionization current charges the input capacitance of the electrometer. The voltage reading follows the rising input voltage. The ionization current can be calculated from the values of the input capacitance and the time, measured by a stop watch, within which the needle covers a given distance on the scale. With this method it is advantageous to employ the system shown in fig. 7.

4) Switching-over of the electrometer itself. The measuring range can of course also be extended by giving the electrometer itself various degrees of sensitivity. In our instrument this has been done in the manner indicated in fig. 5: full deflection is obtained at an input voltage of 1000, 300 or 100 mV, according to whether the switches \(S_1\) and \(S_2\) are in the position 1, 2 or 3.

In the designing of this switching method we started from the consideration that the sensitivity of the moving-coil meter had to be kept unchanged, so that at the full deflection \(E_2\) has the same value (about 970 mV) in all the three positions.

If, in order to get lower sensitivity, the moving-coil meter were shunted, then for the full deflection a higher alternating voltage would be required at the input of the rectifier and also a larger amplitude of the auxiliary alternating voltage \(v_3\) supplied by the oscillator to the rectifier (fig. 5). The latter might result in a heavy loading of the oscillator; moreover the load would change when switching over to a different sensitivity, which might impair the constancy of the oscillator frequency and amplitude.

![Fig. 10. Electrometer constructed as dosimeter, with scale in r/min. \(I =\) ionization chamber.](image-url)
with the switch \( S_1 \). The amplification cannot reach such values as to give rise to danger of oscillation. Table I shows the voltages produced at full deflection.

Table I. Direct voltages at full deflection in the three positions of the switches \( S_1 \) and \( S_2 \) (fig. 5). \( E_1 \) = voltage to be measured, \( E_2 \) = output voltage, \( aE_2 \) = negative feedback voltage, \( E_1 - aE_2 \) = direct voltage across the vibrating capacitor.

<table>
<thead>
<tr>
<th>Position</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_1 )</td>
<td>1000</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>( E_2 )</td>
<td>970</td>
<td>970</td>
<td>970</td>
</tr>
<tr>
<td>( aE_2 )</td>
<td>970</td>
<td>291</td>
<td>97</td>
</tr>
<tr>
<td>( E_1 - aE_2 )</td>
<td>30</td>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>

For various fields of applications of X-rays a summary is given in table II of the possibilities mentioned sub (1), (2) and (3) which form a favourable combination, whereby \( E_{\text{max}} \) may be made 1000 or 100 mV.

Table II. Table of the dose rates occurring in various fields of applied roentgenology, the ionization chambers used by us when measuring the doses, and the currents and voltage thereby obtaining...

<table>
<thead>
<tr>
<th>Application</th>
<th>Dose rate to be measured</th>
<th>Ionization chamber</th>
<th>Ionization current</th>
<th>Measuring resistor ( R_8 )</th>
<th>( E_1 )</th>
<th>( E_{u/\text{sec}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x/sec</td>
<td>volume cm(^2)</td>
<td>gas</td>
<td>A</td>
<td>Ω</td>
<td>mV</td>
</tr>
<tr>
<td>Contact therapy</td>
<td>0.5 - 250</td>
<td>0.025 air</td>
<td>4-10(^{-11}) - 2·10(^{-9})</td>
<td>1000-2000</td>
<td>500</td>
<td>8 - 1000</td>
</tr>
<tr>
<td>Deep therapy</td>
<td>0.1 - 5</td>
<td>6 air</td>
<td>2·10(^{-9}) - 10(^{-9})</td>
<td>100</td>
<td>100</td>
<td>20 - 1000</td>
</tr>
<tr>
<td>Tolerance doses</td>
<td>4·10(^{-7}) - 10(^{-5})</td>
<td>150 Kr *)</td>
<td>2·10(^{-11}) - 5·10(^{-11})</td>
<td>2000</td>
<td>2000</td>
<td>4 - 1000</td>
</tr>
<tr>
<td></td>
<td>9·10(^{-8}) - 10(^{-6})</td>
<td>25 air</td>
<td>10(^{-14}) - 10(^{-12})</td>
<td>( \infty ** )</td>
<td>( \infty )</td>
<td>0.6 - 6 **</td>
</tr>
</tbody>
</table>

*) The data given on this line apply for about 80 kV across the X-ray tube.

**) Measured without measuring resistor and with the system according to fig. 7. The ionization current can be calculated from the rate at which \( E_1 \) increases and the value of the input capacitance.

With a given ionization chamber and a given measuring resistance the moving-coil meter can be calibrated directly in x/sec or r/min (fig. 10). The electrometer itself, as already stated, is insensitive to mains voltage fluctuations and variations in the mutual conductance of the amplifying valves, but changes in the measuring resistor \( (R_8, \text{fig. 9}) \) may cause errors. In order to be able to check the instrument, including this resistor, at any time, we have constructed a reference current generator, an apparatus supplying a very small, constant, known current which, when passed through the measuring resistor, gives a characteristic reading of the electrometer.

Reference current generator

The system applied for this accessory is diagrammatically represented in fig. 11. Use has been made of the familiar property of a pentode that

![Fig. 11. Circuit diagram of a reference current generator supplying a current of 10\(^{-9}\) A for calibrating the dosimeter. \( V_S \) = supply voltage, \( N_e \) = neon tubes for stabilizing the voltage, \( R_8 \) = variable cathode resistor for adjusting the anode current of the pentode to 100 \( \mu \text{A}; C_9 \cdot C_{10} \) = capacitative current divider 10\(^5 \): 1; \( R_8 \) = measuring resistor; \( E \) = electrometer.](image-url)
SECONDARY EMISSION IN OUTPUT VALVES

by J. L. H. JONKER.

Secondary electron emission is often an undesired phenomenon, which may, for instance, have a very adverse effect upon the functioning of tetrode amplifying valves. Known counter-measures are: 1) concentration of the space charge between screen grid and anode, 2) a third grid at low potential, 3) covering the anode with a layer of a substance from which secondary electrons cannot easily emerge. It is discussed why the means under 1 and 2, separately applied, frequently do not yield to the desired result, especially in the case of output valves. As output valves, therefore, pentodes are usually employed in which advantage is also taken of the space charge. Output valves fed from an anode battery, however, operate with too small an anode current to be able to profit from the action of the space charge. Moreover, the supply voltage is low, and as a result the secondary emission consists of proportionately fewer slow, "real" secondary electrons and more rapid, reflected electrons. The latter are capable of passing the suppressor grid more easily. It appears that in such output pentodes the application of the third counter-measure leads to very much better characteristics and a higher output, with a given distortion. The new output pentode DL 41 for battery supply, with prepared anode, gives for instance with 10% distortion an output of approx. 260 mW, as against 200 mW for a similar valve with bare anode.

When electrons impinge upon the surface of a conductor or an insulator at a certain velocity some of them are reflected while the others penetrate into the material and transmit their energy to the electrons already in that material. In consequence some of the latter electrons, given a favourable direction of movement, emerge from the surface bombarded. This is the well-known phenomenon of secondary emission — by which one usually has in mind all the electrons coming from the bombarded surface, the emitted as well as the reflected ones. Several articles have already been written on this subject in this journal 1).

Whereas in some cases good use can be made of this secondary emission, in others it is a most undesirable phenomenon and means have to be sought to suppress it as far as possible.

A familiar form of an electronic valve in which secondary emission may be highly injurious is the tetrode. The (primary) electrons which pass through the openings in the screen grid may strike the anode with considerable force and thereby liberate secondary electrons. When the tetrode is used as an amplifier, due to the anode load, the anode potential consists of an alternating voltage superimposed on the direct voltage. As a result the anode voltage may be temporarily lower than the constant screen-grid voltage. When this is the case the electrons are attracted towards the screen-grid, thereby considerably reinforcing the screen-grid current at the cost of the anode current i_a. In the characteristics representing i_a as a function of the anode voltage v_a, irregularities then occur in the form saggings (fig. 1) which are apt to give rise to distortion. The anode current may not only drop to zero but may even be reversed in sign.

Means of suppressing secondary emission have already been discussed in this journal 2) and consist mainly of the following measures:
1) concentration of the space charge between screen grid and anode,
2) the application of a third grid (at low potential),
3) covering the anode with a layer of a substance tending to prevent the emergence of electrons from the anode 3).


A similar effect is obtained when fins or vanes are provided perpendicular to the anode surface as mentioned in the article quoted in footnote 3). Such fins are not considered here.


3) A similar effect is obtained when fins or vanes are provided perpendicular to the anode surface as mentioned in the article quoted in footnote 3). Such fins are not considered here.