A TRANSISTORIZED RADIATION MONITOR

by M. van TOL and F. BREGMAN.

This article adds the first measuring instrument to the long list of transistor-equipped devices that have been described in this Review in recent years. The emphasis here lies on the special requirements the circuit of a measuring instrument has to satisfy.

Radiation monitors are simple portable instruments for the detection and measurement of ionizing radiations. They are used in laboratories and hospitals whose staffs work with radioactive substances or with apparatus generating ionizing radiations (X-ray equipment, for example). Another field of application is the tracing of radioactive ores. These simple radiation meters are also suitable for special purposes such as in portable instruments for measuring the level of liquefied gases in cylinders.\(^1\)

Batteries are the obvious form of power supply for portable radiation monitors, and since it is important that their dimensions and weight be small, the designer will be concerned to keep current consumption as small as possible. A radiation monitor which contained only one electronic tube apart from its Geiger-Müller tube, and which in consequence was very economical in operation, was described in this Review in 1953.\(^2\) It nevertheless required three batteries — a 40 volt anode battery, a 1.5 volt heater battery and a battery for giving the control grid a negative bias of 14 volts. The latter was rendered necessary by the special circuit developed to operate with only one tube.

Small portable electronic devices represent an extremely worthwhile field of application for transistors. In such devices the fullest advantage is taken of the characteristic properties of transistors, namely the small bulk, the low power consumption (and hence low heat dissipation) that results from the lack of heater currents, and the modest voltage requirements that can be met by small batteries, i.e. batteries comprising few cells. A prototype two-transistor radiation monitor, supplied from a single three-volt battery, was in fact developed in the Eindhoven Research Laboratories as early as 1954.

Transistors have less convenient aspects too, these being the spread in characteristics displayed by different individuals of the same type and the sensitiveness of their characteristics to temperature changes. Forming as they do an obstacle to precision, these drawbacks are ordinarily more serious in a measuring instrument than in an audio-amplifier, for example, where no great harm is done if the amplification changes slightly. However, a radiation monitor is a measuring instrument in which the demerits of transistors are not felt so keenly. For one thing, the main requirements are reliability and sensitivity rather than high accuracy; what is more, the measurement in question is based on pulse-counting, and for this purpose one can employ circuits in which the transistor characteristics have little or no influence on the actual reading. It is understandable that reliability should be given first place, for the purpose of the monitor is to measure radiation that is hazardous to human beings. Great sensitivity is called for because in certain cases it may have to detect radiation levels well below the human tolerance level. These requirements can certainly be satisfied just as well with transistors as with tubes.

Two commercial versions, types PW 4014 and PW 4012, have finally been evolved from the prototype. Equipped with four and five transistors respectively, the commercial models (illustrated in fig. 1) do not differ in any essential respect from the prototype, merely being improvements thereon.

We shall now discuss the circuit of the prototype, given in fig. 2. It can be divided into the following parts:

(a) H.T. supply circuit.

(b) Geiger-Müller tube supplied from this circuit, and delivering electrical pulses when exposed to ionizing radiation.

(c) Pulse-shaper that standardizes the height of the pulses.

(d) Diode pump-circuit which, supplied with a random sequence of pulses of uniform height, transforms them into a direct current whose value is proportional to the average number of pulses per second. This current is measured with the aid of meter \(M\).

The H.T. supply is generated by a simple oscil-
Fig. 1. Two commercial versions of a transistorized monitor for hard $\gamma$ and $\beta$ radiation which have been evolved from the prototype developed in the Philips Research Laboratories in 1954 and discussed in the present article.

a) Type PW 4014, pocket radiation monitor.
b) Type PW 4012, pistol model.

A transistor operating at a frequency of about 10 kc/s, using a transistor $T_1$, type OC 71. The voltage delivered by the oscillator is stepped up in the transformer and applied to a cascade circuit of three stages, which converts the alternating voltage into a direct voltage of treble its amplitude. The cascade circuit is equipped with selenium diodes.

A direct voltage of the same value could be obtained from a cascade circuit having some other number of stages and a transformer with a different output voltage. Losses in the cascade circuit increase with the number of stages; those in the transformer increase with the transformation ratio. The overall loss curve exhibits a shallow minimum corresponding to the use of three stages, as in the circuit under discussion; however, the particular transformation ratio and number of cascade stages decided upon make hardly any differences to the bulk and weight of the circuit.

The G.M. tube is of type 18 503 or 18 504; in both types the quenching gas is a halogen. On account of their robustness and almost unlimited life, these types of tube are particularly suitable for use in an instrument whose prime requirement is dependability. Moreover, their characteristics exhibit a long "plateau" with a particularly gentle slope (fig. 3). The high tension across the tube can therefore vary within wide limits (370 to 650 V) without greatly affecting the rate at which the tube delivers pulses when exposed to radiation of constant intensity $^3$). For this reason it is possible to use a high-tension supply circuit of such simple design; for the same reason, there is no need to pay overmuch attention to the characteristics of transistor $T_1$. Provided the oscillator oscillates — and that is not asking a great deal — a usable high-tension supply will be available.

The voltage supplied is about 500 V, and the average current taken by the G.M. tube does not exceed 30 $\mu$A. The maximum power required is therefore 15 mW. A three-volt battery supplies the oscillator (and the other circuits). The high-tension circuit has an efficiency of about 60%, and therefore takes less than 0.01 A from the battery — a very low current for a rod battery.

As already stated, the value of the high-tension voltage has little effect on the rate at which the G.M. tube delivers pulses. It does, however, have an effect on the height of the pulses. Since there is no stabilization of the H.T. supply, the average current through the G.M. tube cannot be used directly as a measure of the count rate. For this reason the pulses are fed to the pulse-shaping circuit c (see fig. 2), which consists of a type OC 71 transistor $T_1$ and a transformer $T_r$. Circuit c is a blocking oscillator 4). $T_2$ acts as a switch that closes each time the G.M. tube delivers a pulse. When this happens, the primary winding of $T_r$ carries the full battery voltage (3 V). The secondary winding of $T_r$ thus has induced in it a voltage pulse whose amplitude is related to the battery voltage by the ratio of the numbers of turns. The time that $T_2$ remains in the conductive state, and hence also the width of the voltage pulse in the secondary winding of $T_r$, depend amongst other things on the characteristics of the transistor. These also have an influence on the slope of the pulse edges, but the height of the pulses depends on the battery voltage alone.

A diode pump-circuit $d$ measures the rate at which the voltage pulses, now of standard height, are produced. The circuit owes its name to the analogy with a piston force pump, in particular as used for compressing a gas. Diodes $D_1$ and $D_2$ represent the suction and delivery valves respectively; storage capacitor $C_1$ may be compared with the barrel of the pump, and the much larger buffer capacitor $C_2$ with the tank into which gas (i.e. electrons) is being pumped. However, charge continually drains away from the latter via resistor $R$ and ammeter $M$.

A characteristic property of the circuit is that the current through $M$ is dependent on the number and the height of the pulses entering it but not — provided they are sufficiently wide, allowing $C_1$ to be fully charged — on their duration or the slope of their edges. (Compare with the piston force pump, which displaces a quantity of gas that is dependent on the number of strokes per sec and on the pressure of the gas entering the pump, but not on the manner in which the barrel fills up, provided only that it fills with gas up to the full inlet pressure.) The diode pump-circuit is therefore very suitable for handling the pulses of uniform height that are delivered by the pulse-shaper c. It is possible, by a correct choice of values for $C_1$, $C_2$ and $R$, to make the current through $M$ proportional, or nearly so, to the pulse rate. A recent article in this Review 6) may be referred to for a more detailed discussion of the way in which a diode pump-circuit functions.

We have seen above that the constituent parts of the monitor have been adapted to one another with the object of getting a meter reading that is independent of transistor characteristics. We may recapitulate as follows.

The H.T. voltage yielded by circuit a (fig. 2) depends on $T_1$. It is applied to G.M. tube $b$, which delivers pulses at a rate which is independent of the voltage applied and hence of $T_1$. The height of the pulses is dependent on $T_1$. Pulse-shaper c gives these pulses a constant height. Their shape (i.e. their duration and the slope of their edges) depends, however, on the characteristics of $T_2$; the influence of $T_1$ has been eliminated. Diode pump-circuit $d$ converts these pulses of standard height into a current that is independent of their shape. Thus the influence of $T_2$ has also been eliminated.

Even so, the current through the measuring instrument is still dependent on the battery voltage, for the height of the pulses delivered by circuit $c$ is proportional to that voltage (see above). Facilities for checking the battery voltage have therefore been provided in the commercial versions in fig. 1, the indication being given on the meter ($M$).

The ranges measured by pocket radiation monitor PW 4014 are 0 to 3 mrjh (milliröntgen per hour) and 0 to 30 mrjh 6). The pistol model, PW 4012, has the ranges 0 to 1 mrjh, 0 to 10 mrjh and 0 to 100 mrjh. The design of both models allows for the

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4) For the functioning of a blocking oscillator see, for example, B. Chance et al., Waveforms, No. 19 of the Radiation Laboratory Series, McGraw-Hill, New York 1949.

6) J. J. van Zolingen, Philips tech. Rev. 21, 134-144, 1959/60 (No. 4/5), in particular p. 138 et seq.

6) Röntgen, röntgen per hour and other units relating to ionizing radiation were discussed in N. Warmoltz and P. P. M. Schampers, A pocket dosemeter with built-in charger, for X-radiation and gamma radiation, Philips tech. Rev. 16, 134-139, 1954/55.
To give some idea of the significance of these figures, we would add that 5 röntgens per year is regarded as an acceptable dose for persons exposed to radiation by reason of their occupation. In a working year of 2000 hours this amounts to 2.5 mr/h. The tolerance dose for other classes of the population is lower.

A circuit giving a new kind of meter scale

A new circuit has meanwhile been developed in the laboratory in which the scale of the meter is progressively compressed (though not logarithmically) at higher pulse rates. This means that, as for a logarithmic scale, more economical use is made of the available scale length than when a linear scale is used. The deflections obtained with this circuit differ from those of a logarithmic scale in that zero deflection corresponds to absence of radiation and full-scale deflection to an infinitely high radiation level. Consequently the needle never goes beyond the extremes of the scale — a very convenient feature in a radiation monitor: the user always has immediate indication of the radiation level without range-switching.

The principle of the new circuit is as follows. Fig. 4 shows a flip-flop circuit with two transistors $T_3$ and $T_4$. Negative pulses from the G.M. tube arrive at terminal $A$ at an average rate of $N$ per second. After such a negative pulse on $A$ the circuit is left in the stable state in which $T_3$ conducts; suppose the current $i_3$ then flowing through $T_3$ is $I_3$. A pulse generator supplying negative pulses of constant repetition frequency $N_0$ is connected to terminal $B$. After each of these pulses the circuit is left in the state in which $T_3$ is non-conducting. The mean current through $T_3$ is now a measure for $N$; this can be seen with the help of figs. 5a and b. In each diagram the pulses arriving at $A$, those arriving at $B$ and the current through $T_3$ are plotted one below the other as functions of time; the current $i_3$ through $T_3$ can only have one of two values, zero or $I_3$. When $T_3$ has been rendered conducting by a pulse from the G.M. tube, a current $I_3$ flows until stopped by the next pulse of the regular train from the generator. It will be seen from fig. 5a that if $N$ is much less than $N_0$, as in that diagram, then the mean current through $T_3$ will have a low value. Indeed, if the G.M. tube stops delivering pulses altogether, the mean current will be zero. Fig. 5b shows the situation when $N$ greatly exceeds $N_0$. Here $T_3$ is conducting almost all the time. At very high radiation levels the mean current through the transistor has a value approaching $I_3$.

The two extreme cases $N \ll N_0$ and $N \gg N_0$ lend themselves to a simple quantitative treatment, as follows.

For the case $N \ll N_0$ almost every one of the $N$ pulses delivered by the G.M. tube per sec will reach $T_3$ when it is in the cut-off state. At any instant the average time that will elapse before the next pulse arrives from the generator is $\frac{1}{N_0}$ sec. Roughly, then, $T_3$ conducts for a proportion of the time given by $\frac{1}{N}N_0$ and the mean current through it is $\frac{1}{2}(N/N_0)I_3$. The lower end of the scale therefore has a linear character.

The case $N \gg N_0$ can be dealt with analogously. Of the $N_0$ pulses delivered by the generator each second, almost every one reaches $T_3$ when it is in
the conducting state. At any instant the average time required for the next pulse to arrive from the
G.M. tube is $1/N$ sec. (The factor $1/2$, appropriate
to pulses arriving in a regular train, is absent here
on account of the statistical distribution of the
pulses delivered by the G.M. tube.) Roughly, then,
$T_3$ is cut off for a proportion of the time given
by $N_0/N$, and the mean current through it is
$(1-N_0/N)I_3$. At the upper end of the scale, therefore,
the deflection of the needle approaches the
full-scale value ($I_3$) hyperbolically.

$$
\Delta x = \frac{1}{x} \frac{dx}{d\alpha}
$$

Hence the relative error in $x$ per unit deflection
error is equal to $(1/x)(dx/d\alpha)$; this expression,
plotted as a function of $\alpha$, is therefore a suitable
yardstick for comparing the merits of different
scales. In fig. 6b the dimensionless quantity
$$
F = \frac{a_{\text{max}} \ dx}{x \ da}
$$
is plotted as a function of another dimensionless
quantity $a/a_{\text{max}}$ to give curves that are independent
of the unit in which $a$ is expressed. $a_{\text{max}}$ stands
for the full-scale deflection. $F$ denotes the percent-
age measuring error proceeding from a deflection
error $\Delta \alpha$ that is $1\%$ of $a_{\text{max}}$. If it is stipulated that
$F$ shall nowhere exceed 10, then it will be clear
from fig. 6b that the linear scale has a usable range
extending from $a/a_{\text{max}} = 0.1$ to $a/a_{\text{max}} = 1$, while
that of the new scale extends from $P$ to $Q$. i.e.
from $a/a_{\text{max}} \approx 0.11$ to $a/a_{\text{max}} \approx 0.9$. The usable
portion of a linear scale covers a measuring range
whose upper limit occurs at a value 10 times greater
than the value read at its lower limit. On the new
scale in fig. 6a points $P$ and $Q$ occur at values of
approximately 0.233 and 10 respectively; the upper
limit thus occurs at a value 10/0.233 times or a good
40 times greater than the value read at the lower
limit. Fig. 7a shows two linear scales covering ad-
joining ranges; together they cover the range from
0.3 to 30 mr/h with a percentage measuring error $F$
nowhere exceeding 10. Two scales of the new type
covering adjoining ranges, so chosen that the lower
useful limit of the top scale again lies at 0.3 mr/h,
are reproduced in fig. 7b; with the same maximum
$F$ value of 10, these have an overall range going up
to 500 mr/h. A reasonable estimate can moreover
be made up to 2000 mr/h.

Calibration of the new scale is particularly easy.
The flip-flop circuit is held first in one and then

$$
\text{mr/h}
$$

Fig. 6. a) Scale obtained with the new circuit; it provides
readings of $N/N_0$, the ratio between the average number
of pulses delivered by the G.M. tube per sec and the constant
number of pulses delivered by the pulse generator per sec.
b) The quantity $F$ indicates the percentage measuring error
arising from a (constant) deflection error of $1\%$ of $a_{\text{max}}$ the
full-scale angular deflection. $F$ is plotted logarithmically as a
function of $a/a_{\text{max}}$ for a linear scale (curve 1) and for the
new scale (curve 2).

The general formula for the mean current $I_3$
through $T_3$ is:

$$
I_3 = \frac{1 - e^{-N/N_0}}{N/N_0}
$$

A scale in terms of the ratio $N/N_0$, based on the
above formula, is drawn in fig. 6a. If $N_0$ is made
equal to the G.M. pulse rate corresponding to 1
mr/h (this rate depends on the properties of the
tube employed), then we obtain a scale whose unit
division corresponds to 1 mr/h.

Comparison of the new scale with a linear scale
makes clear how economical the former is in its
use of the available scale length. The most obvious
basis for comparing two meter scales, both of which
are used for measuring a quantity $x$, is the relative
error of measurement, $(\Delta x)/x$. This error in $x$
proceeds from the error $\Delta \alpha$ in the deflection $\alpha$
undergone by the needle, and is given by

$$
\frac{\Delta x}{x} = \frac{1}{x} \frac{dx}{d\alpha}
$$

The flip-flop circuit is held first in one and then

$$
\text{mr/h}
$$

Fig. 7. a) Two linear scales which together cover the range
from 0.3 to 30 mr/h with a percentage measuring error $F \leq 10$.
b) Two complementary scales of the new type. Here the total
range covered, over which $F \leq 10$, extends from 0.3 mr/h
(as on the linear scale in a) to 500 mr/h (0.5 r/h).
in the other of its stable states; the circuit is adjusted so that the meter reads zero in the state in which \( T_3 \) is cut off and adjusted to give full-scale deflection in the state in which \( T_3 \) conducts. All that is now necessary is to give \( N_0 \) the desired value. The normal practice will be to place the monitor in the radiation field of a standard radioactive preparation and then to adjust the generator to give a pulse repetition frequency such that the correct meter reading is obtained. Thus only one point has to be calibrated on each measuring range, as in the case of a linear scale. The new scale is much more convenient to calibrate than a logarithmic scale. Owing to the lack of a zero, a logarithmic scale has to be calibrated at two points, and adjustment at one point entails readjustment at the other.

Summary. Portable radiation monitors are an obvious case in which transistors can be used to advantage. As measuring instruments, however, the circuit employed must be so designed that the readings are insensitive to the transistor characteristics (which may shift considerably with changes of temperature). A circuit of this kind is described. The authors also discuss a method of arriving at a (non-linear) scale that covers the whole range between zero radiation (zero deflection) and an infinitely high radiation level (full-scale deflection). Readings are sufficiently accurate (less than 10\% error for a deflection error equivalent to 1\% of the scale length) over a part of the scale extending from 0.1 to 0.9 of the scale length. The radiation-level reading at the upper limit of this range is a good 40 times higher than that at the lower limit. The instrument can easily be adjusted to bring any given radiation level within the usable range. The calibration procedure is particularly straightforward.