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ABSTRACT

An inexpensive and highly reliable pocket-sized (1 by 2-1/4 by 3-1/2 inches) warning device has been developed for use by workers around radiation sources. Electrical circuitry incorporates some important features made possible by recent technological advances, including use of low-cost NPN silicon transistors for temperature stability. No specially made or individually selected components are used.

Mechanical design features include shock-mounted printed-circuit construction to minimize damage due to dropping and to simplify repairs, and provision for optional addition of a sensitivity-changing switch and external-speaker output, for remote monitoring purposes.

Based on the original concept of R. H. Dilworth and C. J. Borkowski of Oak Ridge, this instrument gives an audible indication of approximate gamma-radiation intensity between about 10^{-4} and 1 roentgen per hour by means of scaling or integrating of Geiger-Müller tube pulses, and gives a steady loud tone indication of higher intensities up to above 10^{6} roentgens per hour. Uncalibrated thermal-neutron sensitivity is achieved by use of an optional thin silver foil surrounding the G-M tube. Response to radiation from

pulsed radiation sources is limited by the G-M tube's dead time of approximately 20 μsec. Battery life is about 2000 hours. Approach of the end of battery life is indicated by a change in the output signal, although the instrument's calibration is retained throughout the battery's useful life.

INTRODUCTION

In the past few years there have appeared a number of miniaturized devices for the immediate warning of workers against unexpected radiation hazards. These were made possible only by the recent development of transistorized circuits to provide high voltage from small low-voltage batteries, and loud sounds with high efficiency. Some have used ion chambers and other detectors, but the most sensitive and generally useful detectors in these devices have been Geiger-Müller counter tubes, with the radiation-induced pulses causing sounds or operating meter movements.

Several instruments of this kind have been in use at this Laboratory, and while some have proved to be quite useful and reliable, most have suffered from one or more defects in special applications. The work reported here is in response to a demand from experimenters and group leaders for a reliable instrument that combines and improves upon the best features of those already available, and avoids some of their defects.

EARLY DEVELOPMENTS

The earliest and simplest of these warning devices[1,2,3] consisted only of a high-voltage supply, the detector tube, a simple pulse amplifier and click-producing speaker, and a few other parts, as shown in Fig. 1. Refinements were sometimes added, such as a miniature meter movement to indicate the frequency of the clicks and, consequently, the intensity of radiation.

This type of instrument is quite useful at very low radiation levels, where the time interval between clicks is great enough to be noticed. But a point is very soon reached where a further increase in radiation intensity causes either no change or an actual lessening in the sound output level. This problem becomes more serious around some types of pulsed radiation sources having a radiation pulse long compared to the Geiger-tube dead time, but too short for the ear to distinguish a single click from many coming together.

A radical improvement upon this basic idea was introduced in 1959,[4] with further developments reported in 1960[5] and 1961[6] by R. H. Dilworth and C. J. Borkowski working at Oak Ridge National Laboratory. Their "personal radiation monitor" was constructed in the shape of a fountain pen, to be carried in the user's pocket. In place of the speaker which makes a click with every detector tube pulse, Dilworth and Borkowski added a very simple pulse scaling circuit consisting of a capacitor and a neon bulb, as shown in Fig. 2. This circuit gives an output signal--a discharge of the capacitor through the neon lamp--only after there have been enough detector tube pulses to charge the capacitor to the neon-lamp's firing voltage.

The output of the pulse scaling circuit was not used to make clicks as before, but was made to trigger an oscillator circuit tuned to the frequency to which the human ear is most sensitive, about 3000 cycles per second. By the use of a speaker which was naturally resonant at this frequency, it was possible with very little power to make a loud warning signal--more easily heard than a simple click--which has been referred to as a "chirp" or "beep."

Because this type of scaling circuit responds not to a specific number of pulses but to a definite amount of charge built up on the capacitor, there is a slight variation in the number of detector pulses for each scaler output pulse, due to differences in the size of individual pulses. Another source of variation is the effect of very small leakage currents over long periods of time at very low radiation levels, when the scaler fires only a few times in an hour. But for short periods of a minute or less between neon bulb firings, this variation is small, and there is a very nearly linear relation between the number of chirps or beeps in a given time and the radiation intensity as indicated by the pulse rate of the detector tube, provided that high-voltage regulation is maintained and that the scaling capacitor is not too large. Both conditions had been very nearly achieved in the latest reported version of Dilworth and Borkowski's personal radiation-monitor circuit, in 1961.[6,7]

The performance of this circuit in very high radiation fields is a matter of some interest. As the repetition rate of scaler output pulses becomes higher--and the time between pulses smaller--a point is reached where the neon lamp remains on continuously, and is no longer flashing intermittently. This condition persists as the effective resistance of the detector tube becomes indefinitely small and the alarm signal remains on. This circuit has been tested in radiation levels higher than 10^6 R/h, with no sign of the blocking or faulty operation that is common with conventional transistor multivibrator scalers used with similar detectors. The Geiger tube used here is of the halogen-quenched type, which is typically much more resistant to adverse conditions than the older organic-quenched tube.

An interesting use of the same principle with photoconductor and semiconductor radiation detectors used in satellites was reported by J. W. Freeman in 1962.[8] In this application, the detector acts as a variable resistance in the range 10^5 to 10^{11} ohms: this resistance controls the time required to charge the scaling capacitance to the voltage at which it discharges through the neon bulb and begins recharging.

MECHANICAL CONSTRUCTION

The instrument to be described here has the same basic type of circuit as that of Dilworth and Borkowski, but differs in special features which have been made both desirable and possible by our special requirements and by recent advances in semiconductor technology.

Instead of the miniaturized penlight style of construction, conventional printed-circuit methods have been used, as shown in Figs. 3 and 4 to simplify fabrication and repairs, at the expense of compactness. Improved temperature stability, increased battery life of about 2000 h, and connections for optional external speaker output and sensitivity changing have been made possible by circuit developments described later.

For protection against damage by mechanical shock, elastic weatherstripping material has been used for shock-mounting between the circuit board and case, and between the detector tube and the circuit board. Repeated shock tests of a prototype instrument showed that it could easily withstand repeated drops from heights of 10 to 20 ft with no damage other than small cracks in the case, which is easily replaceable.

The 4-volt battery is held in place by two right-angle 1/32-in. phosphor-bronze brackets, each of which has one side soldered to the appropriate place on the printed-circuit board, in order to save space and minimize the number of connecting wires between the battery and other components. Part of the circuit board has been left unused, to leave room for future additions or modifications such as a sensitivity-changing push-button switch or external-speaker output connector, or both.

Several types of cases of similar size have been used in experimental models of this instrument. Two commercially available types are shown in Fig. 5. Others which have been considered and found satisfactory include plastic soap dishes and cigarette-package containers, available in local drug stores.

ELECTRONIC CIRCUIT

The complete circuit diagram shown in Fig. 6 requires a fuller explanation than that given in the simplified scaling-circuit block diagram considered earlier, in order to be easily understood. The electronic components of Fig. 6 are listed in Table 1.

To obtain the high potential--about 520 volts--needed to operate the detector tube, the current must be switched from the 4-volt battery on and off through a step-up transformer and voltage-quadrupling diode-capacitor system. The switching action is accomplished by transistor Q1, operating as a blocking oscillator, whose rate of oscillation is determined by the effective resistance between the base and the positive side of the battery--that is, by the parallel combination of R8 and the scaler pulse-amplifier system consisting of Q2 and Q3. Normally the oscillator runs at a very low rate, about 50 pulses per second, which is just enough to maintain a suitable voltage on the detector tube at low radiation levels.

At the same time that the oscillator is generating high voltage, it is also sending a signal to the sound amplifier Q4 and loudspeaker, through C7 and C8. Because the sound amplifier is almost turned off at this point, the speaker produces only a faint ticking sound. Battery drain is very low, about 0.5 mA, at low radiation levels, which permits a battery life of about 2000 hours or almost three months of continuous operation with the battery shown in the diagram.

In the presence of high radiation levels, several things happen at once. Pulses from the detector tube build up a charge on the scaler capacitor C5, which then fires the neon lamp, sending a pulse of current to transistors Q2 and Q3, where it is amplified and lengthened to about one-half second. The lengthened and exponential-shaped scaler-output pulse is then sent to turn on the sound amplifier Q4 and at the same time to speed up the blocking oscillator's rate of oscillation from 50 to about 3000 pulses per second. The oscillator rate then decays exponentially back to its idling rate during a time determined by the length of the scaler pulse, or, in other words by the size of the scaler-pulse stretching capacitor C6. This produces the characteristic beeping or chirping sound through the loudspeaker.

The speeding up of the oscillator in response to a scaler pulse has another very important function, in addition to providing a signal for the sound amplifier. It also generates high voltage at a greater rate to compensate for the increased current through the detector tube. This effect, together with zener-diode regulation of the size of high-voltage pulses in the transformer's secondary winding, permits regulation of the high-voltage output to within a few percent for all normal conditions of load, battery voltage, and temperature, throughout the battery's useful life.

There are two possible ways to achieve zener-diode regulation of the size of high-voltage pulses in the transformer's secondary winding. The best and simplest is that suggested by Dilworth and Borkowski,[6] using a single 260-volt zener diode or any equivalent series combination as the first of four rectifiers in the voltage quadrupler.

The only disadvantage of this method is the difficulty of obtaining suitable high-voltage zener diodes. Dilworth and Borkowski recommend selection from a batch of 200 peak-inverse-voltage (p. i. v.) rated silicon diodes, rejecting those whose breakdown voltages fall outside of the 250- to 270-volt range. This is a cumbersome and time-consuming process. Quite recently, some manufacturers have begun to offer specially designed diodes with suitable breakdown voltages, which have been used in this application with promising results.

Another way to accomplish the same effect is to use a low-voltage zener diode and a blocking capacitor, as shown in dotted lines between points A and B in Fig. 6, and high p. i. v. diodes in all four positions in the voltage quadrupler. Regulation is not quite as good as in the earlier method, but the difference is too small to be detected in the operational performance of the entire circuit, and the ease of obtaining this type of diode may in some applications compensate for the increased number of components.

In the interest of reliable performance over a wide temperature range, silicon rather than germanium transistors have been used wherever possible, because of their characteristic lower leakage current and susceptibility to damage. A notable exception is the blocking oscillator transistor Q1, which is shown as a germanium type 2N1304. It was found that commonly available silicon transistors typically cannot be made to oscillate at a very low rate and still remain reliable at near-freezing temperatures, especially under the additional adverse conditions of moderate or high radiation levels and low battery voltage. Although more reliable performance is obtained by speeding up the oscillator's idling rate (by decreasing R8), it is doubtful that the resulting increased frequency of battery replacement would be considered a fair price to pay for the presumably greater life expectancy of a silicon transistor, since the incidence of failure of high-quality germanium transistors in this application has proved to be extremely small in the temperature range 0 to 60°C. Nevertheless, in sustained high-temperature environments, where freezing temperatures are not encountered, a high-gain silicon transistor would be preferable here. The only circuit changes necessary would be to reduce R8 to 100 000 ohms and R4 to 15 000 ohms.

Sensitivity of this instrument can be changed by changing capacitor C5, within the limits 0.001 to 0.05 μF: the relation between capacitor size and time-integrated radiation exposure necessary to turn on the alarm signal is approximately linear, for reasonably short periods. The capacitor value shown in Fig. 6 was chosen as the most suitable for most LRL uses of this instrument; with this value, one chirp every 5 seconds indicates about 5 mR/h; one every half second means that the radiation intensity is 50 mR/h, as calibrated with a radium-226 source of known strength. In anticipation of possible future need for instant sensitivity changing while an intrument is in use, provision has been made for adding a miniaturized highly reliable momomentary-contact push-button switch to put a larger capacitor in parallel with the smaller.

Because the greatest biological hazard around particle accelerators and reactors is usually that due to neutrons rather than to the beta or gamma radiation to which the detector responds, many users have emphasized the desirability of adding some degree of neutron sensitivity. A solution to this problem has recently been proposed by A. R. Smith[9] and L. D. Stephens[10] of this laboratory. A small piece of 5-mil-thick silver foil is wrapped around one-half of the detector tube's sensitive volume. Activation of the silver by thermal neutrons, with a 24-sec half life, produces counts in the detector. When the instrument is carried in the user's pocket, the thermalizing effect of the body permits indirect response to fast neutrons. Beta and low-energy gamma sensitivity is retained, though somewhat reduced, by leaving half of the detector tube uncovered.

PERFORMANCE LIMITATIONS

There are a number of limitations on the usefulness of this type of warning device, and they should be understood by every user. Although it is true that the number of alarm signals within a given time is, in general, proportional to radiation intensity, for a particular particle or gamma-ray average energy, the energy response characteristic of the silver-covered detector tube and surrounding case material is not sufficiently uniform to permit accurate evaluation of dose rate for a radiation source of unknown energy, particularly in the case of a mixed gamma and neutron radiation field. Accurate measurements under such conditions can be made only by specialized radiation-survey instruments.

Another limitation arises in the case of pulsed radiation sources, as for example some types of particle accelerators and reactors. The dead time of the detector tube is a period of about 20 μsec following every detector tube pulse, during which the detector is insensitive. This means that a radiation pulse lasting, for example, 70 μsec, can cause either 0, 1, 2, 3, or at most 4 detector pulses to go to the scaling circuit, depending upon the intensity of radiation pulse. Hence the detector has a dynamic range of only a factor of four above the level needed to produce one detector count for each radiation pulse. An increase by a factor of 10 or 100 in radiation level would not produce a corresponding detector response. Although this limitation is less serious for pulsed neutron sources, because of the time required for the decay of activated silver foil, it is still an important consideration for applications where the radiation pulse length is not long in comparison to the detector tube's dead time.

It is obvious that, in the design of equipment for the protection of personnel, the question of both electronic and mechanical reliability must be very carefully considered. It is especially important that a radiation warning device should not fail at a critical moment when it is most needed.

Nevertheless, there are unavoidable limitations which make the ideal of infallible or completely reliable performance unattainable in any instrument of this type. It cannot be more reliable than the least reliable of its components, and there is one component that is practically certain to fail at least once during the instrument's lifetime. The battery is limited not only in total energy output but also in shelf life, and may fail even when not in use. Although the battery life of about 2000 h is long by ordinary standards, it may still wear out while the user is near hazardous areas, and give a false impression of safety. An attempt has been made to partially solve this problem by making the alarm signal frequency and loudness change rapidly with decline in battery voltage, while maintaining constant high voltage and calibration, by means of the particular resistance values chosen for R5, R6, and R7. This will cause a change in the sound indication when the battery is approaching the end of its life, but this change may not be noticed by an untrained observer.

There are a number of other infrequent but nevertheless important causes of instrument failure which have been observed during about 30 000 hours of testing of early models of this instrument. The detector tube and neon bulb are particularly susceptible to mechanical shock, although some have survived drops of more than 15 feet, because of shock-mounting attachment to the circuit board, as described earlier. Semiconductors can also be damaged by shock as well as by temperature extremes and high-voltage transients,[11] although only one such case has been observed in this circuit. Accidental battery reversed may cause damage to tantalum capacitors. As noted in the table, in applications where batteries are likely to be replaced backwards, capacitors C6, C7, C9, and C10, all 1 μF, can be of the low-voltage ceramic type, which are slightly larger in size and higher in cost. The variation of capacitance with temperature and applied voltage that is characteristic of ceramic capacitors is not sufficient to have an adverse effect on the circuit's performance. Battery reversal does not cause damage to transistors in this circuit.

Many people have suggested omitting any on-off switch from this instrument to insure that it will always be on to provide continuous protection. But to do this would be to imply a kind of infallibility, and a corresponding faith on the part of users, that are not consistent with the limitations of battery-operated equipment. This would also reduce the effective battery life by using power when no useful information is being given.

SPECIAL-PURPOSE CIRCUIT MODIFICATIONS

During the course of this work, a number of variations on the basic circuit of Fig. 5 were found to be useful in special situations. One of these variations was the use of a larger and more sensitive detector tube, of a type commonly used in portable radiation-survey instruments which requires an operating potential of about 1000 v. To achieve this higher voltage, it is necessary to add stages to the voltage multiplying network D1 to D4 and C1 to C4. The number of additional stages needed can be reduced somewhat by slightly increasing both the battery voltage and the zener-diode breakdown voltage. It is possible to use as much as twice the recommended supply voltage with the specified high-voltage transformer, but only at the expense of somewhat lower reliability. This type of regulated high-voltage supply circuit can be adapted for use with transformers originally intended for transistor interstage coupling. These transformers, generally larger in size and higher in cost, have a 100- to 1000-ohm low-impedance center-tapped winding and a 50 to 500 kilohm secondary winding. The voltage step-up ratio is approximately equal to the square root of the impedance ratio of the secondary to one-half of the primary winding. The values of R7 and C8 will in general have to be changed to obtain a 100- to 200-μsec flat-topped output pulse followed by an equal- or greater-amplitude flyback pulse of opposite polarity. Transformer substitutions should be made with care, however, because interstage transformers are not always made to withstand high secondary voltages.

The alarm signal quality--particularly important as a means of best using the resonant properties of different types of speakers to obtain a loud sound output--can be varied by making small changes in the values of C6 and R7. The sound-output circuit can also be modified to act as an independent tuned oscillator rather than as an amplifier of the signal from the high-voltage oscillator. This can be done simply by removing C7 and adding a resistor and a capacitor in series (about 1500 ohms and 1 μF depending on the sound quality required) between the base of Q4 and the upper primary winding of transformer T2.

COST

In considering the total cost, over a long period, of instruments intended for personnel protection, the initial unit cost is only a part, and often a small part, of the whole. Replacement of batteries, time spent in maintenance, the time and expense involved in obtaining replacement parts, particularly those which are hard to find, can sometimes add up to more than the initial cost within a few years. Clearly nothing is gained by small savings in initial cost at the expense of long-term reliability and high standards of performance. The instrument described in this report has been designed not for low initial cost, but for low total cost over a long period of use. This has been done by combining mechanical simplicity and ruggedness with electronic reliability, and by the use of quality components which are likely to be readily available in the event of any need for replacement.

It is difficult to give a precise figure for the initial unit cost for this instrument, because of wide variations in the costs of some components and of fabrication. At the time of this writing, the initial cost of electronic components alone, not including the circuit board or case fabrication and assembly is, in small quantities, about thirty to forty dollars per unit, about half of which is due to the detector tube.

ACKNOWLEDGMENTS

The work presented in this report involved the advice and participation of members of the Health Physics Department and the Counting Equipment Group of this Laboratory.

In particular, the author is indebted to Stanley L. Klezmer for contributions to the evolution of the electronic circuit of this instrument; to John T. Lavrischeff for advice in the matter of component reliability; to Robert H. Dilworth for valuable suggestions; to Lloyd D. Stephens, Alan R. Smith, and William W. Wadman for their part in establishing initial specifications and for contributions during the course of this work; and to members of operating crews of LRL accelerators for their help in testing and evaluating early models.

The basic circuit design described in this report is covered by U. S. Patent No. 3,015,031, issued December 26, 1961, to R. H. Dilworth and C. J. Borkowski, and assigned to the U. S. Atomic Energy Commission.

FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

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10. L. D. Stephens, Lawrence Radiation Laboratory, Berkeley, private communication.

11. J. T. Lavrischeff, Lawrence Radiation Laboratory, Berkeley, private communication.

Table 1. Description of electronic components shown in Fig. 6.

Comp. No.	Description
B1	Battery, 4 V, mercury type TR-133
C1-C4 C8, C11	Capacitor, 0.0022 μF, 600 V, ceramic
C5	Capacitor, 0.005 μF, 200 V, mylar
C6, C7, C9, C10	Capacitor, 1.0 μF, 10 V or higher, tantalum or ceramic
C12	Capacitor, 56 μF, 6V, tantalum
D1	Diode, Zener, 260 V, 400 mW (See text.)
D2-D4	Diode, silicon, IN 3255 or equivalent (rated 600 peak inverse voltage)
D5	Diode, Zener, IN 963B, 11 V, 400 mW (See text.)
Q1	Transistor, germanium, high-gain, general-purpose, type 2N1304 or equivalent
Q2-Q4	Transistor, silicon, high-gain, planar, general purpose, type 2N697, 2N2714, or equivalent
R1	Resistor, 2.0 MΩ, 1/4 W
R2, R4	Resistor, 100 K, 1/4 W
R3, R5, R6	Resistor, 5.1 K, 1/4 W
R7	Resistor, 1.5 K, 1/4 W
R8	Resistor, 470 K, 1/4 W
Sp	Loudspeaker, 8-ohm voice coil, 2-in.-diam (Calrad PM-2, Thorotest S-2, or equivalent)
Sw	Switch, s.p.s.t., miniature slide type (Lafayette No. 25-459 or equivalent)
T1	Transformer, miniature DC-DC converter, with center-tapped primary, turns ratio 1:1:44 (Microtran type M-8073 or equivalent)
T2	Transformer, miniature output type, 400 to 500 ohm c.t. to 8 ohm (Lafayette No. TR-116, Microtran No. UM-27F, or equivalent)
V1	Geiger-Müller detector tube, halogen-quenched (Amperex 18509 or equivalent; Lionel type 308 is suitable for some applications.)
V2	Neon lamp, 1/25 W, type A1B or Ne-2
(Hardware)	Printed circuit board
	Battery clamp
	Case, metal or plastic
	Insulating ring-shaped spacer, 1/16 in. thick, 1-3/4 in. o.d., 7/8 in. i.d.
	Weatherstripping material plastic foam type, size 1/2 by 5/16 in.
	Connecting wire, No. 24 stranded.

FIGURE LEGENDS

Fig. 1. Block diagram of early type of radiation warning device using Geiger tube detector, with radiation-induced pulses making clicks in a loudspeaker.

Fig. 2. Simplified block diagram of the circuit for Dilworth and Borkowski's personal radiation monitor. In the actual circuit, the "alarm-tone generator" function is performed by a signal from the high-voltage supply oscillator to a sound amplifier and speaker.

Fig. 3. Photograph of the circuit board and electronic components of the Lawrence Radiation Laboratory-type personal radiation monitor. The cylindrical magnet of the speaker at right fits in the hole of the circuit board with the speaker cone facing downward. The switch is mounted on the case.

Fig. 4. Printed circuit and board layout. The actual size of each is about 2-1/8 by 3-13/32 in. Battery-clamp brackets are made from 1-1/4- by 1/2- by 1/32-in. strips of phosphor bronze, beryllium copper, or similar spring material. A conventional, ready-made battery holder may be used if the case size permits. The high-voltage section of the board should be painted with silicone resin after assembly. A ring-shaped insulating spacer is used between the speaker frame and circuit board.

Fig. 5. Photograph of two types of cases.

Fig. 6. Circuit diagram. Refer to Table 1 for a description of the components.

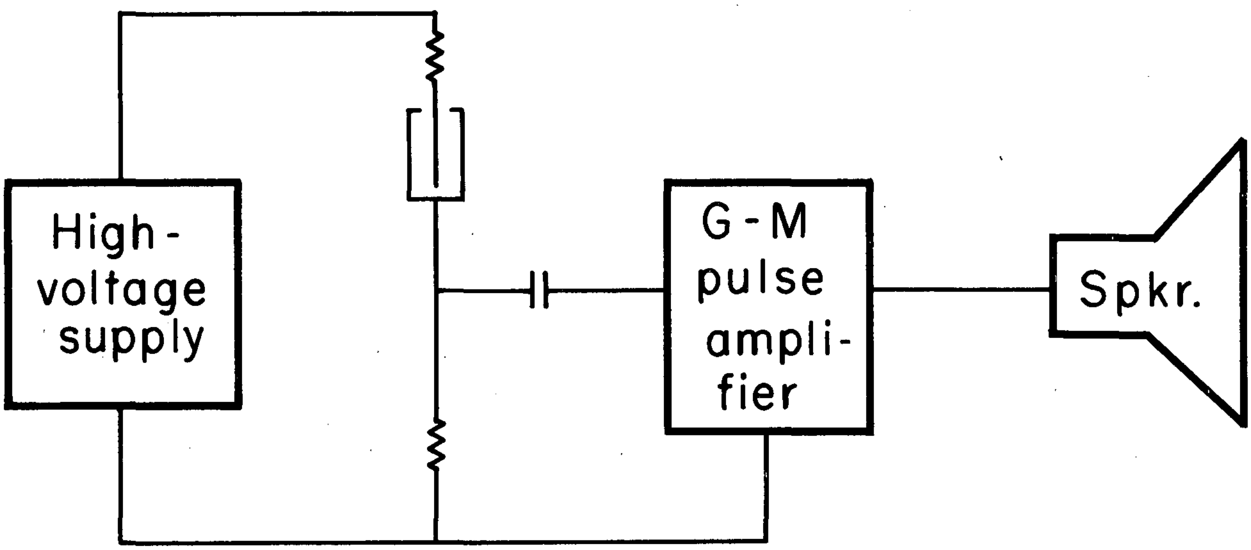


Fig. 1

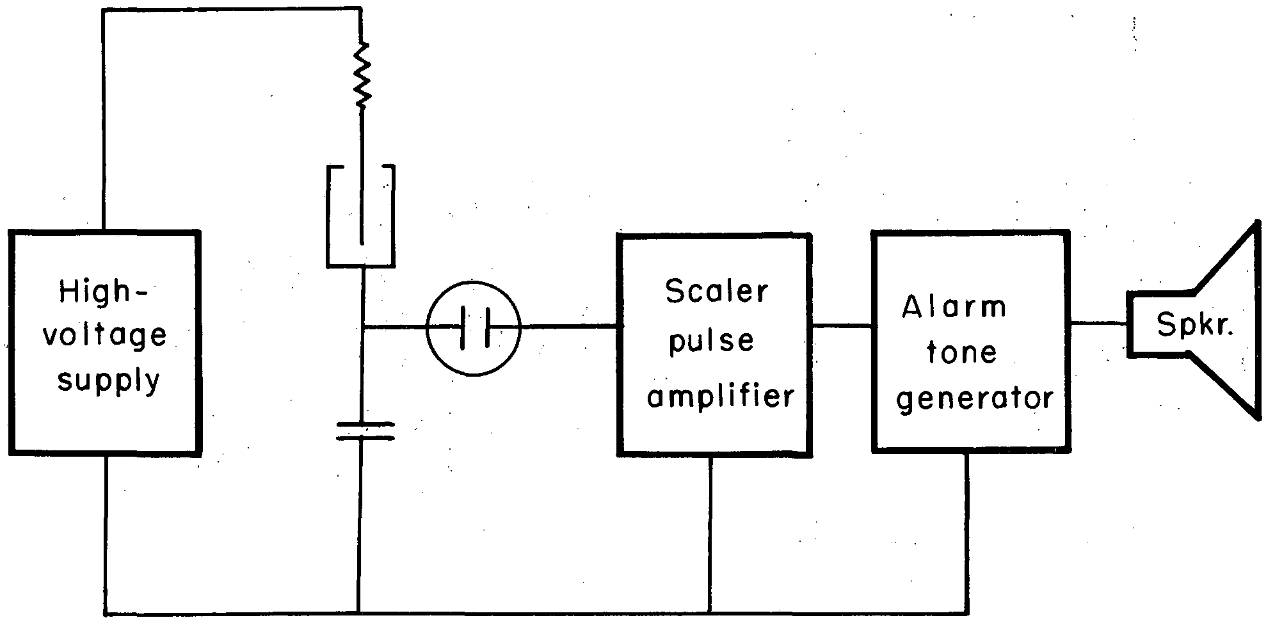
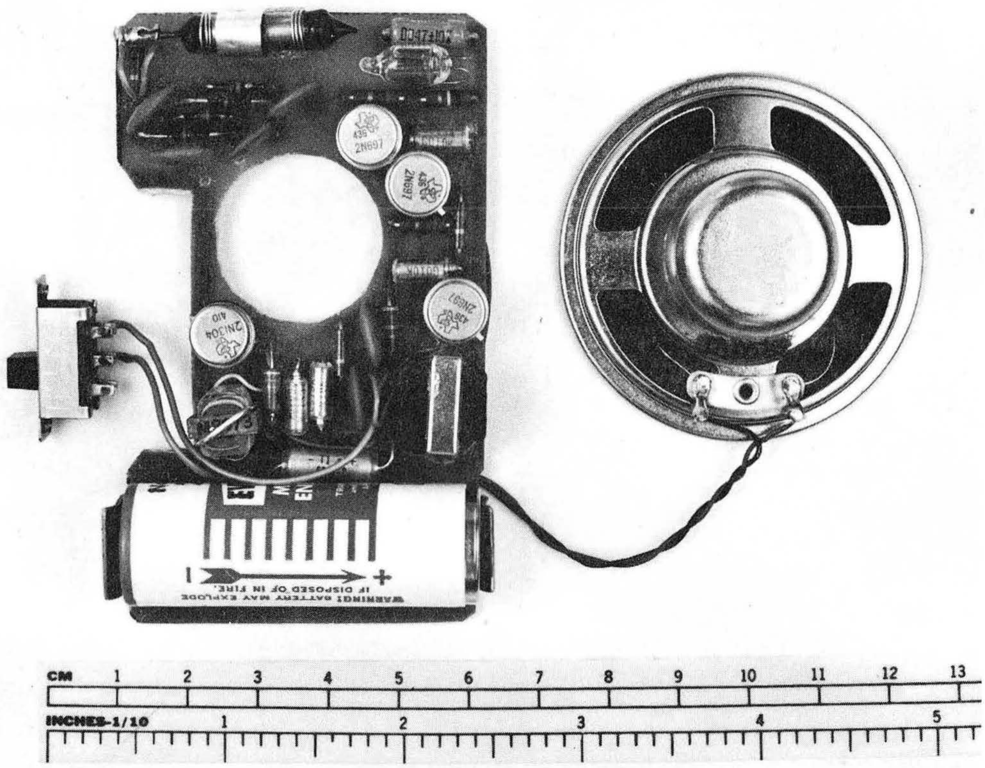

High-
voltage
supply
Scaler
pulse
amplifier
Alarm
tone
generator
Spkr.
MUB-3029

Fig. 2



ZN-4299

Fig. 3

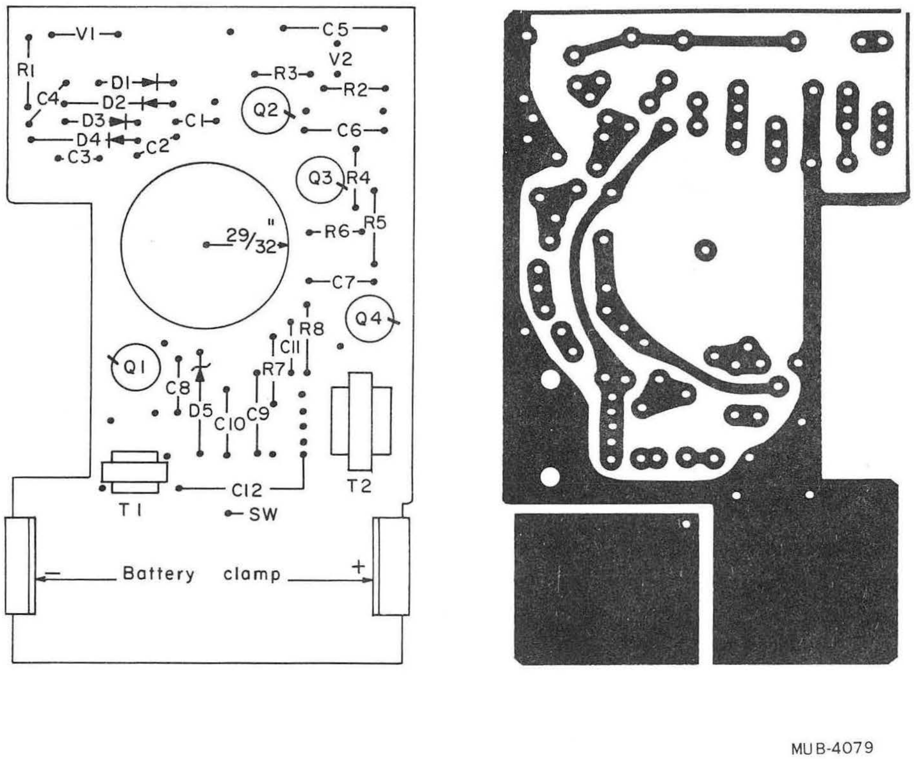
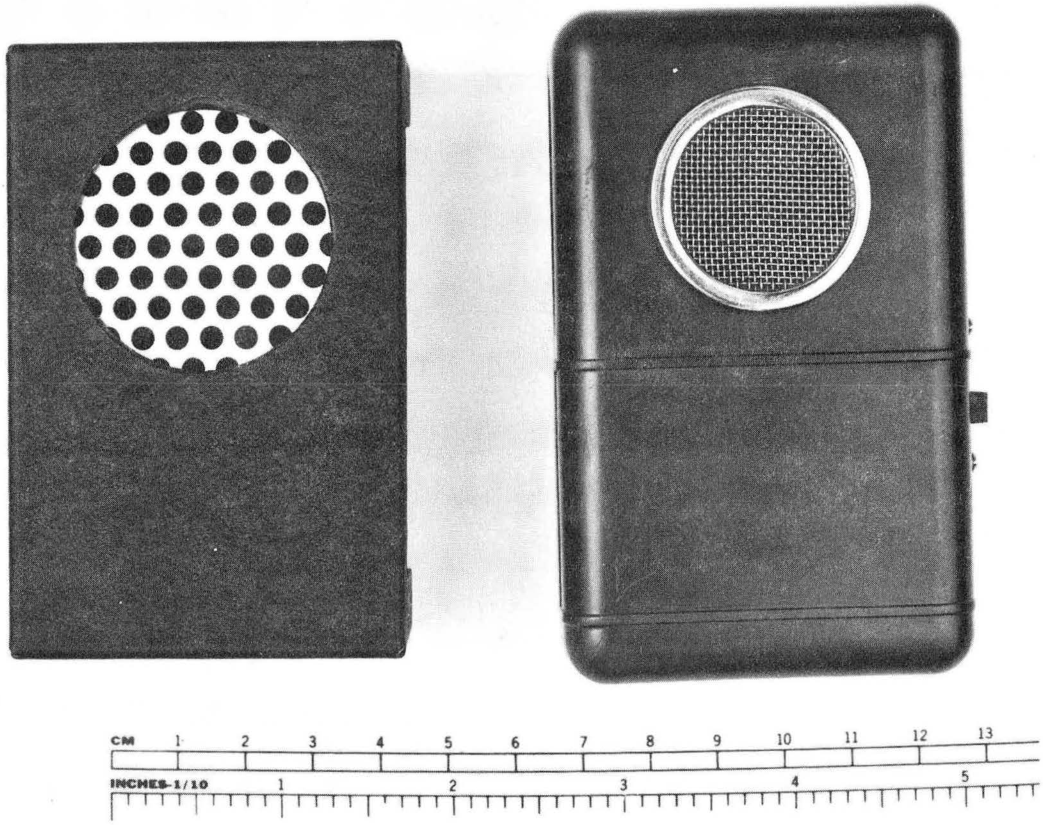

V1
C5
V2
R1
D1
R3
R2
C4
D2
Q2
D3
C1
C6
D4
C2
C3
Q3
R4
29/32"
R6
R5
C7
Q4
R8
C11
Q1
R7
C8
D5
C10
C9
T1
C12
T2
SW
Battery clamp
+
MUB-4079

Fig. 4



ZN-4298

Fig. 5

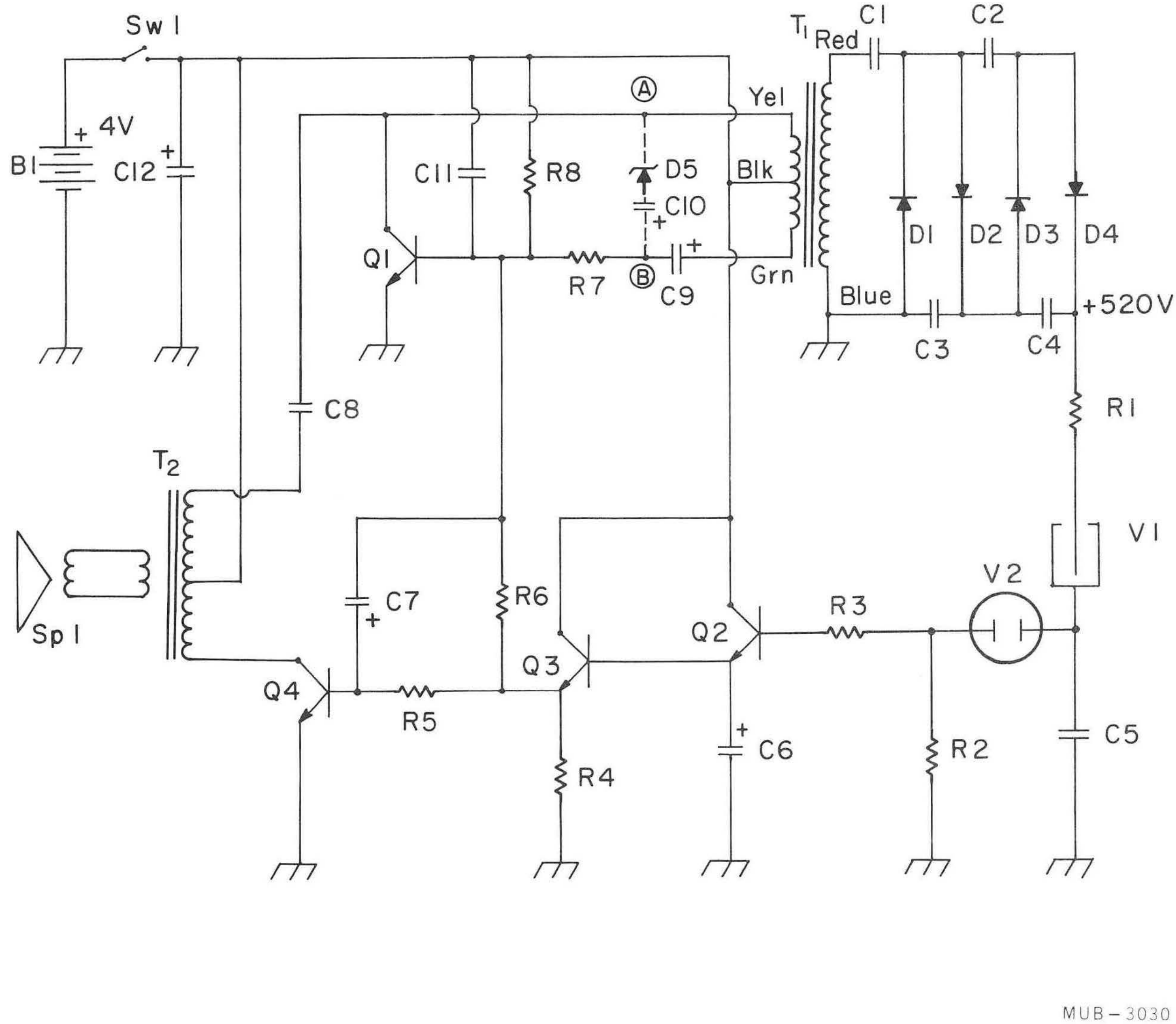

Sw I
B1
+ 4V
C12
T1
Red
C1
C2
Yel
Blk
Grn
Blue
A
B
C11
R8
D5
C10
Q1
R7
C9
D1
D2
D3
D4
C3
C4
+520V
R1
C8
T2
V1
V2
Sp I
C7
R6
Q2
R3
Q3
Q4
R5
C6
R2
C5
R4
MUB-3030

Fig. 6