Scintillation Radiological Survey Meters

By J. G. ELLO

Radiation Measurements
and Instrumentation
Industrial Hygiene and Safety Division
Argonne National Laboratory

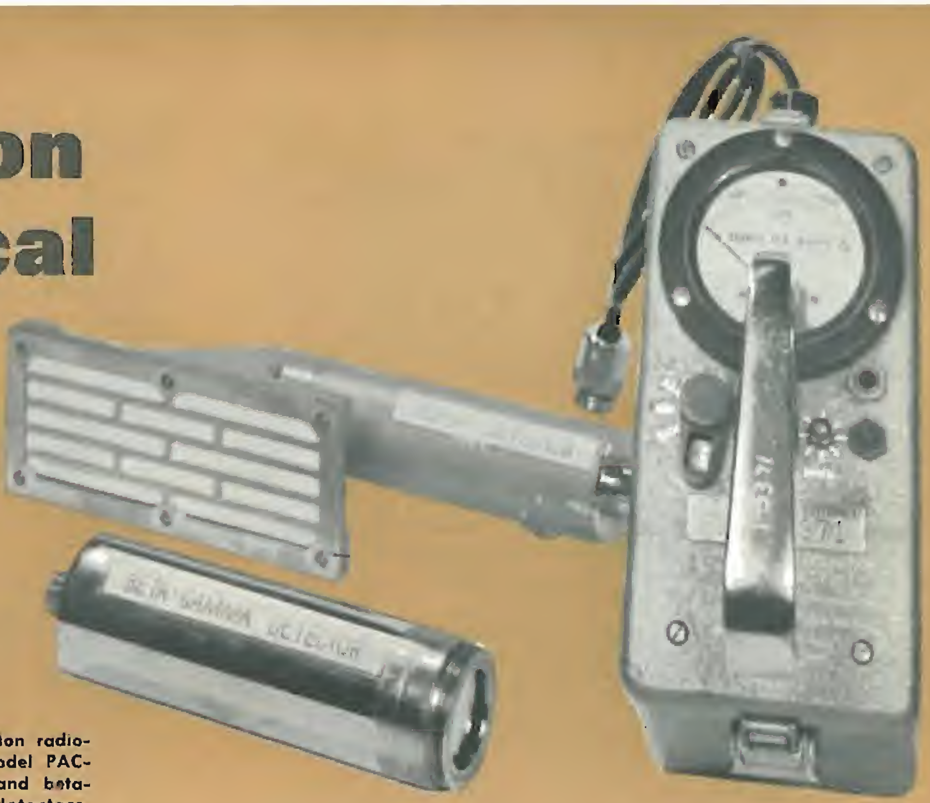


Fig. 1 Eberline scintillation radiological survey meter, Model PAC-1S shown with alpha and beta-gamma scintillation detectors.

The operation of radiological survey meters, specifically the scintillation type, is thoroughly discussed by the author. A complete description and maintenance techniques for a typical survey meter, the PAC-1S, are also included in the article.

FOR a number of years, the nuclear instrumentation field has progressed at a steady pace, with many innovations in radiological detectors and their associated counting systems. Although many of the earlier types of survey meters, such as Geiger-Muller, ionization, and proportional counters (see ELECTRONICS WORLD, January, 1966) are still in wide use, they do not meet all present-day requirements. Along with the demand for sophisticated instruments is an ever-increasing demand for the nuclear instrument specialist. The author hopes that through this article he will help electronics technicians in the profession by increasing their knowledge of basic nuclear instrumentation.

Radiological instrumentation is now found in military, medical, and industrial fields as well as in research. This wide application of radiation has resulted in the development of new instrumentation and new types of detectors, such as thermoluminescent dosimeters, semiconductor detectors, and improved scintillation detectors.

Of the three types of detectors mentioned, the scintillation type is well established and in wide use in research and commercial work. The detector, with its photomultiplier tube (photo-tube), has a wide range of applications as compared to the Geiger-Muller or ionization types. It is particularly useful in accelerator studies where short resolving time and coincidence counting is required. In addition, the scintillator can measure the radiation energy and distinguish between types of radiation.

There are a number of scintillation-type counters used in the nuclear field which have the same principle of operation. In this article, the author discusses the *Eberline* survey meter, Model PAC-1S, shown in Fig. 1 with its detectors. Among other manufacturers that produce scintillation survey meters are: *Nuclear Chicago, Ludlum Measurements,* and *Victoreen Instrument Corporation.* Selection of the *Eberline* instrument for discussion should not be construed as an endorsement of the meter, nor as an adverse criticism of any of the meters used in the nuclear field today.

Scintillators

Scintillation counting is not new to the nuclear instrument field. With innovations in nuclear instrumentation, the scintillator has become a primary tool for the detection and measurement of *alpha, beta,* and *gamma* radiation.

Scintillation, by definition, is a spark, flash of light, or a twinkle of a star. The phrase "scintillation counting" goes back many years. Originally studied by Becquerl and Crookes, they found that some materials would emit flashes of light when exposed to nuclear radiation (similar to a radium watch dial). These flashes of light are referred to as "scintillations."

To make a scintillation detector, we must first have a phosphor material which scintillates when exposed to nuclear radiation. The phosphor should be able to absorb *alpha, beta,* or *gamma* radiation and thereby produce ionization and excitation within itself. For practical purposes, we could say that nuclear energy is converted to light energy. This fluorescent radiation or scintillation, as we shall see later, is what the photocathode of the photomultiplier sees and amplifies.

An ideal phosphor material is one which readily absorbs nuclear radiation, is highly efficient in converting nuclear energy to light energy (photons), has a fast scintillation decay, is transparent to its own scintillations, and has an emission wavelength matching the photocathode sensitivity of the photo-tube used.

At present there are five classes of phosphors (scintillation material). These are organic liquid and solid solutions, organic crystals, inorganic crystals, and noble gases. The type to be used depends on the type of radiation to be detected. For example, if *gamma* radiation is of interest, we may use an inorganic sodium-iodide crystal activated with a small quantity of thallium to create luminescent centers.

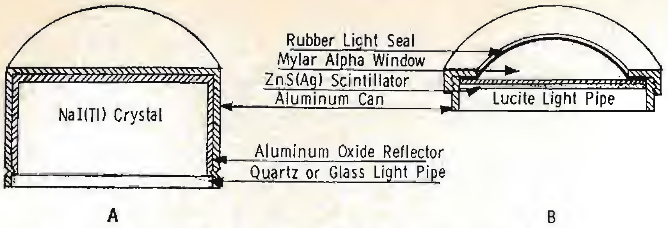


Fig. 2. Cross-sectional views of (A) gamma and (B) alpha scintillator packages showing physical and chemical makeup.

For *beta* radiation, an organic anthracene crystal may be used, and for *alpha* radiation, a very thin layer (powdered screen) of organic zinc-sulfide activated with silver is used.

For practical purposes, we can say there are three types of scintillation forms in use, that is, the phosphor material may be in a liquid, crystal, or powder form. Since we are discussing battery-operated survey meters, our interest lies in the latter two: the crystal state and powder scintillators.

An important property of a scintillator is the efficiency with which it converts nuclear energy to light energy, that is, the number of photons produced per nuclear event. The photons produced must pass through the scintillator to the photocathode to be counted. For this reason, the packaging of the scintillator is also of great importance.

Since the type of radiation to be detected determines the packaging technique to be used, we should review some of the basic properties of nuclear radiation.

Nuclear Radiation

Back in 1898, when Pierre and Marie Curie concluded that uranium gave off rays which were characteristic of that element and not related to its chemical state, they referred to this phenomenon as "radioactivity." As research work continued in the early part of this century, other elements were found to be radioactive which were also characterized by the emission of one or more of three types of radiation. The three types were named after the first three letters of the Greek alphabet.

The first, called *alpha* (α) rays or *alpha* particles, are helium nuclei each consisting of two protons and two neutrons with a positive charge. When ejected from a radioactive atom, the particle moves with considerable speed, approaching 20,000 mi/sec. It can only travel through 1 to 2 inches of air and is unable to penetrate a few sheets of newspaper.

The second type of radiation is called *beta* (β) rays or *beta* particles. The *beta* particle is emitted from the nucleus of a radioactive atom and has a mass and charge equal in magnitude to that of an electron. *Beta's* can travel several hundred times farther than the *alpha* particle and at speeds approaching the speed of light. A *beta* particle, with the same energy as an *alpha*, will move much faster and go farther before its velocity is brought to zero by collision with the atoms which it ionizes. In other words, a *beta* particle, which can pass through a number of sheets of newspaper, is easily absorbed (stopped) by a ¼-inch sheet of Lucite even though its energy is the same as the *alpha* particle. This is logical since the mass of the *alpha* particle is approximately 7500 times greater than that of a *beta* particle.

The third type of radiation is referred to as *gamma* (γ) rays. Unlike *alpha* and *beta* radiation, *gamma* radiation does not consist of particles. It is a short-wavelength electromagnetic radiation of nuclear origin. It is emitted from a disintegrating atom when an excess of energy remains after the ejection of an *alpha* or *beta* particle. *Gamma* rays move at the speed of light and are similar to x-rays, therefore, they have a greater penetrating ability.

Protection against α and β particles can be obtained by a shield made of glass or a ¼-inch thick plastic such as Lucite. However, with γ rays, a lead, steel, or concrete shield is necessary. The best protection against nuclear radiation is to keep as far as possible from the source and limit exposure time.

Scintillator Detectors

As mentioned earlier, the packaging of a scintillation detector depends on the penetrating ability of the radiation to be detected. It can be packaged in many shapes and sizes with the primary consideration being given to the prevention of any light transmission from the outside. The diagram of Fig. 2A is a cross-section view of a packaged *gamma* scintillator. It incorporates sodium-iodide activated with thallium to form an *NaI(Tl)* crystal which is enclosed in a 0.0312-inch thick aluminum can. The inside of the can is coated with a very thin layer of aluminum oxide for the purpose of light reflection. The photo-tube end of the can is sealed with a 0.01560-inch thick glass, quartz, or Lucite window, referred to as a light pipe, and in this case, equal in area to that of the photocathode of the photo-tube. The scintillator package is then placed in a light-tight container housing the photomultiplier and its associated circuit, as seen in Fig. 1. When installing the scintillator package to the face of the photo-tube, it is necessary to have good optical contact between the two surfaces to minimize any reflection at the interfaces. The optical connection may be accomplished by sandwiching some transparent material, such as silicone grease, between the photo-tube and the light pipe.

A scintillator for detecting *beta* particles is packaged in a similar manner, except that a 0.1875-inch thick anthracene crystal is used in place of the *NaI(Tl)* crystal. Also, the aluminum can must have the end opposite the photo-tube removed and replaced by a 1-mil (one thousandth of an inch) thick aluminum foil, which acts as the *beta* window. The window permits the *beta* particle to come in contact with the crystal and is similar in design to the *alpha* scintillator window shown in Fig. 2B.

An *alpha* scintillator may be housed like the *beta* type, that is, like the *beta* scintillator, it needs a very thin light-tight window to allow passage of low energy particles. The aluminum can must have both ends open. The photo-tube end of the can has a light pipe attached for light transmission and is equal in area to that of the photocathode. The opposite end of the can, which is the *alpha* window, is constructed from a 0.25-mil thick opaque layer of aluminized Mylar. Directly under this Mylar window is the *alpha* scintillation material, consisting of a silver-activated zinc-sulfide powder *ZnS(Ag)*. A very thin layer of this powder has been specially fabricated as a decalcomania scintillation screen. This screen is highly sensitive to *alpha* particles, that is, they are readily absorbed, whereas the *beta-gamma's* are not and go on through the screen undetected. The zinc-sulfide screen, as seen in Fig. 2B, adheres to the transparent Lucite light pipe. In some instances, the screen can be applied directly to the face of the photo-tube, thus obviating the need for a light pipe.

When an *alpha* particle penetrates the Mylar window, it strikes the *ZnS(Ag)* screen, which undergoes a change and emits a minute flash of light which is seen by the photo-tube and is amplified accordingly. This same phenomenon occurs in the radium dials of clocks and watches. Here a small amount of radioactive material, such as radium, is mixed with some zinc-sulfide so that the *alpha* particles are always colliding with it, thereby emitting light. This light can then be seen on the dials in the dark. By using a sensitive photoelectric cell, such as the photomultiplier tube, these scintillations can be converted into electrical energy as is done in the *alpha* scintillator.

Photomultiplier Tube

In the early stages of scintillation counting, an attempt was made to use an ordinary photo-tube. This particular tube may work fine in chain stores to open and close doors, but it is unsatisfactory for scintillation counting. The drawbacks with this tube are its poor response toward faint light flashes and the high level of noise generated by its associated circuit. In 1944, it was decided to construct a special photo-tube which would be self-contained, consisting of a photoelectric cell followed by a high-gain amplifier that depended on the phenomena of photoelectric and secondary emissions. To understand this phenomenon, we should understand that electrons are held captive in various materials by means of the potential barrier and that to release them sufficient energy must be applied to these electrons so that they are able to cross this barrier. For example, if incident (primary) electrons bombard a material and transfer all or part of their energy to the electrons the material contains, they in turn would release additional electrons which causes so-called secondary emission.

By examining the basic configuration of a photomultiplier tube, shown in Fig. 3, we find it consists of four major interior parts: (1) The *photocathode,* which is a semi-transparent photosensitive film deposited on the inside of the flat end of the tube's glass envelope. This photosensitive material should be dependent on the light wavelength of the emission spectra of the scintillation material used. A sensitive material consisting of an alloy of cesium-antimony is widely used because of its sensitivity to light wavelengths up to about 6500 Å, which is well within the emission spectra of most scintillators. The main function of the photocathode is to convert light energy to electric energy by means of photoelectric emission, that is, to absorb photons and in turn release electrons. (2) The *electron optical element* or funnel, as it is more commonly called, acts as a guide to insure that all the electrons released by the photocathode are directed to the first dynode. When a proper voltage is applied to the funnel, it acts as a focusing electrode which accelerates the freed electrons to beam onto the first dynode; that is, all the freed electrons, irrespective of the emanating point on the photocathode, reach the first dynode. (3) The *dynode* assembly, the key factor of the photomultiplier tube, comprises the first dynode and all succeeding dynodes. The assembly may consist of from 6 to 14 dynodes, arranged in a cascade (ladder-like) configuration. By means of the secondary-emission phenomenon, each dynode is in itself an electron multiplier (current amplifier), thus the name, photomultiplier. The dynodes are constructed so that each one acts as an electron optical element for drawing the secondary electrons from one dynode to the succeeding dynode. To enhance secondary emission, an alloy of cesium-antimony, silver-magnesium, or copper-beryllium is coated on the dynodes. (4) The *anode,* sometimes called the collector, which collects all the electrons from the last dynode. The output from the anode of the photomultiplier is than coupled directly to the output counting circuit.

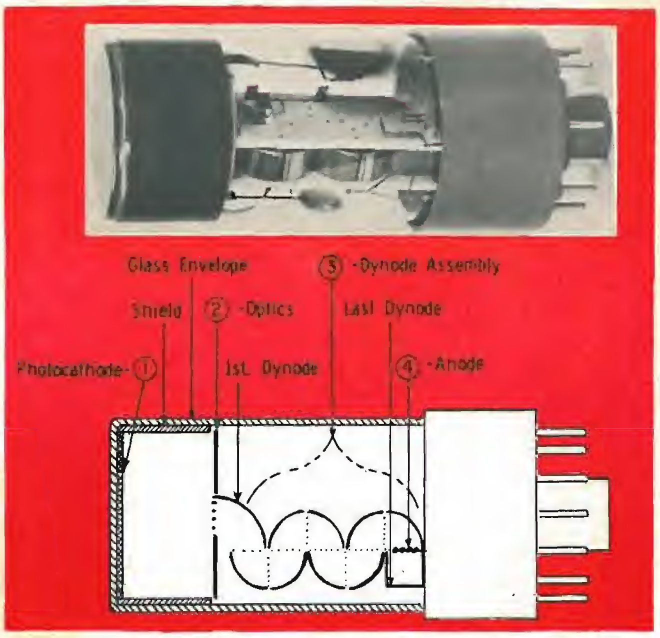


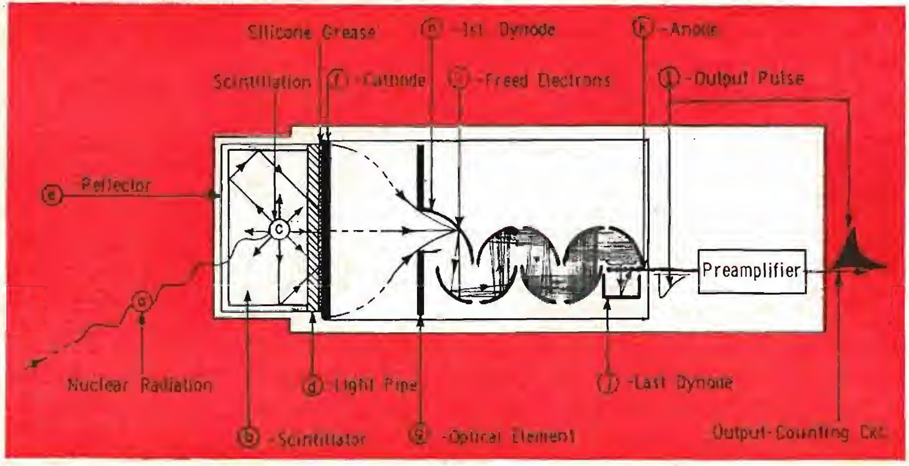
Fig. 3. Photograph and cross-sectional view showing the four major parts of a photomultiplier tube. The dynodes, by the secondary-emission phenomenon, act as electron multipliers.

Fig. 4 is a schematic of the scintillation detector assembly consisting of a scintillator, photo-tube, and preamplifier. With reference to Fig 4, the action within the detector is as follows. Nuclear radiation (*a*) is absorbed by the scintillator (*b*) causing ionization, which is the conversion of nuclear energy into light energy (*c*), referred to as scintillation. By means of the light pipe (*d*) and reflector material (*e*), a large portion of the scintillation reaches the photocathode (*f*). By means of photoelectric emission, the freed electrons from the photocathode are funneled by the electron optical element (*g*) to the first dynode (*h*). At the first dynode, as well as the other dynodes, the secondary-emission phenomenon occurs. The freed electrons released by the first dynode (*i*) are funneled to the second dynode. Upon impact, additional electrons are freed and, in turn, are attracted by the succeeding dynodes in sequential order. At each dynode, the number of freed electrons multiply by the electron-multiplication process. At the last dynode (*j*) all electrons are then funneled to the anode (*k*), producing an output pulse (*l*) which may then be coupled to its associated counting equipment *via* the preamplifier.

PAC-1S, Functional Operation

The PAC-1S (Fig. 1) is a commercially available scintillation counter built to meet governmental and commercial specifications and designed primarily for scintillation counting. The PAC is battery operated by five standard "D" cells or five RM-42 mercury cells and is referred to by such names as "Radiac," "Scint Pac," and the early models as "Poppy." Scintillation counters are widely used by governmental agencies, commercial and national laboratories, and many educational institutions. The PAC can be used with either an *alpha* or *beta-gamma* detector and is calibrated to present a meter reading from 0 to 2,000,000 counts-per-minute (CPM) of nuclear radiation in four range scales (×1, ×10, ×100, and ×1000). Meter readings are indicated on a 0-20-μA meter and an audio output phone jack is also included. Each meter count gives an audible click.

Fig. 4. Schematic representation of gamma scintillation detector showing functional relationship among scintillator, photomultiplier tube, and preamplifier.



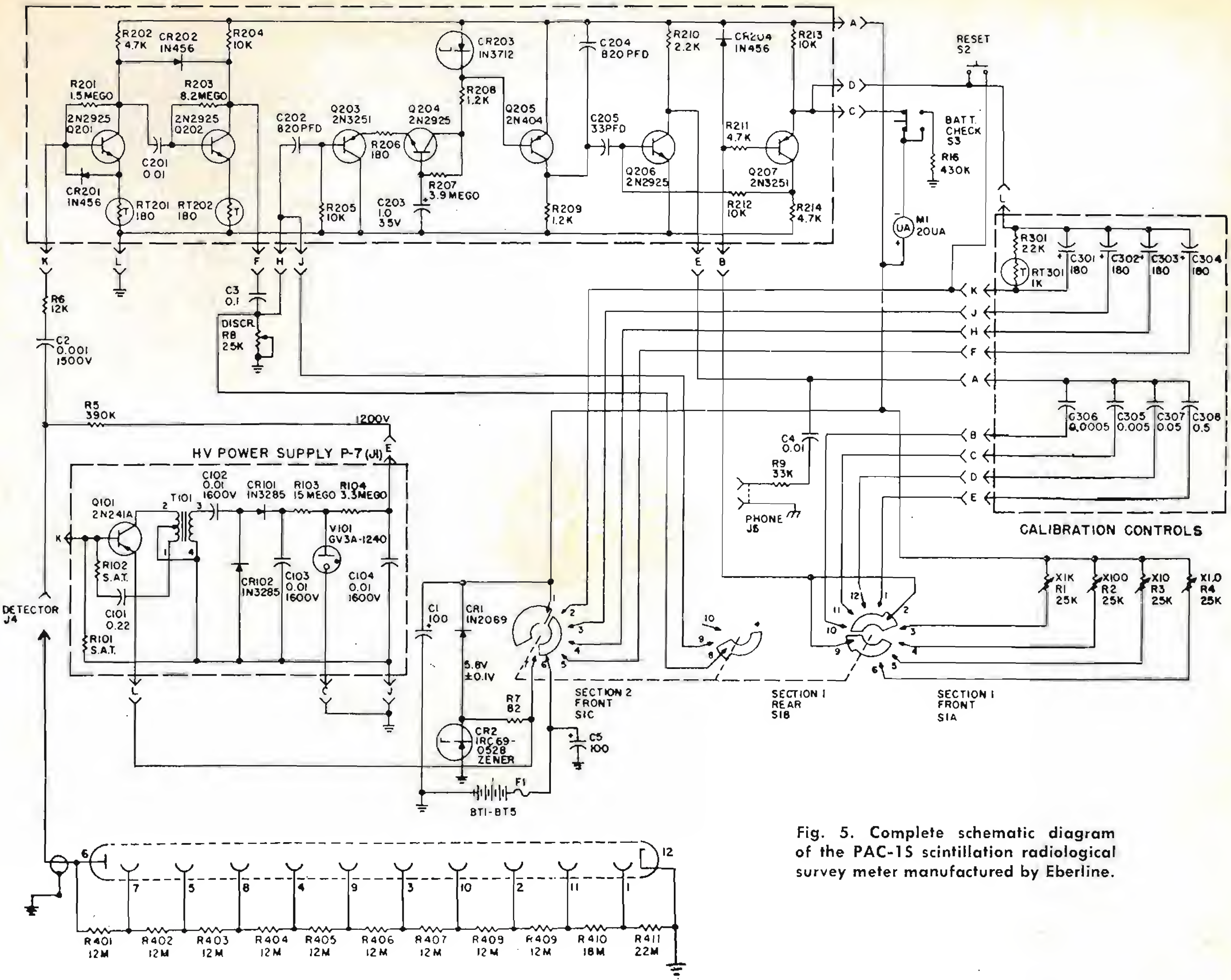


Fig. 5. Complete schematic diagram of the PAC-1S scintillation radiological survey meter manufactured by Eberline.

The electronic circuits are: a high-voltage supply for the detector, an amplifier, a pulse-height discriminator, and a trigger circuit. The panel-mounted controls (Fig. 1) consist of a range-selector combination "on-off" switch; a battery-check button that, when pressed, will indicate on the meter the battery supply condition; a "Reset" button which returns the meter pointer to zero; and a discriminator control, "Discr.," to determine the minimum size pulse to be accepted from the detector. In addition to the range-selector switch, each range has an internal calibration control as shown in Fig. 5.

Referring to the circuit diagram of Fig. 5 the basic operation of the PAC is as follows. Regulated high voltage is supplied by a blocking oscillator circuit made up of transistor *Q*101, transformer *T*101, and their associated components. The a.c. voltage produced by the oscillator induces a voltage in the secondary winding of *T*101. Capacitors *C*102 and *C*103 and diodes *CR*101 and *CR*102 make up the voltage doubler and filter network. The resultant detector high voltage is regulated at 1240 volts by corona regulator tube *V*101. Capacitor *C*104 further filters this voltage which is then applied to the detector voltage-divider network through resistor *R*5. The divider network consists of a series-resistor string (*R*401 through *R*411) which provides each photo-tube dynode with the proper voltage for electron multiplication.

When the detector is placed in a radioactive field and the proper regulated high voltage is applied to the detector, a negative-going output pulse will be coupled through capacitor *C*2 to the two-stage amplifier circuit, consisting of transistors *Q*201 and *Q*202 and their associated components. To compensate for temperature changes in the input components, the amplifier contains two temperature-sensitive resistors (*RT*201 and *RT*202) for stability. Diode *CR*201 is used to help prevent damage to the input transistor if the detector voltage should be shorted to ground. Diode *CR*202 is used to limit the amplitude of large input pulses. When panel-mounted discriminator control "Discr." (*R*8) is set at maximum, the over-all gain of the amplifier is approximately 250. The amplifier output is coupled to the pulse-height discriminator stage through discriminator control network *C*3, *R*8, and *C*202. Discriminator input transistor *Q*203 is a common-collector circuit and its output is directly coupled to transistor *Q*204. Resistor *R*205 provides the bias for *Q*203, and resistor *R*206 supplies a negative feedback between *Q*203 and *Q*204. Transistor *Q*204 is wired as a common-base circuit and drives tunnel diode *CR*203. The function of *Q*204 is to supply a current source to control the tunnel diode. When this current source reaches 1 mA, it drive the diode into a high-voltage state (negative resistance). This voltage is sufficient to saturate transistor *Q*205, which is normally cut off. *Q*205 will remain saturated as long as the diode is in the high-voltage state. When the diode current decreases sufficiently, the tunnel diode will revert to its normal state and *Q*205 will cut off.

If pulses are of minimum amplitude, the trigger circuit which is a monostable multivibrator composed of transistors *Q*206 and *Q*207 and their composite parts, will go into operation. In its quiescent state, both transistors are at cut-off (non-conducting). When a proper size positive-going pulse appears at the base of transistor *Q*206, it turns *Q*206 on (conducting) and this, in turn, sets the trigger circuit into operation. With this action, a negative-going signal is developed across resistor $R210$ which is coupled through preselected timing capacitor $C308$ and resistor $R211$ to the base of $Q207$, causing it to conduct. This, in turn, generates a pulse across collector resistor $R214$ of $Q207$. A portion of this pulse is fed back to $Q206$ through resistor $R212$, thereby maintaining $Q206$ in saturation. This additional voltage also holds timing capacitor $C308$ in a charged state which, in turn, maintains $Q207$ in saturation. During the charging time of $C308$, the base of $Q207$ approaches the battery voltage, driving it out of saturation. During this time its collector voltage will also start to decrease, thereby causing $Q206$ to start out of saturation. At this point, $Q207$ will cut off, causing its collector voltage to drop to near-ground potential. This drop in collector voltage is coupled to the base of $Q206$ causing it to cut off. The time that $Q207$ conducts depends on the preselected timing capacitor ($C305$, $C306$, $C307$, or $C308$) and their associated resistors ($R1$, $R2$, $R3$, or $R4$) which are also preselected by the panel-mounted range selector ($S1A$).

During the conduction period of $Q207$, a current will flow through the indicating meter ($M1$), developing a voltage drop across it. This voltage will charge up one of the preselected meter integrating capacitors ($C301$, $C302$, $C303$, or $C304$). When $Q207$ stops conducting, the preselected integrating capacitor will discharge through the meter, maintaining an average meter reading. The same pulses affecting the meter are also applied to the phone jack ($J5$) for aural monitoring.

Maintenance

Many scintillation survey meters, although ruggedly constructed, are delicate instruments. Severe shock to them might result in damage to the microammeter movement, the photomultiplier tube, or cause the scintillator to crack. A word of caution: *the indicating meter is very delicate.* If it is necessary to make continuity checks, the meter should be shorted out by placing a wire across its terminals. The electronic components used in most survey meters are standard parts and can be checked readily by conventional means. It is good practice to remove the instrument from its case periodically and inspect for moisture, dirt, and battery-voltage contact corrosion. In due time the contacts become corroded and also electrodeposition action sets in, causing the survey meter to be erratic or fail to operate. When battery-operated instruments are to be stored, they should be kept in a dry place with batteries removed.

The scintillation detector is the most expensive part of the survey meter, therefore it should be handled with care. A single photo-tube may cost from $25.00 to hundreds of dollars, depending on size. It is strongly recommended that photomultiplier tubes be stored in complete darkness and, when used in a survey meter, never be exposed to light when connected to the power supply. This is one of the main causes of failure of the *alpha* and *beta* scintillation detectors. The light-tight Mylar windows are very easily damaged by careless use, resulting in scratches or ruptured windows, thereby allowing excessive light to reach the photosensitive cathode. Whenever the window is damaged, the meter will indicate an excessively high reading or may saturate and give no reading at all. The damaged area can be repaired temporarily by applying a small amount of black lacquer over the damaged area, sealing the light out. It should be kept in mind that the lacquered area will not pass low energy particles such as *alpha's.*

The scintillator is also expensive and should be handled with care. A scintillator can be affected by various conditions. For example, a false reading will be indicated on the meter if the scintillator is exposed to ambient light, mechanical strains, heating, and to certain chemicals. Some crystals may rupture when exposed to excessive temperature changes. A sodium-iodide scintillator, which is hygroscopic, must be hermetically sealed so as not to come in contact with moisture.

ABNORMAL INDICATION	PROBABLE FAULT
No indication on meter	(a) connections, battery contacts; (b) batteries; (c) controls; (d) meter movement
Indicates high reading on all ranges	(a) contamination; (b) detector; (c) noisy cable; (d) calibration; (e) see last abnormal indication
Indicates low reading on all ranges	(a) calibration; (b) batteries; (c) high voltage is low; (d) detector
Indicates erratically	(a) connectors, battery contacts; (b) detector; (c) dirty insulators
Meter saturates (reads up then drops to zero)	(a) detector; (b) high radiation field
Resists proper calibration	(a) detector; (b) controls; (c) batteries
Incorrect reading when checked with check source	(a) calibration; (b) batteries; (c) detector
Indicates up-scale with no radiation present	(a) calibration; (b) detector; (c) high voltage too high

Table 1. Fault-location chart for scintillation survey meter.

Other components that can cause erroneous readings are the detector insulators, high-voltage insulators, and the feedthroughs. The slightest contamination of these parts by perspiration, dirt, or oil will create leakage paths. If surface leakage is suspected, cleaning with 170-proof methyl alcohol is recommended.

False readings can also result if the *alpha* detector is exposed to high concentrations of *alpha* or *beta-gamma* nuclear fields or nuclear contamination of the detector. For example, in some cases, should the *alpha* scintillation detector be exposed to high levels of *alpha,* the detector light level becomes so great that the counting circuit cannot resolve the pulses, resulting in a zero or near-zero reading. As for the high levels of *beta-gamma,* an erroneous reading will result if *alpha* radiation is to be measured in an area also contaminated with *beta-gamma* radiation. If this kind of situation exists, the surface area of the detector should be blocked out with paper, this would then block out all *alpha* radiation. If the survey meter still indicates and the detector is not contaminated, one of two procedures should be used. (1) Measure the *beta-gamma* reading and subtract this value from the total *alpha, beta-gamma* reading, or (2) adjust the discriminator or sensitivity control until there is no *beta-gamma* indication on the meter (this makes the meter less sensitive). After the initial adjustment is made, be sure to check for *alpha* sensitivity with an *alpha*-check source. If the reading is lower than the calibrated value, all further *alpha* readings must be corrected by this factor. Upon completion of the survey, the meter should be recalibrated for a proper *alpha* reading. *Warning: Calibration of all types of survey meters should be done only by qualified personnel trained in the use of nuclear radiation.*

In addition to the above limitations, a fault-locating chart (Table 1) is included. It indicates some of the typical malfunctions encountered and their probable causes.

In general, most battery-operated survey meters have an accuracy of ±10 to 20 percent of full-scale reading. They are designed to be used as indicators of radiation and not for absolute measurements. When purchasing any instrument, it is a good practice to read the instrument's maintenance/operator's manual. A person can learn a lot about the instrument from its manual. For example, operational instructions, theory of operation, diagrams, preventive maintenance, calibration curves and procedures, pictorial illustrations, parts list, and above all, instrument limitations are usually included in the manual. Most reputable manufacturers supply this information on request. ▲

Article is based on work performed under the auspices of the U.S. Atomic Energy Commission.