

PART OF:

Measuring External Radiation

Some of the early measurement systems for measuring x-ray and gamma-ray intensities and exposures were described in Chapter 1. Further developments led to the instruments and systems that form the basis of radiation protection of workers and members of the public from external sources of radiation. The story is largely one of detectors: new ones, based on novel physical processes, that have either proved practical and reliable or been dropped and old ones, known from the earliest days of radiation. Indeed many of the devices regularly used today rely on physics that was well understood a century ago.

Of course, the electronics that turns a detector into a usable instrument have developed enormously, first with the valve (“tube” in the USA) and then the transistor and integrated circuit. The increasing complexity and functionality have been built around the same basic devices so, on the whole, no attempt has been made here to trace in detail the developments in commercial instruments in the last few decades.

The fact that radiation could cause ionisation was known early on. Electroscopes discharged under the influence of x-rays and Becquerel found the same effect near radioactive substances only weeks after his initial discovery. However, it was to need decades of development of radiation detectors and of the electronics to go with them before practical robust instruments were readily available.

When an ionising particle passes through a gas it produces electrons and positive ions. A typical counter set-up is a thin cylindrical cathode surrounding a central anode. If an electric field is applied across the gas then the electrons migrate towards the positive electrode and the positive ions the other way. At low voltages the probability is that the ions will

recombine before they reach the electrodes but, as the voltage increases, it is more and more likely that they will be collected at the electrodes. When all the ions produced are collected there is said to be saturation and increasing the voltage will, for a significant increase in voltage, not increase the collected charge because there are no more electrons and ions to collect. This is the region where ionisation chambers work. The chambers can be used in either a current mode and a pulse one. In the current mode the chamber current is related to the intensity of radiation while in pulse mode the tiny charge released in individual events is proportional to the energy deposited by individual particles or photons.

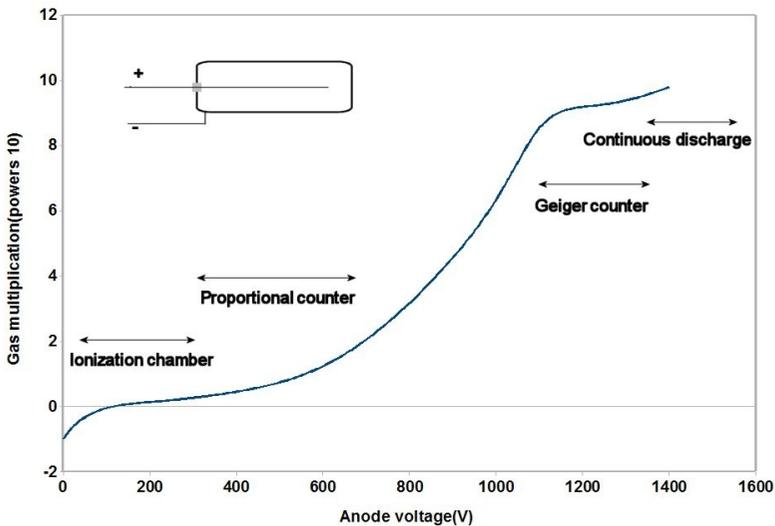


Figure 10: Schematic counter tube performance

If the voltage is increased substantially then a new process will start to occur. As electrons reach the high electric field near the anode they may acquire enough energy to themselves cause ionisation on collision and introduce another ion pair. The process may then be repeated in a kind of avalanche so that the initial electrons are multiplied many times. This is gas amplification and the amount of amplification increases with the voltage applied. Devices that operate in this region are called proportional counters because the output charge from them for an event is proportional to the initial amount of ionisation. The useful gas amplification ranges to perhaps 10^6 . Proportional counters are used in pulse mode with the significant advantage that they give a relatively large signal pulse which is proportional

to the energy deposited in the counter.

If the voltage is increased still further then the proportionality relation begins to degrade until a regime is reached where the output is much larger than from a proportional counter but is independent of the size of the initial ionisation. At this point the electron avalanche spreads through the tube because the uv photons produced in ion recombination cause further ionisation. This is the region where Geiger counters work. They operate only in pulse mode and, while the output is the same whatever the energy of the ionising particles, the output pulse is so large that relatively unsophisticated electronics can be used. If we take the voltage higher still a continuous discharge takes place making the tube useless for counting.

The electroscope used by the earliest workers was an essentially qualitative device. If measurements were to be made with ionisation chambers, a very sensitive device was required to measure the tiny electric charges released. Quadrant electrometers were established devices of high accuracy and sensitivity (with perhaps the Dolezalek quadrant electrometer of around 1896 being a pinnacle) but they depended on the charges generated deflecting plates suspended from a fine filament. While accurate and sensitive, they were delicate laboratory instruments. The string electrometer that became available in a practical form just after 1910 was rather more robust. It depended on measuring, with a microscope, the deflection of a tensioned, metal-coated quartz fibre in an electric field when charge was introduced onto it. It was a non-linear instrument but it was to be, in one variant or another (and there were versions down to Lindemann, Lutz-Edelmann and Wulf among others), a key component of many of the devices developed up to the outbreak of the Second World War.

The first practical ionisation chambers that could be used for routine measurements on patients were probably those made around 1920 by William Duane [295,296] but they were quickly followed by those produced by Glasser and Fricke [297] and the ionometer of I Solomon [298]. It was the Glasser and Fricke design that was the core of the first practical instrument when, in 1928, John Victoreen founded the Victoreen Instrument Company in Cleveland, Ohio to manufacture the Fricke-Glasser x-ray dosimeter, an instrument calibrated in R-units that would “eliminate the possibility of x-ray burns” [299]. This was the condenser r-meter in which a small ionisation chamber was connected to a string electrometer that could be viewed with a built-in microscope. It was intended for measurements in x-ray beams to control dose delivery to patients and was calibrated in roentgens per minute.

In 1930 Victoreen began to manufacture an r-meter based on the Glasser-Seitz dosimeter (Glasser, Seitz and others at the Cleveland Clinic

had designed a new dosimeter in 1929). In this version the chamber (usually made using Bakelite) could be charged, removed from the electrometer during exposure and returned for reading. Known as the Model 70, it was provided with a selection of chambers with ranges from 0 - 0.25 R to 0 - 100R. A rugged and reliable instrument (similar in appearance the earlier instrument), it was in use for more than 50 years.

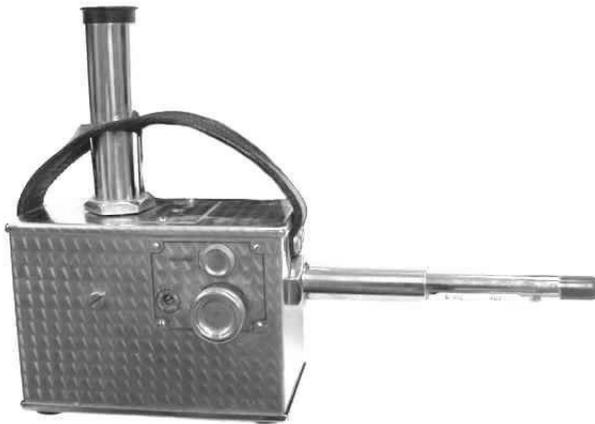


Figure11: the Victoreen Model 70 [ORAU]

Lauriston S Taylor at the National Bureau of Standards developed a portable survey meter in 1929 after he suffered an accidental exposure [300] as he sat for several minutes in the full beam of an x-ray set after someone left out a lead shielding panel. Investigation showed that the whole-body exposure was around 200R which left Taylor relieved: it was “less than that commonly used in therapy at the time”. He later said: “Since I was not aware that one should become nauseated at this exposure, I was not nauseated either” [300]. However, it decided him to make a portable instrument. This was made with a spherical spun-aluminium ionisation chamber connected to a version of the Lutz-Edelmann string electrometer then in use at his laboratory. The three batteries for the ionisation chamber, total potential about 135 V, were housed in a wooden box with the chamber and electrometer on the top. The system was “relatively rugged” and maintained its calibration over a long period. Three chambers were made and these could be interchanged to vary sensitivity. With the largest, 75 mm diameter, chamber the full scale-range was 2 mR.

The Lauritsen electroscopes [301] was developed in 1937. The electrometer here was a gold-covered quartz fibre where the electrostatic

forces were balanced by tension in the charged fibre. The deflection was measured against a graduated scale with a microscope. Charging was done with a friction charger, batteries or, a little later, a valve rectifier. It was produced by the Fred C Henson Company of Pasadena and a Model 2, with the electroscope enclosed in a case with a built-in power supply and light source, appeared shortly afterwards. It made a rugged, portable and sensitive survey meter and it was reportedly still being used in the 1970s.

There were clearly possibilities to use radio valves (“tubes” in the USA) to replace the measuring electrometer and a number of circuits were designed in the late 1920s so that ordinary radio valves could be used to measure very small currents. However, while some were apparently successful, the electrometer remained the instrument for such measurements. The problem was that the available valves were simply not designed for low-current dc measurement.

The first custom-designed tube, the General Electric “FP-54 plotron” described in 1930 by Metcalf and Thompson [302], was capable of amplifying currents as small as 10^{-17} A. To measure such small currents it is essential that the grid input resistance of the valve is extremely high because it is the high resistance that results in measurable voltages when the minute currents pass through it. In ordinary valves of the time this resistance was perhaps $10^8 \Omega$. By running the filament at low power, keeping the anode voltage below 8 V and introducing an extra grid, Metcalf and Thompson managed to increase this resistance to about $10^{16} \Omega$. A number of practical circuits using the valve, really adaptations of existing circuits, were described by DuBridge in 1930 [303]. In particular he showed how a second valve could be used to amplify the tiny current enough to register on a conventional microammeter and he speculated how further improvements could be made. While he did encounter a few problems – the valves needed to warm up for at least 30 min before reliable readings could be taken – the way to produce practical, rugged ionisation chamber instruments based on valves was now clear. The FP-54 was the only electrometer valve available until the end of the 1930s and it, and its 6 V storage battery, were too big to incorporate into a portable ion chamber survey meter. This had to wait for a miniature electrometer valve, the VX-41, developed by a Dr Ewing, a professor of physics at Northwestern University, for use in hearing aids [299]. A number of these were obtained by the US health physicist Dale Trout and they formed the basis for the first commercial ion chamber survey meter. The prototype of this was put together by Trout and John Victoreen with materials to hand: for example, the counting tube was a cardboard mailing tube coated with Aquadag to make it conducting. A

version of the survey instrument, probably the model 241 dating from the early 1940s, is in the Oak Ridge Associated Universities (ORAU) museum [304].

An example of some early work in the UK using an electrometer valve circuit for measurements of voltage on small ionisation chambers is that of Farmer [305] reported in 1942. Farmer sought a simpler system than the usual one - then based on the Wulf or Lindemann string electrometer. He used a Marconi ET1 electrometer valve in a two valve circuit so that the electrometer valve could be used at low anode voltage. The capacity of the chambers were around 1 pF while that of the valve was about 3 pF so simply connecting them to the grid would drop the voltage by a factor of four and introduce uncertainty. Farmer solved this problem by shielding the cable from the chamber and connecting the shield to the cathode of the electrometer valve.

Ion chambers have almost always been used in the direct current or integrating mode but pulse operation caused by cosmic rays was recorded by Lindholm in 1928 and the gridded ion chamber devised by Frisch in 1944 removed the problem of position dependence of pulse size, to produce a high-resolution alpha device used to detect alpha-emitters in gases. Pulse-type ion chambers have also been used as fission chambers for neutron detection. They were made sensitive to neutrons by coating the cathode with a fissile material - usually $^{235}\text{U}_3\text{O}_8$. When a neutron is absorbed by the uranium and fission occurs, the fission fragments cause large pulses that can be fairly readily detected.

Gas amplification was discovered in about 1900 by J H Townsend [306] but practical use came from Rutherford and Geiger in 1907 [307]. They were using cylindrical gas-filled tubes with central electrodes and discovered that alpha particles gave much larger electrometer readings than had previously been seen. Geiger and Klemperer [308] exploited the proportional region in 1928 and could differentiate between alpha and beta by pulse size. This characteristic, with the benefits of gas amplification and the relatively short dead-times, was to make them valuable instruments throughout the rest of the century.

Three broad types of proportional counter evolved:

- Gas flow counters with and without windows
- Air proportional devices for alpha counting
- Sealed proportional counters for special purposes e.g. BF₃ and He-3 neutron detectors

Argon has been preferred as a fill gas but hydrocarbons have been used and the tissue equivalent gas 64% methane, 32% carbon dioxide and 3% nitrogen called P-10, developed by John Simpson in 1940s, has been widely employed for gas flow proportional counters. Air-filled counters have been used for alpha counting because they allow the use of thin windows without gas flow.

Taylor [300] describes the use by Simpson [309] of large area air proportional counters with thin nylon film windows in an installed alpha-contamination hand monitor [310]. For such uses they had “no competitors”.

The devices first used by Rutherford and Geiger at Manchester [307] were refined by Geiger in 1912 and 1913 after his return to Germany [311] as a point counter in spherical geometry. The counter was used in laboratories and was the detector employed in 1925 to confirm the Compton effect. Hans Geiger continued to refine the device and in 1928, working with Muller [312], he developed counters with much larger sensitive volumes and using various fill gases that were very close to the Geiger-Muller(G-M) tubes we know today.

One problem with early G-M tubes was the long dead-time – the time after one event before another could be detected. This occurs because the avalanche initiated in the tube by a particle continues until the potential gradients near the anode are reduced below a critical value by the accumulation of positive ions. This brings the avalanche to an end and makes the counter ready to respond to the next particle. This “quenching” action was initially achieved with a high “quenching” resistance but this resulted in dead times of perhaps 10 ms, limiting greatly the use of the device. In the 1930s active valve circuits were designed [313,314] that removed the potential from the tube briefly after a pulse and gave shorter dead-time values, down to perhaps 100 μ s these but added to complexity. In 1937 Trost [315] discovered organic quenching. This meant adding a small quantity of an organic vapour such as ethanol that would quickly terminate avalanches and make the tube self-quenching with a dead time of around 200 μ s. Tubes that relied on organic quenching had a limited life because a tiny fraction of the organic quenching agent is destroyed in terminating the discharge but it was found by S H Liebson, while working on his PhD thesis in 1947 [316], that an added halogen-compound vapour would have a similar quenching effect. Since the halogen compound normally recombines after quenching, such tubes had a much longer life. Halogen-quenched tubes quickly caught on once they became commercially available around 1950 and remain the norm.

Practical tubes were made from the 1930's in a variety of shapes and sizes. The early ones were made of glass but by the late 1940's they were being routinely made from metal with, if required for alpha or beta detection, thin windows made from mica.

The first commercial instrument, using a glass-walled G-M tube and earphones, was probably developed by Victoreen in the 1930s [299]: a pair of high-impedance headphones were used to hear the events in the tube. The refinements of the ratemeter – combined with headphones in the ORNL “Walkie Talkie” instrument shown in Figure 12 – and counting circuits were to come in the next decade. The simplicity resulting from the large pulse coming from the tube meant that the G-M tube was rapidly established as a tool for surveys and contamination measurement.



Figure 12: Walkie Talkie [ORAU]

By the late 1940s several companies were producing survey meters not too different from those in use today – although usually rather heavier – with shutters to exclude shorter-range radiation. The large civil defence and uranium prospecting markets after the war gave rise to a large number of basic but robust instruments.

The versatility of the G-M detector is illustrated by Taylor [310] who describes a doorpost monitor to detect gamma-emitters developed at Harwell before 1950, based on two 1.5 m long G-M counters.

The spintaroscope was a popular scientific toy in the early days of radioactivity. It relied on the fact that when an alpha-particle struck a zinc sulphide screen a tiny flash of light was generated. In darkness the flashes

could be seen through a low-power microscope as minute scintillations. This was the scintillation detector with the human eye as the register of the scintillations (and the eye could detect a flash of as little as 30 photons) used in some of the most important experiments of early nuclear physics. Birks [317] recounts that, in one famous lab, students interested in pursuing nuclear physics were tested in a dark room; if they failed the eye test they were directed towards less physically exacting areas of physics. The last major experiment to use a human detector was that of Cockcroft and Walton in 1932 when they studied the disintegration of lithium by protons. Of course, while it depended on the trained eye in the darkened room it was not a practical instrument for radiation measurement so the scintillation counter had to wait until a device that could reliably measure very low light levels became available during the Second World War.

The photomultiplier tube (PMT) depends on a simple effect: if an electron is accelerated by an electric field and made to impact on a suitable surface, several secondary electrons are ejected. The electrons can then in turn be accelerated and the process repeated for perhaps a dozen stages so that the initial electron is multiplied many millions of times to give an easily-measurable electrical pulse from just a small number of initial electrons. If the initial electrons derive from a photocathode – a material that emits electrons when struck by light photons – we have a very sensitive detector of light. Following the work on direct detection of ionising particles by Z Bay [318], the practical device that we recognise today originates from the work of J A Rajchman and R L Snyder [319] in 1940.

The first publication of the use of a photomultiplier and ZnS screen is probably that of Blau and Dreyfus [320] for source measurements in 1945. In these the brightness of the ZnS screen caused by an alpha source was measured as proportional to the current in the photomultiplier tube. It was reckoned that, with suitable calibration, an accuracy of about 5% in measuring source strength was possible. However, the first actual use may well have been in 1944 by Curran and Baker [321], in which individual alpha-particles were detected using an RCA 1P21 PMT and an oscilloscope. This was not published (and then as only a rather drastic summary) until 1948 so the modern scintillation detector is generally considered to have come into being in 1947 through the work of Coltman and Marshall [322].

The search for scintillators other than zinc sulphide quickly brought results. Kallmann in 1947 [323,324] detected beta and gamma scintillations from naphthalene and the high efficiency was confirmed by Deutsch [325] who also confirmed the very short pulse length and found solid benzene to have similar behaviour. In 1948 Bell [326] showed that anthracene was a better scintillator still and detected fast neutrons. Also in 1948 Hofstadter

made the important discovery of the thallium-activated alkali halide scintillator NaI(Tl) [327,328]. This material, in which radiation energy absorbed in the sodium iodide is transferred to the thallium luminescence centres, has several important properties: iodine has a relatively high atomic number, it is efficient at converting gamma energy into light, the pulse of light produced is quite short ($<1\mu\text{s}$) and well-matched to photomultiplier photocathodes and it can be made as large single crystals. The high atomic number means a high probability of full absorption of gamma rays within a smallish crystal and thus the generation of a characteristic pulse-height spectrum that made spectrometry possible. One of the disadvantages of the organic scintillators is the likelihood of Compton scattering and loss of the scattered gamma ray (and hence some of the initial energy) from the system. This leads to very degraded spectra virtually useless for gamma spectrometry.

In parallel with the improvements in scintillators there were improvements in PMT design. The original devices (the 1P21 for example) had a curved side window but a design with a flat end window, the RCA 5819 of 1949, gave much better light collection. The development of the Venetian Blind type tube by EMI [329] in the UK and improvements in photocathodes were both significant.

There was a brief interest in photosensitive Geiger counters as alternatives to the PMT in the late 1940s because of their potential simplicity and of the modest electronics needed to run them [330]. However they proved to be less stable and had much larger deadtimes than PMTs and they were relatively quickly dropped.

By the late 1950s methods had been found by the Harshaw Company for producing large single crystals of NaI(Tl) and optically coupling them efficiently to photomultipliers with a photocathode response well matched to the emission spectrum of the scintillator. The efficiency of the resulting detector for gamma rays has not been surpassed for general use although many other materials such as CsI(Tl) and CsI(Na) are available. It found uses in survey instruments, analytical systems and, taking advantage of the ability to produce very large crystals, the whole-body monitor and the gamma camera.

The liquid scintillator.....