MEASURING RADIOACTIVITY

INTRODUCTION By Raffi Katz

This article started when a customer asked about converting cps (counts per second) to Sieverts, the measure radioactivity's effect on the human body; yet the basic unit of radioactivity is the Becquerel. His question was simply: how do you convert these various units so that you end up with a measure of 'risk from radioactivity'.

I asked Nick Hartley, about this. He had his own notes about the maths, along with information about the basic physics. I edited the 'basic physics' so that it would be more understandable to the layman, and I hope that you will find it interesting even if you have only a 'casual' interest in radioactivity. This article, however, is aimed at technicians who need to buy a Geiger counter and want to know more about how radioactivity is measured.

A Geiger counter measures the effect of radiation by detecting the number of radioactive particles entering the sensor (the Geiger Muller tube), shown as cps (counts per second) on a meter (and by a clicking sound). An analogy would be a thermometer measuring the effect of heat reaching the sensor (the glass bulb of the thermometer). A Geiger counter does not measure the energy (particle energy) in the actual reaction and so cannot determine which radio-isotope is the source. An analogy would be that a thermometer will not show you how the heat is generated. As regards 'risk' (to continue the thermometer analogy) - if someone has a high body temperature, you can only say, "They have a temperature", you will not know anything about the level of risk 'caused' by the temperature.

The manufacturer of the actual sensors (the 'counter', the Geiger Muller tubes) is www.distron.co.uk who supply laboratories around the world, though they also supply the complete 'instrument' (the Geiger sensor connected to the box with the meter and clicker), designed by Nick.

NOTES ON RADIOACTIVITY AND ITS MEASUREMENT by Nick Hartley

Radioactivity is the emission of energetic particles from substances with unstable atomic nuclei. It can be produced in a nuclear reactor, as fall-out from a nuclear explosion or in a particle accelerator. It also occurs naturally.

Very few of the 92 elements making up the natural world are radioactive. Those that are, tend to be the ones with high atomic weight (e.g. Uranium, Radium, Polonium) and have a stable form (e.g ^{238}U) and one or more unstable forms (referred to as isotopes, e.g. ^{235}U, ^{239}U). The left superscript refers to the atomic weight (i.e they have the same proton number, in this case 92, hence the same chemical properties, but a different neutron number from the normal, stable element). When an atom emits a particle, it changes into another element (unless a gamma is emitted) which itself may be unstable, then emits another particle and so on until a stable element is reached. In the case of Uranium 235, there is a long chain of so-called daughter radio-isotopes ending in Lead. This process is called radioactive decay, as the source material is eventually spent. The time it takes for half of the source material to be used up is known as the half-life, and can be anything from microseconds to thousands of years.

The basic unit of radioactivity is the Becquerel (Bq). This is the number of radioactive disintegrations occurring per second. Another unit, little-used now, is the Curie (Ci = 3.7×10^{10} Bq, a large number, so milli- or micro-Curies are more practical).

A Geiger counter measures counts per second (cps), the number of radioactive particles entering the Geiger Muller (GM) tube through the thin end window. This is directly related to the activity in Bq. However, various factors should be taken into account:

1) Geometrical: radioactivity is random in direction; the GM tube only 'sees' the particles reaching it. For a point source, the number will decrease as the square of the distance from it. Try to get an idea of the extent of the source by taking many measurements in different positions around it.

2) Radioactivity is random in time too: variation in the count rate decrease as the square root of the cps. So higher readings are more accurate. Readings below 10 cps should have the background reading (usually around 1) subtracted.

3) Radiation is absorbed by its passage through air, liquid or solid. Therefore take readings as close to the source as possible. This is particularly true for alpha particles (see below). A single sheet of paper in front of the tube window is enough to screen out alphas.

For these reasons, accurate measurements are usually made in a laboratory with a thin sample presented on a 'planchette' immediately below the Geiger window (thin in order to prevent significant 'self-absorption'). Even then, only half the emitted particles on average are travelling in the right direction to be counted.

There are three main types of radiation; each type also has a characteristic energy, depending on the source material, measured in electron-Volts (eV). 1 keV = 0.16×10^{-15} Joule. 1 MeV = 0.16×10^{-12} J.

Some radio-isotopes emit more than one type of the following particles.

Alpha particles (charged Helium nuclei) are easily absorbed in solids and even in air have limited range, depending on their energy (e.g 1 cm for 2 MeV , 6 cm for 7 MeV).

Beta particles are fast electrons and have greater range, (e.g 15 cm range in air for 0.156 MeV Betas from Carbon 14).

Gamma rays are high energy photons (i.e quanta of electromagnetic radiation) and have the greatest range. These are hardly absorbed by air or other gases at all.

A Geiger counter, such as the Gem-400, measures all three types of particle, but is least sensitive to gammas. This is because gammas are only absorbed in the internal walls of the tube, knocking out some electrons which are counted.

Radioactivity causes ionisation in exposed material, resulting in chemical and physical changes. Each radioisotope radiates its own particle(s) at specific energies. These are well documented (see e.g. Kaye & Labye Tables of Physical and Chemical constants) and see the table below. Knowing the source, the energy deposited in Grays (Joules/kilogram) can be calculated.

Radioactivity constitutes a health risk from the amount of ionisation caused by radioactive particles as they transfer their energy in living tissue and come to rest. Many thousands of atoms are ionised, causing unpredictable chemical activity in living tissue resulting in DNA code mutations, cell necrosis, etc, but the effect of ionisation depends on the nature of the radiation (alpha, beta, gamma). Alpha radiation, which is found to be particularly harmful, is ascribed a Quality Factor of 20, compared with 1 for Betas, Gammas and X rays. Neutrons have a quality factor of 10. This factor multiplies the ionising energy (in Grays) to determine the so-called *Dose Equivalent*, measured in Sieverts (Sv = J/kg). Thus 1 Gy of alpha radiation produces 20 Sv, 1 Gy of Beta radiation, 1 Sv.

A Geiger counter does not measure particle energy and hence cannot determine which radio-isotope is the source. For this an instrument with an energy-dependent response is needed, e.g a scintillation counter, ionisation chamber, proportional counter or semiconductor detector.

Finally, the effect of this radiation depends on the part of the human body exposed, and an additional risk weighting factor is introduced in order to arrive at the "Effective Dose Equivalent". For example:

Organ	**risk weighting factor**
Testes and Ovaries	0.25
Bone Marrow	0.12
Liver	0.06
Thyroid	0.03

The final figure is still measured in Sieverts. For nuclear industry workers the exposure limit is 50 mSv per annum (m for milli – one thousandth), for aircraft crew, exposed to a higher level of cosmic rays (gammas), 10 mSV, for the general public, 5 mSv. The general background level is around 1 mSv p.a. due to cosmic rays penetrating the atmosphere to ground level. (These show up as an approximate 1 count per second on the GEM400.)

Some commonly encountered radionuclides:

Isotope	Particles emitted	Energy (MeV)	Half-life	Comments
^{3}H	beta	0.0186	12.33 years	energy too low for GM detection
^{14}C	beta	0.156	5730 years	
^{19}O	beta	3.26, 4.62 & 4.82	26.9 secs	
	gamma	0.197, 1.356 & 1.444		
^{32}P	beta	1.71	14.26 days	
^{35}S	beta	0.167	87.51 days	
^{60}Co	beta	0.318		
	gamma	1.173,1.333		
^{90}Sr	beta	0.550	28.78 years	
^{99}Tc	beta	0.290	2.11 x 10^{5} years	
^{131}I	beta	0.61		
	gamma	0.364,0.637,0.284		
^{137}Cs	beta	0.21	2.3 x 10^{6} years	
^{147}Pm	beta	0.22	2.6234 years	
^{210}Po	alpha	5.30	138.4 days	
^{223}Ra	alpha	5.54,5.61,5.72,5.75	11.44 days	
	gamma	0.154,0.324		
^{235}U	alpha	4.22-4.60	7.038 x 10^{8} years	
	gamma	0.144,0.186		
^{241}Am	alpha	5.39,5.44,5.49	432.7 years	
	gamma	0.026,0.060		

Establishing the 'Absorbed Dose Equivalent' measured in Sieverts (Sv) in human tissue involves knowing the exact nature of the radiation (Alpha, beta, etc and its energy), its disposition in relation to the individual exposed, including which organs are exposed, and for what time.

Ionization chambers and film or thermoluminescent badges (worn on the body) can give a good measure of this quantity. For a Geiger counter, which only measures the particle flux, on a rough calculation, making many simplifying assumptions:

$D = Q \times A = Q \times N \times q \times (Ep/Eip) \times 33.8 / (V \times d)$ Sv/s = $1.372.10^{-4}$ N(Ep/Eip) uSv/h (microSieverts per hour)

Where

D = Dose equivalent in Sv per second
Q = Quality factor for radiation (above)
N = Number of particles per second
q = charge per ion pair created = 1.6 x 10^{-19} Coulombs
Ep = particle energy (eV)
Eip = energy per ion pair, taken as 33.8 eV here
V = Active volume of Geiger counter (m^3)
d = density of Geiger fill gas (1.2 kg/m^3)

For example (figures show uSv/h)

Radionuclide	Beta energy (MeV)	cps:	5	10	20	50	100	200	500
^{14}C	0.156		3.2	6.3	12.7	31.7	63.3	126.6	316.6
^{90}Sr	0.550		11.2	22.3	44.7	111.6	223.3	446.5	1116.3
^{131}I	0.610		12.4	24.8	49.5	123.8	247.6	495.2	1238.0
^{137}Cs	0.510		10.4	20.7	41.4	103.5	207.0	414.0	1035.1
^{204}Tl	0.760		15.4	30.8	61.7	154.2	308.5	617.0	1542.5