GeigerLog
Calibration Guidance

by ullix

Addendum to GeigerLog
Version 1.5.0

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Calibration

Introduction

“Calibration” seems to be an easy concept, but there are some major problems.

What we measure with a Geiger counter is a ‘count’. And we typically determine the count **rate** like CPM (Counts Per Minute), or CPS (Counts Per Second), or counts per any other time duration, like hours (CPH), days (CPD), etc..

But what we are really interested in is not the plain number count rate, but the health effect to be expected from that count rate.

Now imagine you take a bunch of Geiger counters, using same or different Geiger tubes, with the same or different operating conditions (in particular anode voltage) and measure one unknown radioactive source. You will get different to very different CPM values, like – see table below – CPM=2 to CPM=379!

On what grounds do you decide that the source is harmless or a severe threat?

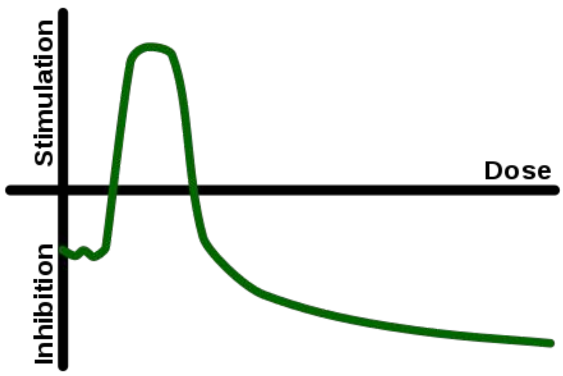
You probably would want first to equalize the readings from the counters. That is rather easy: you take a standardized radioactivity source, call one of the counters your reference, and determine correction factors for all others. So, all counters now give the same answer, but you still don’t know what the health effect is.

Fortunately there is a lot of research on the health topic, and there are standards, which are characterized also with respect to health issues. Now you can not only equalize the readings of all counters, but convert the count rates to an absolute health-relevant factor, and this is our desired calibration factor.

The health effect of a **count** is quantified as a **dose** in units of Sv, which stands for ‘**Sievert**’ [1]), named after the Swedish physicist Maximilian Sievert. The health effect of a count **rate** in CPM is most commonly converted to a dose **rate** in µSv/h (Micro-Sievert per hour).

Notes:

- A count rate like CPM is obviously also a dose rate, just reported in a different unit.
- In converting the units, a **linear** relationship between dose rate in CPM and dose rate in µSv/h is implied! This assumption is anything but trivial, because we know e.g. from chemicals the effect called **hormesis** [2]), which means that a substance can not only have a strongly non-linear dose effect, but also that – simply said – too little may be as bad as too much. (Graph from Wikipedia)



1 https://en.wikipedia.org/wiki/Sievert

2 https://en.wikipedia.org/wiki/Hormesis

Think e.g. of table salt: too much kills you, too little also!

For radioactivity the assumption of linearity is based on the LNT (Linear No-Threshold) [3]) theory, which became the basis for all radioactivity protection regulations worldwide! Hormesis in radioactivity is explicitly **excluded** in this model! This is hotly debated, but it became the norm. And it is implied when using a **single, constant** conversion factor independent of the rate.

- Airline pilots and flight-crews in general are people with significantly higher exposure than the rest of the population to cosmic radiation. I found two large scale studies on this topic, which basically showed "**no effect**"!

  Cancer risks from cosmic radiation exposure in flight: A review
  https://pubmed.ncbi.nlm.nih.gov/36483259/

  Cancer incidence among 10,211 airline pilots: a Nordic study
  https://pubmed.ncbi.nlm.nih.gov/12862322/

GeigerLog's Method for the Conversion between CPM and µSv/h

GeigerLog uses the tube's '**Sensitivity**' as the single, constant calibration factor for the conversion of dose rate in CPM and dose rate in µSv/h. The sensitivity is given in units of **CPM / (µSv/h)**. This value tells you how many counts-per-minute a tube will generate in a gamma-radiating environment of 1 µSv/h. The more sensitive a tube is, the higher the sensitivity values will be!

Please note that this calibration factor – like all other such calibration factors – is valid **ONLY** for gamma radiation!

> **NOTE:** This use of 'Sensitivity' constitutes a difference between GeigerLog Version 1.0 and later and the previous versions, which used 'Calibration Factor' for the conversion instead! But the difference is simple: Sensitivity is the inverse of the Calibration Factor.
>
> The reason for the change is that the quantity Sensitivity is the standard by which established tube manufacturers report this property of their tubes, and is easier to grasp.
>
> Let's do a quick test:
>
> you are given these calibration factors old-style of 0.0065, 0.48, 0.002637, 0.00926, 0.09 and 0.42. Quick, sort them by sensitivity from high to low, and tell by how much the first tube is more sensitive than the last!
>
> Isn't that a lot easier when you get sensitivities of 154, 2.08, 379, 108, 11.1, and 2.38? (The 2 sets of numbers have the exact same meaning, of course!)

3 https://en.wikipedia.org/wiki/Linear_no-threshold_model

Deprecated Radiation Units

Older data sheets may report the sensitivity in units of CPM/(mR/h) (mR = milli-Röntgen) [4]), but as we are dealing with gamma radiation, we may use 1 mR/h = 10µSv/h.

When the units are given as **CPS / (mR/h)**:

X CPS/(mR/h) = (X*60) CPM/(10 µSv/h) = (X*60/10) CPM/(µSv/h) = (**X * 6) CPM/(µSv/h)**

Example : From the manufacturer's Spec Sheet of Tube LND 712:
"Gamma Sensitivity Co 60: 18 CPS/mR/HR"
Sensitivity: 18 CPS/(mR/h) => 108 CPM/(µSv/h)

Conversion formulas between CPM, CPS and µSv/h

The conversion between dose rates in **CPM** and in **µSv/h** is done with these formulas:

Dose Rate [CPM] = Dose Rate [µSv/h] * Sensitivity [CPM / (µSv/h)]
Dose Rate [µSv/h] = Dose Rate [CPM] / Sensitivity [CPM / (µSv/h)]

And for **CPS** the conversion is done with these formulas:

Dose Rate [CPS] = Dose Rate [µSv/h] * Sensitivity [CPM / (µSv/h)] / 60
Dose Rate [µSv/h] = Dose Rate [CPS] / Sensitivity [CPM / (µSv/h)] * 60

For use in GeigerLog the sensitivity numbers will be rounded to leave no more than three significant digits.

4 One often finds units given as: "CPM/mR/hr". Apart from the non-standard use of 'hr' for 'h', this is even mathematically wrong. Correct would be: "CPM/mR * hr" or the setting of parentheses: "CPM/(mR/h)".

A List of Geiger Tubes with Known or Claimed Sensitivities

The following table covers a range of sensitivities from 2 to 379 CPM/(µSv/h). The column Calibration Source gives the source of radioactivity used to establish the sensitivity value.

Tube Name	**Calibration Source**	**Sensitivity (CPM/ (µSv/h)**	**Comment**
M4011	Unknown	154	Setting in GQ counters
J305	Unknown	154	Setting in GQ counters. This is another low-cost tube. It seems to be used by GQ as a – perhaps cheaper – replacement for the M4011 tube. Against all odds, the identical sensitivity setting is used!
SI3BG	Unknown	5.15	Setting in GQ counters (2nd tube in GMC-500+)
SI3BG	Th & K	2.08	own experiments using Th and K. May have beta component! http://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=5369 Russian Spec Sheet: https://www.pocketmagic.net/tube-si-3bg-c%D0%B8-3%D0%B1%D0%B3-small-geiger-muller/ Working Dose Range: 300 R/h (very high!) Sensitivity to Gamma Radiation: 188 – 235 Pulses/s/R/h Own Background: 0.2 Pulses/s
SI3BG	Synchrotron	2.38	Synchrotron data provided by GeigerLog user Ikerrg; sensitivity relative to M4011=154
J707	Co-60	15	From data published at AliExpress, see: **Appendix K – Tubes** in the GeigerLog manual.
STS-5 (CTC-5)	Co-60	132	“Gamma Sensitivity Co60 (cps/mR/hr) = 22” from: https://www.ebay.de/itm/322696408848 https://www.etsy.com/de/listing/630346629/sbm-20-sbm20-20-a-g-sts5-geiger-counter
STS-5 (CTC-5)	Ra-226	174	“Gamma Sensitivity Ra226 (cps/mR/hr) = 29” from: https://www.ebay.de/itm/322696408848 https://www.etsy.com/de/listing/630346629/sbm-20-sbm20-

			20-a-g-sts5-geiger-counter
SBM20	Co-60	132	Russian Spec Sheet: http://www.gstube.com/data/2398/ “Gamma Sensitivity Co^{60} (cps/mR/hr) = 22”
SBM20	Ra-226	174	Russian Spec Sheet: http://www.gstube.com/data/2398/ “Gamma Sensitivity Ra^{226} (cps/mR/hr) = 29”
LND712	Co-60	108	LND spec sheet: “GAMMA SENSITIVITY CO60 (CPS/mR/HR) = 18 “ https://www.lndinc.com/products/geiger-mueller-tubes/712/
LND7121	Cs-137	108	The LND 7121 tube is identical to the 712 in all mechanical and electrical aspects, except that it uses a stainless steel window (for more stability???)! However, this tube now is specified with a sensitivity of the exact same 108 as the 712, but now claimed for a Cs-137 source as opposed to the original Co-60 (what a strange coincidence ...).
LND7317	Co-60	348	LND spec sheet: “GAMMA SENSITIVITY CO60 (CPS/mR/HR) = 58” https://www.lndinc.com/products/geiger-mueller-tubes/7317/
LND7317	Unknown	379	Setting in GQ's GMC-600 counters, see user Kaban, Reply#3 http://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=4948
LND7317	Cs-137	334	Geiger counter: "Radiation Alert Ranger": “Sensitivity (cpm per mR/h) = 3340” https://seintl.com/products/radiation-alert-ranger
LND7311	Cs-137	330	The Ludlum 44-9 Geiger counter uses the LND 7311 tube, which has exact same dimensions as the LND 7317, both use a Mica window, but they differ in electrical specs and claimed sensitivity.
SGP-001	Cs-137	~~12~~ 8.33	Not a Geiger tube, but a solid state gamma radiation sensor using PIN photo-diodes; can be used as a GeigerLog AudioCounter http://allsmartlab.com/eng/smart-geiger-pro/ After my review I have downgraded the sensitivity [5]).
GDK-101	Cs-137	~~12~~	Not a Geiger tube, but a solid state gamma radiation sensor

5 https://sourceforge.net/projects/geigerlog/files/Articles/GeigerLog-Review%20PIN%20Diode%20Geiger%20Counters-v.1.0.pdf/download

		8.33	using PIN photo-diodes; can be used as a GeigerLog I2C device, or on a Raspi, with the Raspi acting as WiFiServer. http://allsmartlab.com/eng/294-2/ After my review I have downgraded the sensitivity [5]).

The Dilemma

A sensitivity will be determined with a specific setup, and is valid **ONLY** for the conditions used in the setup. While this seems trivial, it is largely ignored when it comes to Geiger counters.

What setup is being used for determining the sensitivity for the M4011 tube in a GMC Geiger counter? Well, we don't know!

To my knowledge, GQ has never reported how the sensitivity had been determined. Nor has the manufacturer – it isn't even known who the manufacturer is – of this tube ever released a datasheet. If it exists at all, it has not been made public. So, which sensitivity can be used?

Looking Elsewhere for Specs

There is a SBM20 tube, an old Russian Geiger tube, similar in shape to the M4011, albeit it is made from steel, not from glass. And for the SBM20 one does find specifications, like here: http://www.gstube.com/data/2398/

Gamma Sensitivity Ra^{226} (cps/mR/hr)	**29**
Gamma Sensitivity Co^{60} (cps/mR/hr)	**22**

The units are different from what we use, but we can make these arguments: Co60 is a beta and gamma emitter; Ra226 is an alpha, beta and gamma emitter. However, for calibration standard purposes both are typically packaged such that only gamma can escape the package, and if so we can assume pure gamma emission. With that we can equate mR with mRem, and with 1 mRem = 10µSv, we get:

Sensitivity	**new-style**	**old-style (calibration factor)**
Ra226: 29 * 60 / 10 =	**174 CPM / (µSv / h)**	0.0058 µSv / h / CPM
Co60: 22 * 60 / 10 =	**132 CPM / (µSv / h)**	0.0076 µSv / h / CPM
Average of the two:	**153 CPM / (µSv / h)**	0.0067 µSv / h / CPM
GQ's M4011 sensitivity:	**154 CPM / (µSv / h)**	0.0065 µSv / h / CPM

GQ's sensitivity is strikingly close to the average of the two, and with nothing better at hand we'd say that this is the base for GQ's sensitivity. And perhaps it is the sole base, we don't know.

Thus, when the two tubes are directly compared, they should give the same results. Both tubes can be run with the same voltage, and the SBM20 can even be used instead of the M4011 in the GMC counters. I used the M4011 and the SBM20 in an GMC-300E+ counter and published the results [6]).

As shown in Figure 1 the SBM20 background is 3% higher than the M4011 background. However, this seems to be well within statistical uncertainty, and the conclusion is that the background is not different.

When measured with the radioactive sources Potassium and Thorium, the SBM20 shows elevated counts of 41% … 45% for both sources, as shown in Figure 2.

6 http://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=4571

However, as we started with the assumption that the SBM20 calibration has been made with pure gamma emitters, any comparison of the tubes can only be made with pure gamma emitters. But both K and Th are not only gamma, but also strong beta emitters.

Therefore from the experiment shown in Figure 2 we can **NOT** draw the conclusion that the SBM20 is more sensitive **to gamma** than the M4011; the question remains open.

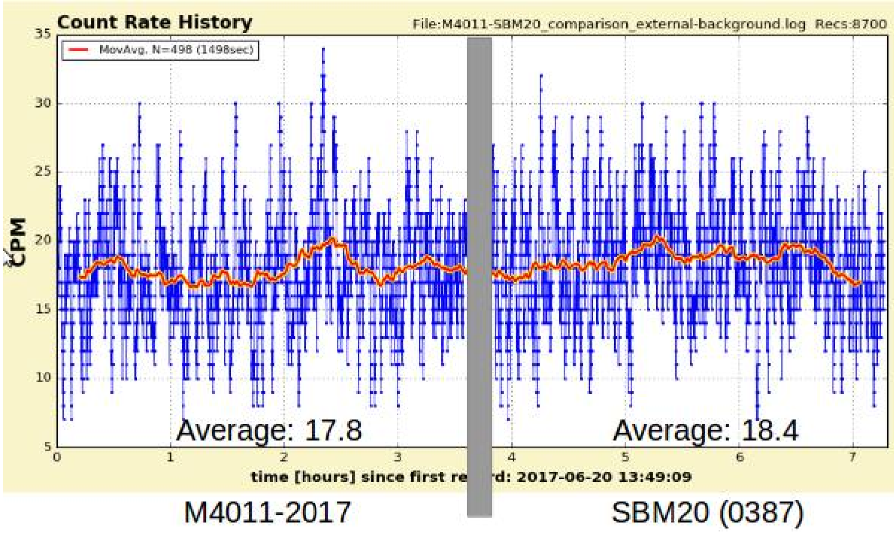


Figure 1: Comparison of a M4011 and SBM20 tube – background The tubes are inserted into a GMC-300E+ counter and measure background

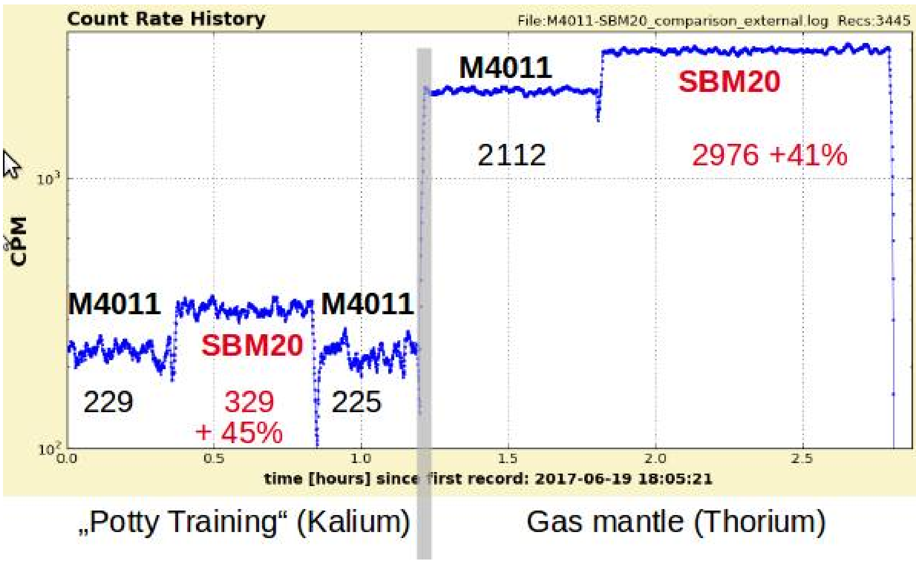


Figure 2: Comparison of a M4011 and SBM20 tube – K40 & Th232 The tubes are inserted in a GMC-300E+ counter measuring a Potassium and Thorium source, resp.

In extension, we also have to assume that the calibration for a M4011 is only for pure gamma emitters, and NOT for beta emitters. We simply do not know what the sensitivity is for beta!

And likewise, using a sensitivity with unknown specification, and likely relevant for gamma only, on tubes with sensitivity for alpha when measuring alpha radiation, is simply additional nonsense! When you measure any alpha radiation, report the CPM and describe tube used and setup. But do not report dose rate in µSv/h, because that tells the reader that you did not understand what you were doing!

The Tube-Sensitivity Dependency on Type of Quantum and its Energy

Attempts to calibrate a Geiger tube requires consideration of multiple problems:

- The type of quantum: gamma rays, X-rays, beta-particles, alpha-particles (ignored here)
- The energy and energy distribution of these quanta
- The sensitivity of a Geiger tube for a given quantum and energy

Gamma Responses

While no two Geiger tubes have an identical response curve to gammas, they all have a typical common feature as shown by the red curve in Figure 3 [7]):

> The company Ludlum Measurements Inc. [8]) should be commended for publishing their measurements on their Geiger tubes on their web pages. Other companies don't even make any measurements, let alone publishing them :-(.

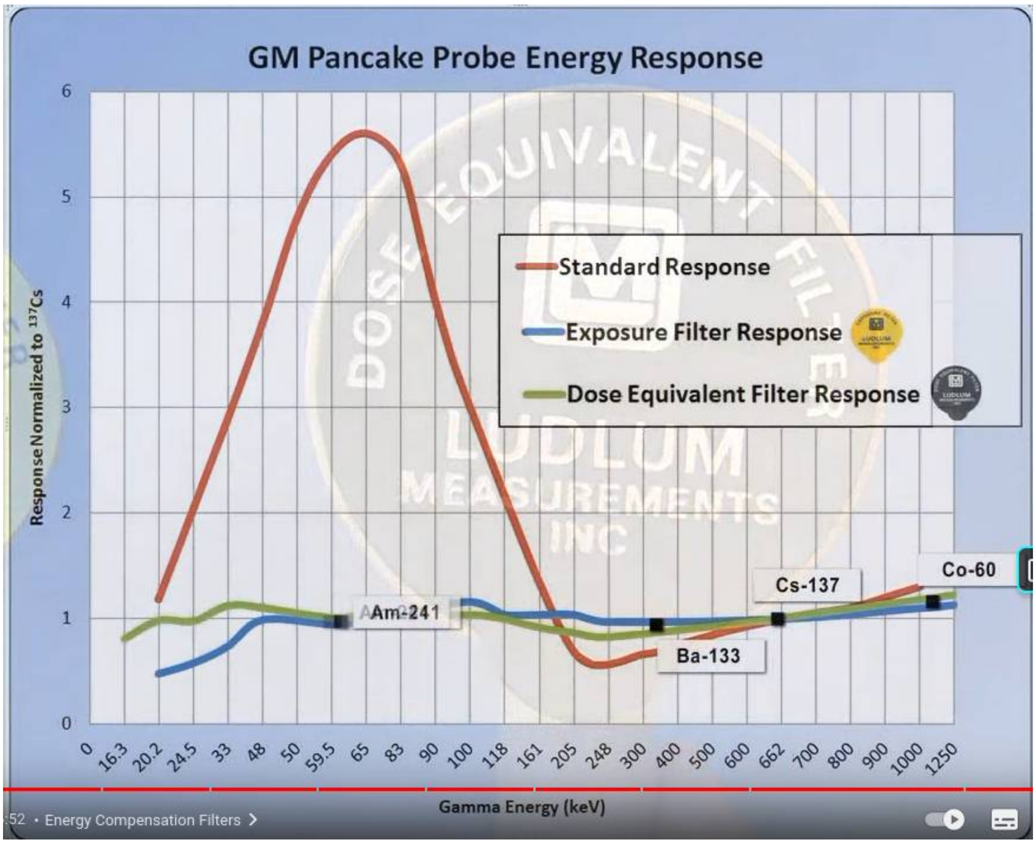


Figure 3: Geiger Tube Response to GAMMA Radiation

There is a low sensitivity at high gamma energies (from 0.2 MeV upwards), and much higher sensitivity at lower energies, typically with X-rays associated with those coming from medical applications.

7 see: https://ludlums.com/products/all-products/product/model-44-9#graphs

8 https://ludlums.com/

While physically gammas and X-rays are the very same thing – and the same thing as radio waves, radar, micro-waves, and light, just their energies are different – this drastically different response to high and low energies gives some credence to distinguish gammas and X-rays in the context of Geiger tubes.

Gamma-Energy Compensated Tubes

One further thing should be noted: the blue and green curves in Figure 3 represent the sensitivity of the very same Geiger probe after applying the yellow and black filter disks. Clearly, the response is now constant over an almost 2 orders-of-magnitude gamma energy range! However, this has been achieved by **REDUCING** the sensitivity to the lowest possible common value over the whole range!

While this has value for certain applications, hobbyists are usually interested in seeing a higher, and not a lower count rate! When shopping for energy-compensated tubes keep in mind that you will see reduced count rates! Anyone interested should look at the video presented by Ludlum [9]).

Other tubes

Because data on Gamma energy dependence of Geiger counters are so scarce I am adding abother example [10]). The response of this very different Geiger tube is actually quite similar to the Ludlum Geiger counter data.

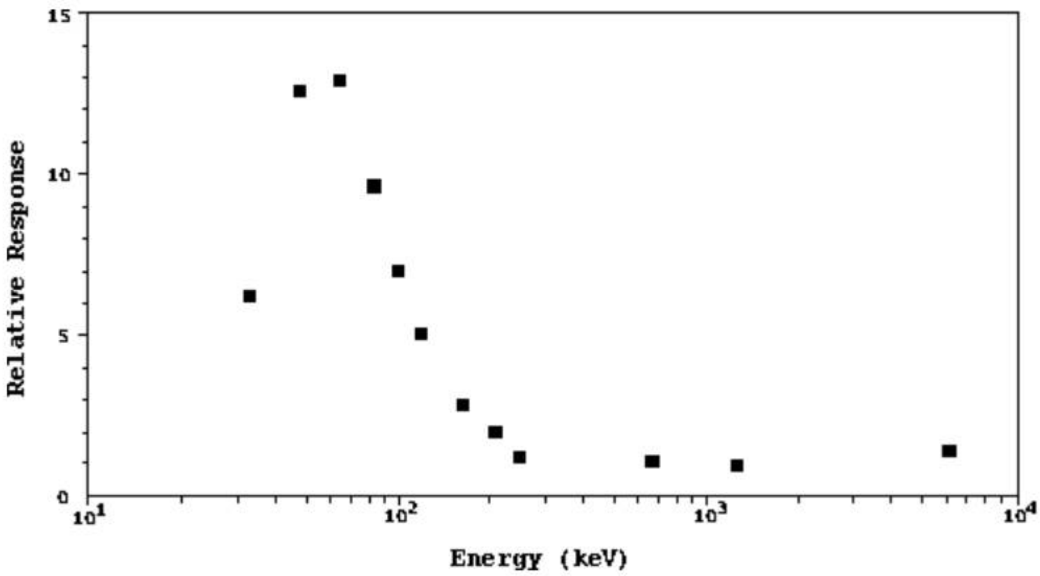


Figure 4: Relative Response of a Geiger Tube with Respect to Gamma Energy

Photon Energy Response of N116-1 miniature "thin wall" GM tube, normalized to unity at 662 keV with beam perpendicular to detector wall.

Tube M4011: no data of any kind are available for this tube!

9 https://www.youtube.com/watch?app=desktop&v=z1rxUxwQKu8

10 The N-16 Gamma Radiation Response of Geiger-Mueller Tubes, https://hps.org/hpspublications/articles/allard.html

Beta Responses

The published data are again coming from company Ludlum. The sensitivity is increasing linearly from 0.5% at 17 keV up to 33% at 565 keV. For reference: the beta_max energy from a Potassium-40 decay is 1.33 MeV. I don't know whether sensitivity should be higher or lower at this energy.

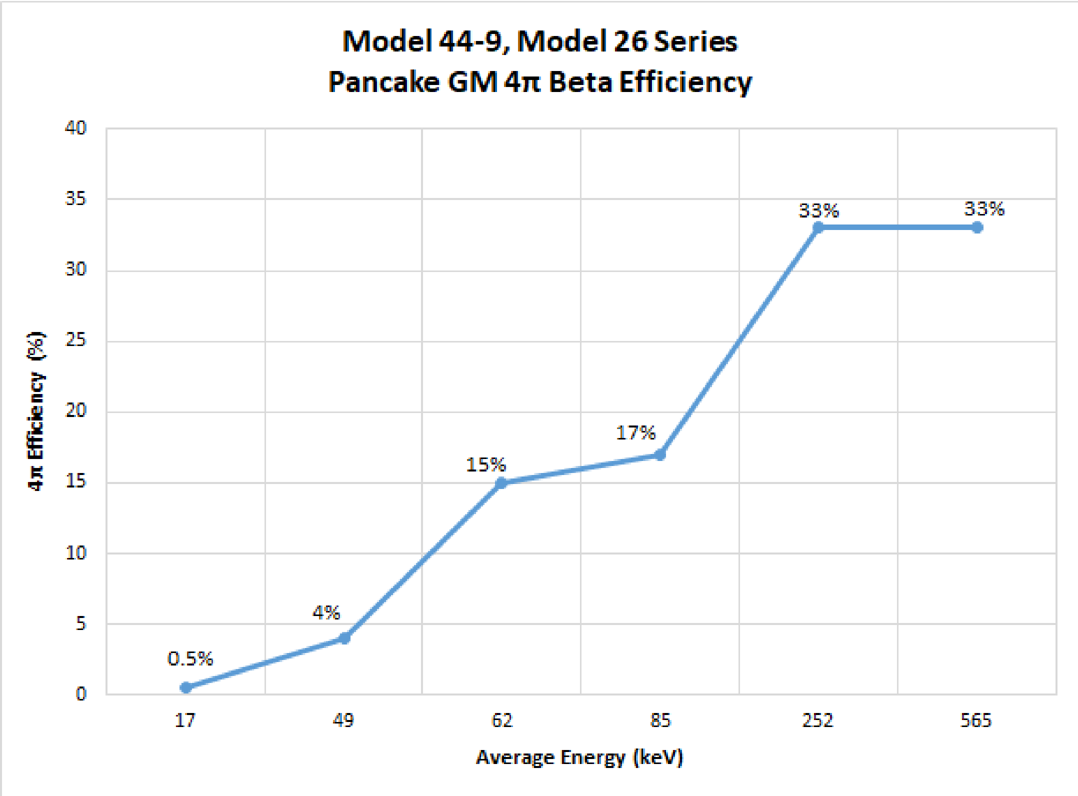


Figure 5: Geiger Tube Response to BETA Radiation

The energy and energy distribution of gamma quanta

The Geiger tube sensitivity is typically reported with respect to a calibration done with one of these radioactive, chemical compounds:

- Co60 - Cobalt
- Ra226 - Radium
- Cs137 - Cesium

Looking at their gamma spectra in Figure 6 and Figure 7 we see significant differences. Co60 is strong above 1 MeV, while Ra226 is mostly below 0.5 MeV, and Cs137 is similar to Ra226, but with clearly stronger radiation at the upper end.

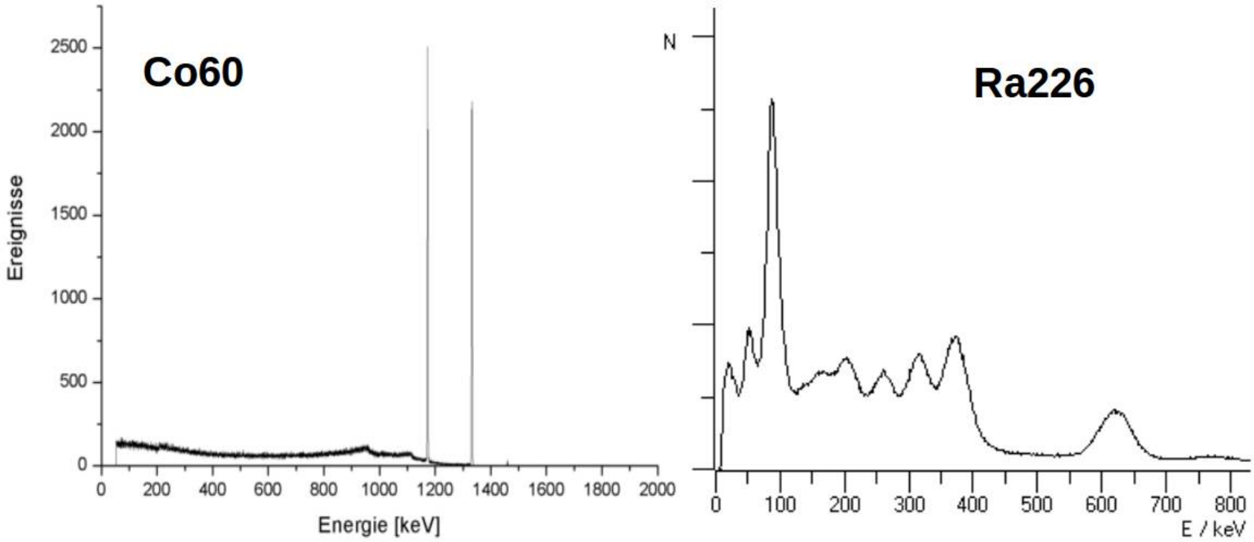
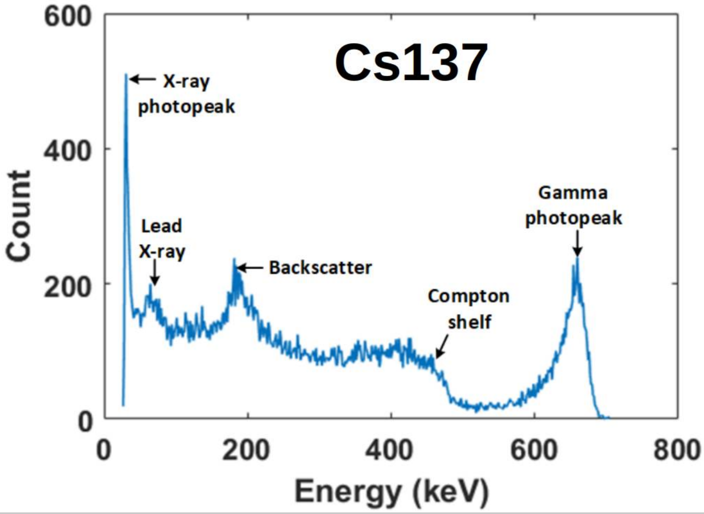


Figure 6: Gamma Spectra of Ra226 and Co60

Figure 7: Gamma Spectrum of Cs137



https://www.researchgate.net/figure/Cs-137-spectrum-from-the-Pulse-Height-Analysis-PHA-algorithm-after-50-000-counts_fig3_325268552

What Gamma Count Rates do we get?

To understand what count rates we get for each of those calibrating compounds, we would have to use the gamma spectra and apply the mathematical operation of folding these to the response curve of the Geiger tube. Given how few data we have on a response curve – if we have one at all – this does not promise to be a very fruitful attempt.

And furthermore, this will be valid **ONLY** for that reference compound. Our source will generally be different, and generally we won't even know its gamma spectrum!

This does not imply that you can't measure anything else but the original calibration source. But you have to specify, which calibration factor you used, and why you chose it. In premium Geiger counters you have the option of applying a calibration factor based on either Co60, Ra226, or Cs137.

But at the end you will be choosing a calibration factor by little more than gut feeling :-/.

One thing should be taken to heart: such procedure to find a sensitivity is **valid ONLY for a pure GAMMA source**! As a consequence, when measuring a source which also has a significant **Beta** component, this Sensitivity is **INVALID**! This implies that reporting any **Sievert-based values is utterly meaningless!**

The energy and energy distribution of beta quanta

The situation isn't better for beta radioactivity, perhaps even more complicated.

At a beta decay the nucleus always radiates 2 particles: one is a beta particle, the other a neutrino. The energy being released by the decay is shared between the 2 particles in ratios from 100:0 up to 0:100. As we cannot see a neutrino – we have no detectors for, not even in a lab – but only the beta, we see the beta having from zero energy up to the Beta_max energy, in other words a continuum.

Figure 8 shows such a beta spectrum continuum [11]). The contour is largely inverse to the Geiger tube beta-sensitivity shown before.

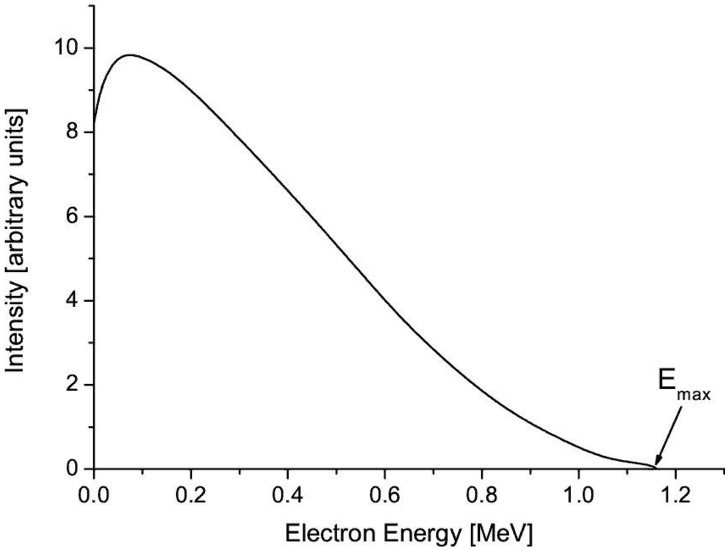


Figure 8: Beta Energy Spectrum from 210Bi

What Beta Count Rates do we get?

Same folding procedure would be needed, but we have even less knowledge on beta-spectrum. In addition the soft-betas are easily absorbed even by air. So, I'd say it is hopeless to predict any count rates. But it will almost always be much more than what you get from gammas!

Remember that the gamma sensitivity is in the sub-1% range, while the beta sensitivity is in the 1% range, i.e. an order of magnitude higher! All Geiger tubes are much, much more responsive to beta!

11 https://de.wikipedia.org/wiki/Betastrahlung

Tuning the counter

Since the case of the counter is basically transparent to at least higher energy gammas, it does not matter to the calibration whether we make the backplate of the counter more permeable by drilling holes, or taking the backplate off completely – especially considering the hand waving we have applied to come up with the gamma calibration.

And when we take it off and get significantly higher count rates with beta emitters, it also does not matter because the calibration, when applied to beta, is wrong in the first place!

The GMC counter calibrations

The GQ GMC counters have 3 calibration points, which would allow to accommodate some non-linearity. However, since the LNT theory has to be applied, there is no non-linearity to be considered! In theory the three points could also be used to correct some dead-time effects at very high count rates. However, that would involve some complicated calculations, as you would not only have to take the dead-time correction into account, but also the shift in the calibration due to that correction.

The proper way of doing that is already implemented in GeigerLog, see the chapter **Formula Interpreter** in the GeigerLog manual. A broader discussion can also be found in several GQ forum topics, like 5357 (in particular look into Reply #9 and Reply #33), 5369, 4578, 4571 [12]).

But, this discusses a mood point anyway, because all 3 points in all GMC counters establish the same slope, hence effectively only a single calibration point is used. This is what GeigerLog reads out from the GMC counters:

```
Device Calibration:
 Calibration Point 1:   60 CPM = 0.39 µSv/h  (0.0065 µSv/h / CPM)
 Calibration Point 2:  240 CPM = 1.56 µSv/h  (0.0065 µSv/h / CPM)
 Calibration Point 3: 1000 CPM = 6.50 µSv/h  (0.0065 µSv/h / CPM)
```

But be aware of counters where this wrong calibration is read out: [13]).

```
Device Calibration:
   Calibration Point 1:      60 CPM =   0.39 µSv/h  (0.0065 µSv/h / CPM)
   Calibration Point 2:   10000 CPM =  65.00 µSv/h  (0.0065 µSv/h / CPM)
   Calibration Point 3:      25 CPM =   9.75 µSv/h  (0.3900 µSv/h / CPM)
```

GeigerLog now uses a default calibration of 154 CPM / (µSv/h) (old value: 0.0065 µSv/h / CPM) for the M4011 tube, and 379 CPM / (µSv/h) (old value: 0.002637 µSv/h / CPM) for the LND 7317 tube in the GMC-600+.

12 https://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=5357
https://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=5369
https://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=4578
https://www.gqelectronicsllc.com/forum/topic.asp?TOPIC_ID=4571

13 GMC-500 counters were delivered with this calibration setting

In recent comments by GQ this was attributed to a GMC-500+ device, and it was explained that this handles the second tube in this device. However, this calibration was found in a GMC-500, which has **no** second tube.

But all calibration factors can be changed, temporarily in GeigerLog during a run, and more permanently in GeigerLog's configuration file.

The latest GMC counter calibrations

The latest GMC counter, presently only the GMC-800, have no only 3, but now 6 calibration points!

Hilariously, they all code only a single factor, **exactly the same as before,** like sensitivity 154 CPM/(µSv/h) for a M4011 tube. ;-))

Sensitivity for the Low-Sensitivity Tube SI3BG

Forum user Ikerrg has thankfully contributed these data. They were generated with the double-tube counter GMC-500+ exposed to data from a Synchrotron [14]). This is a device which can also generate strong gamma radiation.

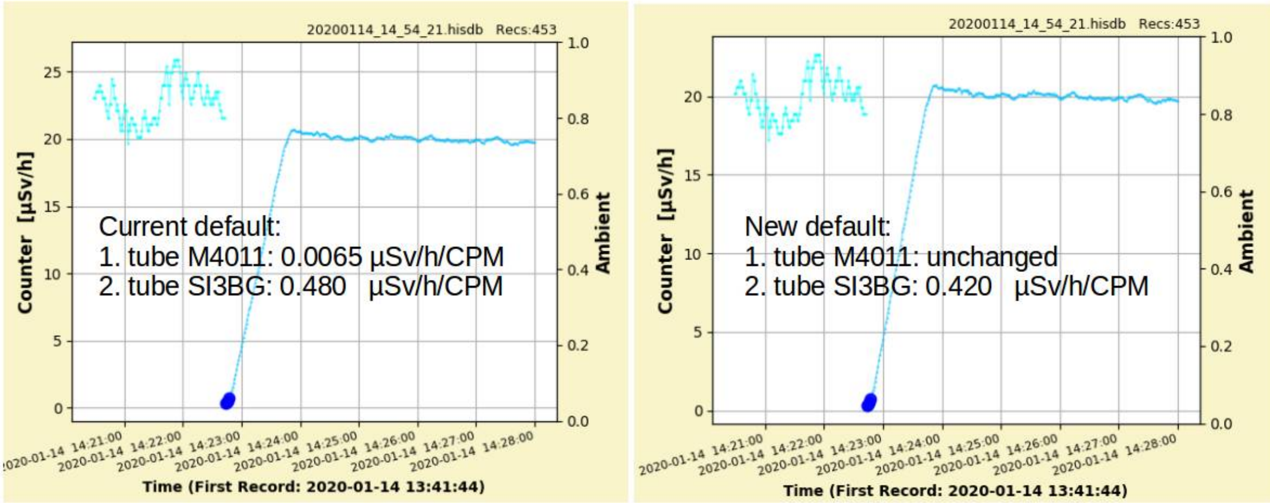


Figure 9: Synchrotron radiation captured with a GMC-500+ counter

History read out and analyzed with GeigerLog

The counter was held into the radiation field, and the counts recorded into its history buffer. The history was read out with GeigerLog and analyzed, as shown in Figure 9.

Note the counter axis is not in CPM but in µSv/h! Data colored in Cyan are recorded with the 1^{st} tube M4011, using its calibration factor 154 CPM / (µSv/h). Then the tubes were switched and recording continued with the 2^{nd} tube colored sky-blue. Relative to the 1^{st} tube the dose rate of the 2^{nd} comes out too low (left picture). This is corrected when the sensitivity of the 2^{nd} is changed from (old-style) 0.48 to 0.42 µSv/h/CPM. In new-style this is a change from 2.08 to 2.38 CPM / (µSv/h) (right picture).

But, as we don't know the energy profile of the Synchrotron radiation, nor do we know for what the original calibration was for – nor if there ever was one – we don't know if that new value is any better or not than the old one.

And anyway, it is only relative to the M4011 tube.

But at least it gives us a ballpark feeling that the 2^{nd} tube is 154 / 2.08 … 154 / 2.38, or 74 … 65 times less sensitive.

14 https://en.wikipedia.org/wiki/Synchrotron