Dead Time Effects on Gamma Detectors[1]

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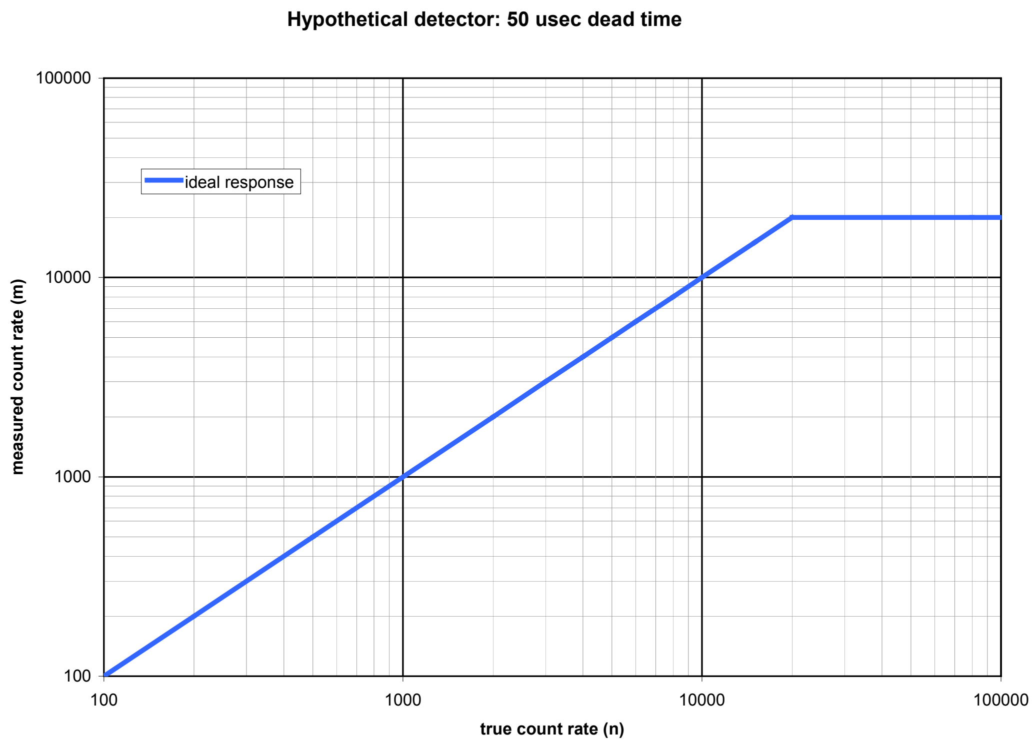
For practically all detectors, there is a point at which events are too close together to be counted correctly. When a gamma interacts with a detector, there will be a period of time (in microseconds) after the interaction during which the detector is incapable of detecting another gamma. This is known as the *dead time*, and is usually represented by the Greek letter τ (tau). Since radioactive events occur randomly, there is always the possibility that a gamma will be lost because it came too quickly after the previous event to be counted. As gamma activity increases, dead time losses can become significant, and detector performance becomes increasing non-linear. This paper will provide a brief summary of dead time behavior in gamma detectors. Procedures to determine dead time parameters will be described., and some examples of actual detector behavior at high dead time will be provided.

First, lets take a look at "ideal" detector behavior. For these examples, we'll ignore detector efficiency issues. If we count for some time period, we will measure a count rate *m*, in cps. In our ideal detector, that is equal to the true count rate, *n*. If the detector takes a short time period τ to recover after each gamma, then the maximum count rate we can measure is $1/\tau$. Let's assume that our ideal detector has a dead time of 50 microseconds (0.00005 sec). We would expect a maximum count rate of 20,000 cps (1/0.00005). If we plotted *m* (measured count rate) as a function of *n* (true count rate), we would expect to see a plot like this:



Note that both scales on this plot are logarithmic and that it only shows response at greater than 100 cps. Since we're discussing dead time effects, we won't worry about what's going on a low count rates.

Knoll[2] discusses two models of dead time behavior that are in common usage. In a *paralyzable* system, a gamma arriving during the dead time period from a previous gamma is not counted, but it has the effect of extending the dead time. In a *non-paralyzable* system, a second gamma arriving during the dead time has no effect – it is simply not counted.

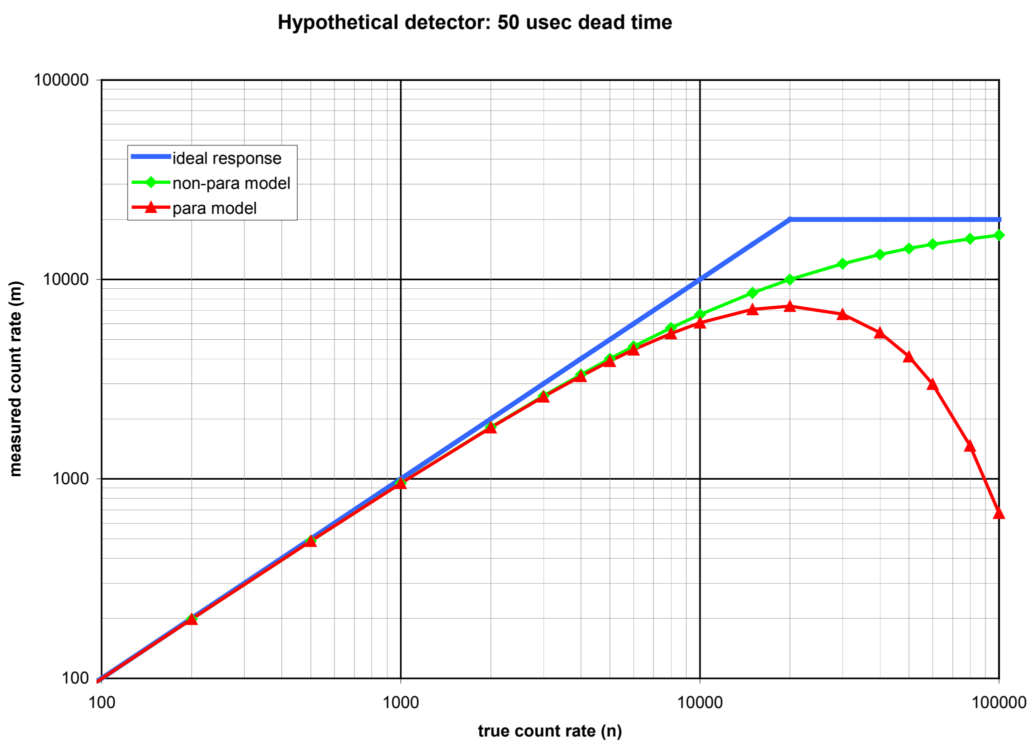
The two models predict similar behavior at low activity and begin to diverge only at high activity levels. The observed count rate is related to the "true" count rate (activity) by:

$$m = ne^{-n\tau} \qquad \text{(paralyzable model)} \qquad (1)$$

$$m = \frac{n}{1+n\tau} \qquad \text{(non-paralyzable model)} \qquad (2)$$

The derivation of both of these equations is given in Knoll, so I'll spare you the math here.

Here's how these systems would perform at high count rates, assuming a dead time of 50 microseconds.



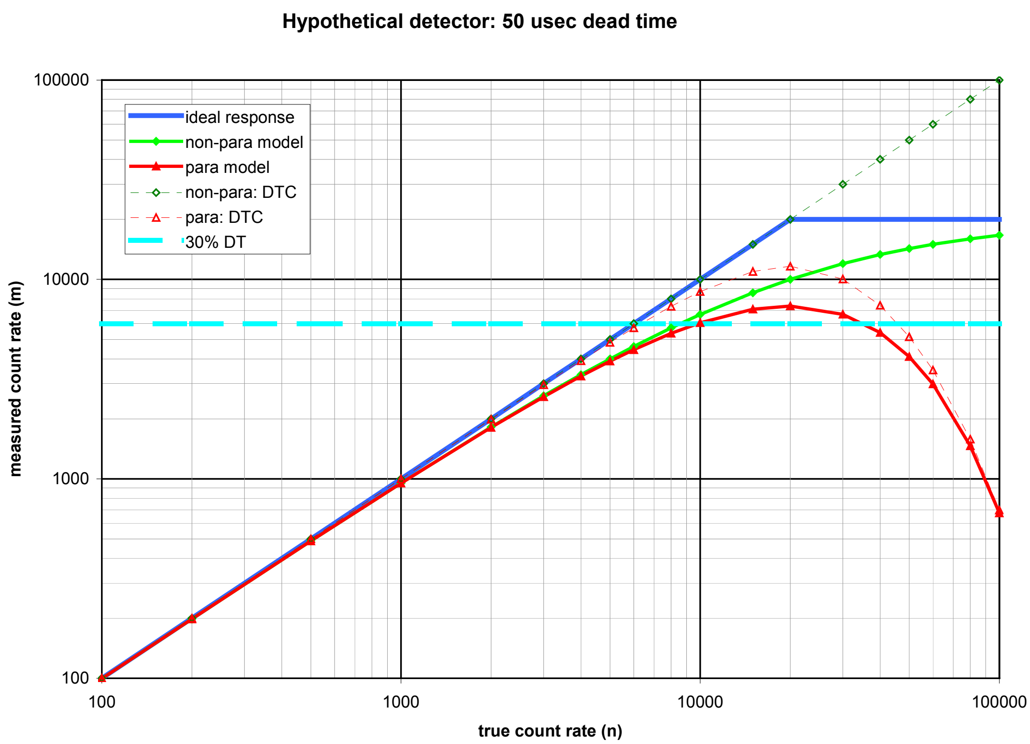
[2] Knoll, G.F., (2000); Radiation Detection and Measurement, 3rd Edition; John Wiley & Sons, New York, 2000 (pp 119-125)

Notice that for both models the measured count rate falls below the true count rate, with the difference increasing with higher count rate. For the paralyzable detector, the measured count rate even begins to decrease with increasing gamma activity.

The paralyzable and non-paralyzable models represent theoretical models – actual detector behavior is likely to fall somewhere in between. We can use either equation (1) or (2) to determine the true count rate from the measured count rate, if we know the detector dead time. For a paralyzable model, this is more difficult, because equation (1) can't be solved directly for *n*: we have to solve it iteratively, which is just a fancy way of saying that we have to make a series of guesses. Since *m* decreases at high count rate, it is also possible that one value of *m* may represent two values of *n*. For example, *m* = 5000 cps might correspond to a true count rate of about 7,000 cps. Or *m* = 5000 cps might also represent a true count rate of over 40,000 cps! Equation (2) for the non-paralyzable model is much easier to use, and most of the time, the non-paralyzable model gives a good correction. By re-arranging terms in equation (2) to solve for *n* we have:

$$n = \frac{m}{1 - m\tau} \qquad \text{(non-paralyzable model)} \qquad (3)$$

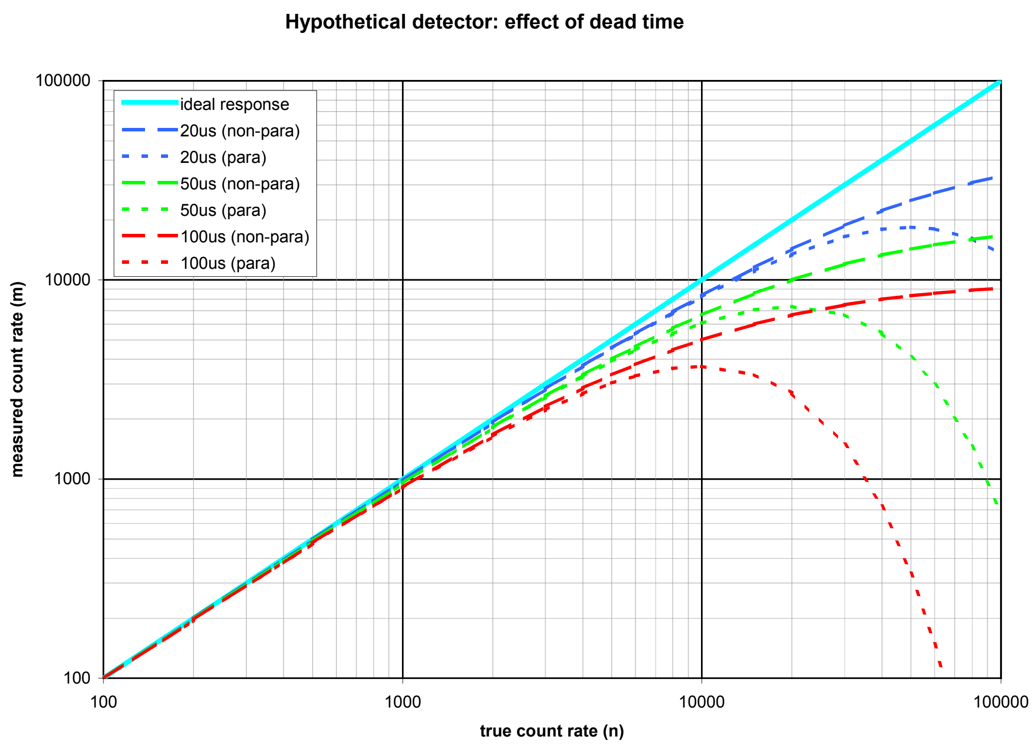
Here's how our the response curve for our ideal detector might look after we calculate a dead time correction, using the non-paralyzable model:



In this graph, the open symbols and dashed lines represent values corrected for dead time, assuming a non-paralyzable model. Notice that the non-paralyzable detector now follows the straight line, even for activity above the theoretical maximum count rate. The paralyzable detector is more linear, but it still falls off at high activity. If you look at the chart, you'll see that the corrected count rate from either model is pretty close to the ideal response, up to about 6000 cps. For $m\tau$ less than 0.3, the difference between the corrected count rate and the ideal response is less than 10%, even for the paralyzable model. Assuming a dead time of 0.00005 sec, then $m\tau$ less than 0.3implies that m must be less than 0.3/0.00005 or 6,000 cps.

Obviously, the dead time is an important parameter for any detector system. For a given detector, the vendor can usually supply a dead time value, but that is only part of the story. The counting circuits and power supply may also play a role. What really counts is the *system* dead time, which may be significantly different from the detector alone.

At low count rates, dead time doesn't have much effect, but it can cause real problems when high activity is encountered. Most of the time, calibrations are performed with relatively low activity. Even if an incorrect dead time is used, the effect of the "dead time correction" is probably negligible. As count rates increase, the effect becomes more prominent. Here's how changes in system dead time affect count rates:



In this plot, the short dashed lines represent a paralyzable model and the long dashed lines represent a non-paralyzable model. Below 1000 cps, it's hard to see much effect from dead time. However, a paralyzable detector with high dead time will probably not count much higher than a few thousand cps.

One way to determine the dead time of a detector system is the two-source method, which is described by Knoll. Basically, the procedure involves two sources of the same radionuclide. Together, the sources should generate enough gamma activity so that $m\tau$ is at least 0.2.

The procedure is as follows:

1. Measure background count rate (m_b)
2. Introduce the first source and measure count rate (m_1)
3. Introduce the second source and measure count rate (m_{12})
4. Remove the first source and measure count rate (m_2)

System dead time is then determined from:

$$\tau = \frac{X(1-\sqrt{1-Z})}{Y} \qquad (4)$$

where:

$$X = m_1 m_2 - m_b m_{12}$$

$$Y = m_1 m_2 \left(m_{12} + m_b\right) - m_b m_{12} \left(m_1 + m_2\right)$$

$$Z = \frac{Y\left(m_1 + m_2 - m_{12} - m_b\right)}{X^2}$$

Another way to estimate dead time is to measure count rate at various activity levels and then fit a curve to the data. For the non-paralyzable model we have:

$$n = \frac{m}{1 - m\tau} \qquad \text{(non-paralyzable model)} \qquad (3)$$

The radiation level should be a linear function of the true count rate:

$$R = F \times n$$

Where F is a linear response factor and R is the radiation level, in whatever units are convenient. Substituting into equation (3):

$$R = F\frac{m}{1 - m\tau}$$

$$R(1 - m\tau) = Fm$$

$$R = Rm\tau + Fm$$

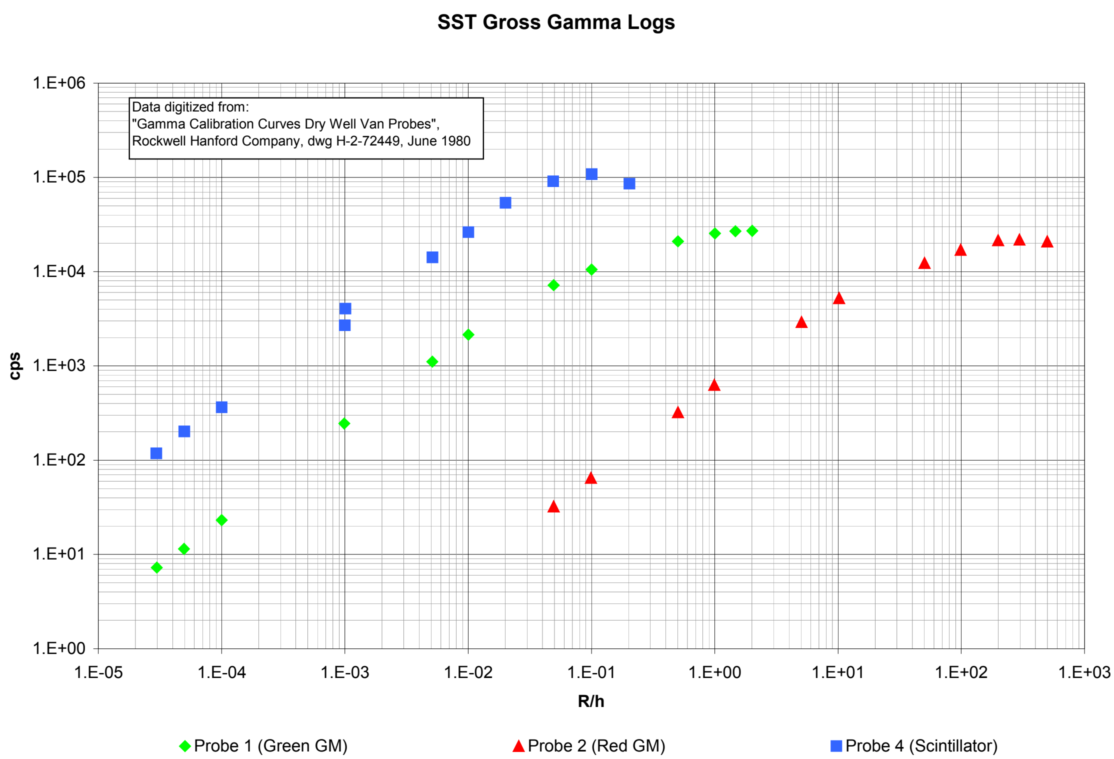
$$\frac{1}{m} = \tau + F\frac{1}{R} \qquad (5)$$

The reason for all these algebraic gyrations is that equation (5) is just a linear equation, if you substitute $y = 1/m$ and $x = 1/R$. This means for any detector, it is possible to measure m as a function of R and then use a linear regression to determine the values of F and τ. However, there are a few caveats to the curve fitting process:

- Since the fit is based on a linear regression to reciprocals, lower values of R and m result in *higher* values in the regression data. If too many points in the lower part of the linear range are included, they may "drive" the regression, with the result that the error between the fit and the data will be concentrated at the higher values, where the fit is actually more critical.

- The fit is based on the assumption that the detector more or less follows the non-paralyzable model. Data points which clearly exhibit paralyzable behavior should also be eliminated from the regression data set and the range of the detector response function should be limited to avoid this region.

Lets look at some real data. The plot below shows response curves for three detectors used to measure gamma activity in drywells around the high-level waste tanks at the Hanford Site.

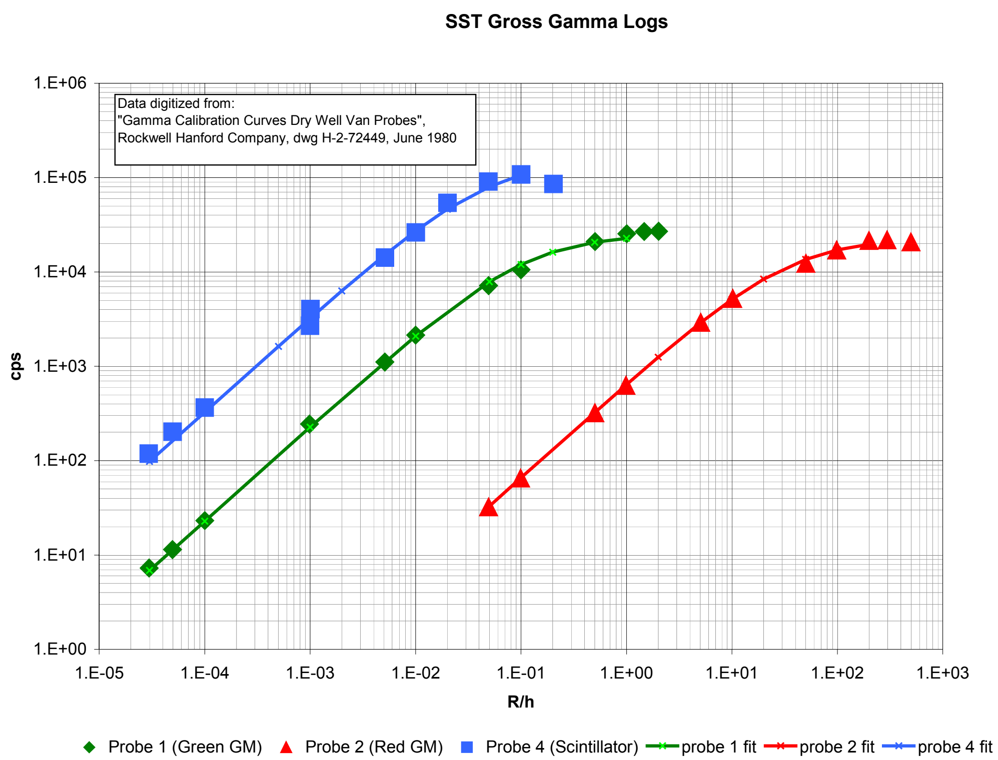


These detectors were used from 1974 to 1994. They were lowered into the drywell on a cable and pulled out at a constant rate, so that they collected counts over intervals of one foot. Probe 1 was a Geiger-Mueller (GM) detector for moderate radioactivity. Probe 2 was a GM detector designed for high radioactivity, and Probe 4 was a NaI scintillator designed for low to moderate radioactivity. A copy of the original plot was digitized and used to calculate response curves for these detectors. Here is the data (from the digitized plot.)

Probe 1		Probe 2		Probe 4	
R/h	cps	R/h	cps	R/h	cps
2.97E-05	7.27E+00	4.92E-02	3.23E+01	2.95E-05	1.18E+02
4.95E-05	1.14E+01	9.91E-02	6.50E+01	4.98E-05	2.02E+02
1.00E-04	2.31E+01	5.02E-01	3.21E+02	1.00E-04	3.64E+02
9.89E-04	2.44E+02	9.91E-01	6.28E+02	9.98E-04	2.70E+03
5.12E-03	1.11E+03	5.06E+00	2.92E+03	1.01E-03	4.04E+03
1.00E-02	2.15E+03	1.02E+01	5.22E+03	5.13E-03	1.42E+04
4.93E-02	7.18E+03	5.02E+01	1.23E+04	1.01E-02	2.62E+04
1.00E-01	1.05E+04	9.86E+01	1.70E+04	2.01E-02	5.39E+04
5.04E-01	2.10E+04	1.99E+02	2.15E+04	4.90E-02	9.07E+04
1.00E+00	2.54E+04	2.96E+02	2.18E+04	1.00E-01	1.08E+05
1.47E+00	2.69E+04	4.98E+02	2.08E+04	2.04E-01	8.56E+04
2.02E+00	2.71E+04				

Look at the plots. The data for each detector plots along a line determined by detector sensitivity. Also notice that the radiation levels go from 0.00001 R/h, which is about background, up to 1000 R/h. Probe 1 (green diamonds) appears to keep increasing to about 27,000 cps. Both probe 2 (red triangles) and probe 4 (blue squares) show clear evidence of paralysis. From the shape of the plots and the maximum count times it appears that probe 4 has a much smaller dead time than either probe 1 or probe 2. This is expected: in general NaI detectors have dead times of a few microseconds and GM detectors are around 50 microseconds.

Here are the response curves:



The response parameters for each detector are:

Curve Fit Parameters for SST Gross Gamma Logs

Probe	Range, R/h	Max Count Rate, cps	Points	R^2	τ, seconds	$F_{R/h}$, R/h per cps
1	0.005 to 2.0	27000	8	0.999	(3.96±0.36) E-5	(4.38±0.05) E-6
2	5 to 300	21800	6	0.999	(4.33±0.24) E-5	(1.52±0.03) E-3
4	0.001 to 0.1	108000	7	0.941	(6.4±1.8) E-6	(3.05±0.34) E-7

For most environmental-level measurements, dead time can be safely ignored. As the count rate increases, one should always be aware that detector behavior will become increasingly non-linear. If a proper dead time correction is not applied, the detector will underestimate the radiation dose. It is even possible at very high dose rates that a detector may show decreasing count rate when gamma activity is increasing.