

# Radiation Detection and Measurement

## ACADs (08-006) Covered

3.2.2.1	3.2.2.3	3.2.3.1	3.2.3.2	3.2.3.8.1	3.2.3.16
3.23.23.8	3.2.3.28.9	3.2.5.5	3.2.5.6	3.2.5.8	4.4.1
4.4.3	4.5.1	4.5.2	4.5.4	4.5.7.8	5.4.1.5a
5.4.1.5b	5.4.1.5c				

## Keywords

Operation, calibration, limitations, Liquid Scintillation Counter, Geiger-Mueller, portable scintillation, decay, thin-window, compensated, efficiency, energy distance, quench.

## Description

This document provides content for lecture or student handout on understanding the principles of operation and calibration, and limitations of Liquid Scintillation and Geiger-Mueller counters, and portable scintillation detection systems, and how to apply these principles to radiation surveys and interpretations of results.

## Supporting Material

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## Radiation Detection and Measurement

**Objective** To understand the components, principles of operation and calibration, and limitations of Liquid Scintillation Counters (LSC) and Geiger-Müller (GM) and portable scintillation detection systems and to apply these principles to performing radiation surveys and interpreting the results.

### Radioactive ( $\beta$ ) Decay

Radioactivity results from an unstable combination of protons and neutrons in the nucleus. The nucleus's consequent attempt to arrive at a more stable combination of particles often results in the emission of an alpha or beta particle, or gamma ray. Because 85% of the researchers at the University use beta emitters, we will concentrate on beta radiation.

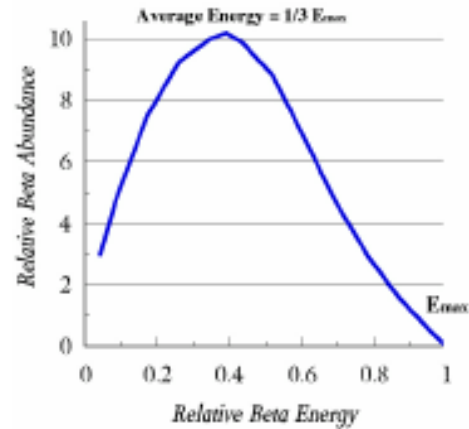


Figure 1. Beta Decay Spectrum

Beta particles are essentially energetic electrons. The energy released by the emission is dependent on the radioisotope and is shared by the beta particle and the neutrino ( $\bar{\nu}$ ). Because of this energy sharing, and the fact that neutrinos are not easily detected, the graph of beta particle energy versus beta abundance (Figure 1) is very broad, starting at 0 keV (i.e., all energy is given to the neutrino) and ending at some  $E_{max}$  keV (i.e., all the energy is given to the beta particle), which depends on the radioisotope. The greatest number of beta particles are emitted with energies approximately a of the maximum energy.

Because of their electric charge, the emitted beta particles transfer their energy to their surroundings, eventually losing all of their energy and coming to rest. These beta particles usually do not travel very far and most are unable to penetrate a liquid scintillation vial.

### Portable Survey Meters

#### GM Systems

A Geiger-Müller (GM or Geiger) detector is made by putting a gas whose molecules have a very low affinity for electrons (i.e. gases which are easily ionized such as helium, neon, argon, etc.) into a conducting shell, mounting a fine wire that is insulated from the shell at the center of the tube, and connecting a positive high voltage of approximately 900 volts between the wire and the shell. Ionizing radiation, such as  $\alpha$  and  $\beta$  particles, enter the detector and strike gas molecules while x- /  $\gamma$ -ray photons interact with the wall (conducting shell) material

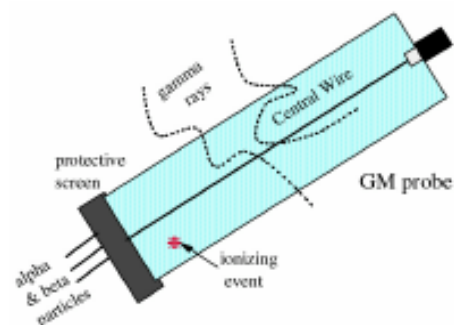


Figure 2. GM Probe

ejecting ionized electrons into the gas which then cause ionizations. From the ion pairs produced, the free electron is accelerated toward the central wire attracted by the positive, high voltage. The electrons acquire such high speeds that they can interact with other gas molecules (i.e.,  $E = 1/2mv^2$ ) and produce more (secondary) ion pairs until finally, approximately 1 microsecond after the first ionizing event, nearly all of the gas in the detector is ionized (Townsend Avalanche). When the electrons reach the central wire they are collected (neutralized) and produce a sharp pulse of several volts which is measured by the meter's electronics.

A GM is a system where almost all particle radiation incident on the sensitive volume is detected. Any radiation particle ( $\alpha$ ,  $\beta$ ) that ionizes at least one molecule of the gas initiates a succession of ionizations and discharges in the detector that causes the central wire to collect a multitude of additional electrons. This tremendous charge (about  $10^9$  electrons) produces a signal of about 1 volt. The meter itself is simply a pulse counter. Because the pulse height is independent of the type and energy of the incident radiation (a single ionizing event produces a pulse), without an external discriminating apparatus (e.g. sliding shields or covers) a GM system tells the user nothing about the energy or type of the radiation producing the pulse.



Figure 3. Readout Dial

Geiger counters are used for radiation surveys because of their high sensitivity for beta particles. Practically every  $\beta$  particle that penetrates the shell and reaches the fill gas will cause a discharge and produce a count. Because gamma rays are less densely ionizing, only a small fraction will interact with the shell and a much smaller fraction interacts with the gas. To compensate for the low number of ionizations produced by x- /  $\gamma$ -rays, a thick (i.e., 200 mg/cm<sup>2</sup>) steel sheath is often placed around the Geiger tube to produce more interactions in the thick wall that will eject ionized electrons into the gas to be counted.

The two basic types of GM detectors are **thin-window** and compensated GM. A **thin-window** GM has a conducting shell with one area covered only by a thin (e.g., 1.5 - 4 mg/cm<sup>2</sup>) mica or mylar cover. This window allows particles to enter the chamber. The shell of the detector is usually made of steel or coated glass approximately 30 mg/cm<sup>2</sup>. A **compensated** GM is similar to a thin-window GM, but is also covered with an additional steel sheath which may have a sliding or rotating window to expose the 30 mg/cm<sup>2</sup> steel shell and allow

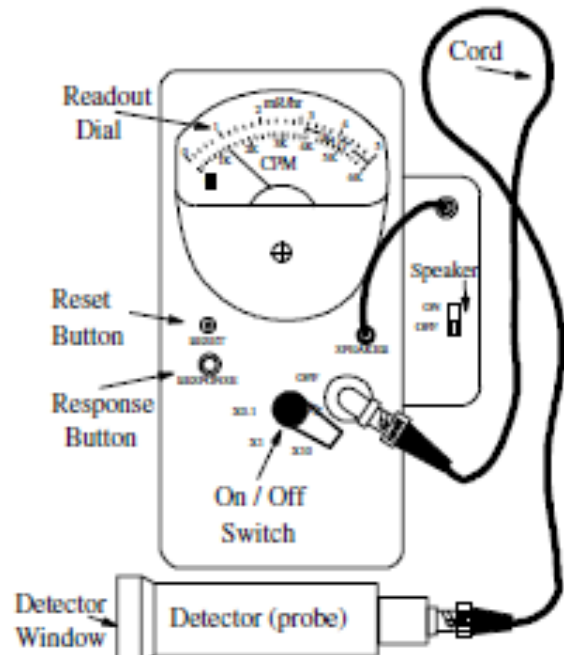


Figure 4. GM-Type Survey Meter

energetic  $\alpha$  particles like  $^{32}\text{P}$  to enter the chamber. Beta particles with energies less than 300 keV cannot be detected with a compensated GM.

A GM is useful because it: (1) has a high sensitivity for particle radiation (less for x- /  $\gamma$ -rays), (2) can be used with different types of radiation, (3) can be fabricated in a wide variety of shapes, (4) produces a strong output signal requiring little or no amplification, (5) is relatively rugged, and (6) is relatively inexpensive.

### GM Detector Efficiency and Energy

Efficiency relates the sensitivity of the detector to the specific radiation being measured and the equation then correlates counts per minute to source activity.

$$\text{eff} = \frac{\text{cpm}}{(\mu\text{Ci}) \cdot (2.22 \times 10^6 \frac{\text{dpm}}{\mu\text{Ci}}) \cdot (\% \text{ of decay})} \approx \frac{\text{cpm}}{\text{dpm}}$$

While there are many factors which affect efficiency, in a GM system, efficiency directly related to the radiation's penetrability (i.e., how far does the radiation penetrate in matter) and the geometry of the source (i.e., where is the radiation source in relation to the detector).

### Alpha particle efficiency

**Most** alpha particles are emitted with energy greater than 4.5 MeV. Because  $\alpha$  particles have high specific ionization, all alpha particles that enter the sensitive volume will be counted and the system efficiency is high. However, alpha particles are easily absorbed. When determining efficiency, factors such as source absorption (i.e., attenuation of particles by source and source housing), air absorption (i.e., attenuation by the air), and absorption by GM window (i.e., even the 4 mg/cm<sup>2</sup> mica window stops some alpha particles) contribute to reduced efficiency. Generally, because alpha particles are emitted with energies between 4.5 - 5.5 MeV, a GM system should have approximately the same efficiency for every alpha emitter.

### Beta particle efficiency

Although beta particles are emitted with lower energies than alpha particles, because of their small size they have longer ranges than alpha particles. Thus, geometry factors, particularly distance from the sensitive volume, is less critical than for alpha detection. All beta particles that enter the sensitive volume will be counted. The wide range of beta energies results in a wide range of efficiencies for the same sample geometry. Higher energy beta particles will have greater range so source absorption and absorption by the GM window will be less and efficiency higher. A thin-window GM has a relatively high efficiency for beta particles and betas with maximum energies ( $E_{\text{max}}$ ) greater than 100 keV (see Figure 7) can readily be detected with this type of GM. Additionally, some beta emitters decay to daughter nuclides which are also beta emitting radionuclides. In this instance, source activity is usually indicated by the parent activity causing the apparent efficiency (when counting check sources) to exceed 1 (i.e., 100%). The daughter may also be more energetic than the parent (e.g.,  $^{90}\text{Sr}$  and  $^{90}\text{Y}$ ) insuring that more of the daughters are detected for the same geometry.

### X- and Gamma ray efficiency

X- and  $\gamma$ -ray photons can travel long distances in air and thus have low specific ionization. Compared to particulate radiation which produces a large number of ion pairs in the fill gas, photons produce very few ionizing events in the gas. Detection of x- /  $\gamma$ -rays normally results because the photons interact with the GM tube's shell (Figure 5), which has a greater density, and electrons are ejected from the walls into the fill gas. These electrons then produce secondary ionizations which are recorded as counts. Photons do not interact with the thin window (e.g., 4 mg/cm<sup>2</sup>) GM tubes used to detect particulate radiation, so GM tubes used to measure photons incorporate a thick (e.g., 200 mg/cm<sup>2</sup>) shield around the tube to compensate for the low sensitivity and produce secondary ionizing electrons. Thus, when conducting a contamination survey where only photons, and particularly where higher energy photons (e.g., > 100 keV), are to be encountered, a thin window GM detector would have a lower efficiency (e.g., < 1%) than a compensated GM. A shielded, thin window pancake-type GM probe (e.g., HP-210) may have a higher efficiency than a thin end-window GM because, after passing through the flat tube, the photon may interact with the shield and eject an ionized electron back into the sensitive volume. For low energy (e.g., < 50 keV) photons (e.g., 125I), a thin window GM is at best capable of detecting a minimum of about 0.04  $\mu$ Ci (88,800 dpm). Therefore, when detecting small amounts of 125I, a low energy gamma (LEG) probe is the system required at the University for researchers using significant quantities of low energy gamma emitters.

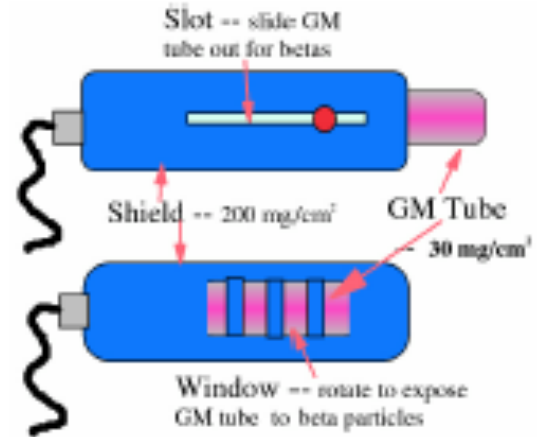


Figure 5. Compensated GM

Table 1. Beta Source Data

Isotope	Half-life	Activity ( $\mu$ Ci)	$\beta$ Energy (keV)
<sup>14</sup> C	5,730 yr	0.158	157
<sup>99</sup> Tc	213,000 yr	0.038	292
<sup>36</sup> Cl	301,000 yr	0.0210	709
<sup>32</sup> P	14.3 day	0.0203	1710

### Geiger Counter Operations

Before operating any new piece of equipment for the first time, the user should read the operating manual becoming familiar with the controls and operating characteristics of that system. Although GM survey meters have similar controls and readout dials, the controls and switches may be located in different places or the readout dial may utilize different units (e.g., counts-per-second). Check the meter for physical damage. Check the calibration sticker (Figure 6) for the date the meter

Use CPM scale only. Cal Date: 7/18/xx  
 Window: Fixed Beam ⊥ to probe center.  
 Battery: OK Check Source: 1500 CPM  
 Isotope: C-14 Tc-99 P-32  
160 keV 300 keV 1.71 MeV  
 Efficiency: 2% 13% 27%  
 @ Cs-137 energy: 2400 cpm / mR/hr  
 DO NOT USE mR/hr SCALES  
 UW Safety Dept. Calibration Lab 262-876

Figure 6. Calibration Sticker

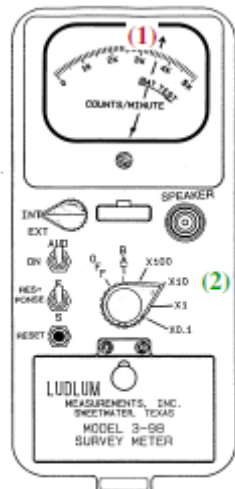


Figure 7. Meter Controls



was calibrated. Meters are required to be calibrated at least once a year. Radiation Safety normally sends a letter to each lab when a lab's meter is due for calibration, requesting the lab bring the meter in for calibration. Safety will calibrate most meters' **cpm** scale against known beta emitting radiation sources. Loaner meters are available for the 2 - 3 days required for the calibration. The calibration sticker indicates a meter's efficiency (cpm/dpm) for three beta emitters:  $^{14}\text{C}/^{35}\text{S}$  ( $E_{\text{max}} \approx 160 \text{ keV}$ ),  $^{99}\text{Tc}$  ( $E_{\text{max}} = 292 \text{ keV}$ ), and  $^{32}\text{P}$  ( $E_{\text{max}} = 1.7 \text{ MeV}$  -- actually  $^{90}\text{Sr}/^{90}\text{Y}$ ,  $E_{\text{eff}} 1.7 \text{ MeV}$ ).

Before actually using the meter, you need to check the batteries and insure the system works properly. For the battery check, turn the selector switch to the **BAT** position. The readout's needle must move into the **BATT OK** range. If not, the batteries are weak and must be replaced. To conserve battery life, turn off the meter (and speaker if separate) when not using.

Check the operability of the detector against the check source which Safety places on all meters. With the meter and speaker turned on, position the selector switch to the appropriate scale, place the detector window over the check source affixed to the side of the meter, and measure the radiation of the source. Compare the response with that given on the calibration certificate (Figure 6). This response should be within  $\pm 20\%$  -  $25\%$  of the indicated response.

Every portable system detects a low-level of background radiation. Determine this level by turning the selector switch on its lowest scale, pointing the detector away from any radiation work areas and measuring the count-rate with no radiation sources. Note that the meter reading must be multiplied by the selector switch scale (e.g., X0.1, X1, X10, etc.). This result is the background reading. Normal background for thin-window GM meters is between 20 - 40 cpm and about 150 - 200 cpm for LEG meters.

To perform a meter survey, insure the speaker is turned on, point the probe window at the area or equipment you wish to monitor for radiation or radioactive contamination. Unless contamination is expected, place the selector switch on the lowest scale. When surveying or entering contaminated areas with unknown radiation levels, turn the meter on outside the area, place the selector switch on the highest range setting and adjust the switch downward to the appropriate scale. Reading the response of the system is usually a two part process: (1) note the indicated cpm on the readout dial and (2) multiply the cpm reading by the selector switch setting. For example, in Figure 7 the needle indicates **3.6K** or **3.7K cpm** and the selector switch is on the **X 10** scale, the radiation count rate is about **37,000 cpm**.

### Geiger Counter Considerations

In order to produce a count (i.e., a click on the speaker), the incident (beta) radiation must ionize at least one fill-gas molecule in the GM tube. We will investigate how the efficiency of a GM

Table 1. Beta Source Data

Isotope	Half-life	Activity ( $\mu\text{Ci}$ )	$\beta$ Energy (keV)
$^{14}\text{C}$	5,730 yr	0.158	157
$^{99}\text{Tc}$	213,000 yr	0.038	292
$^{32}\text{P}$	14.3 day	0.0210	709
$^{32}\text{P}$	14.3 day	0.0203	1710

system is affected by three factors: radiation energy, geometry (i.e., radiation's distance from the detector), and type of radiation (e.g.,  $\beta$  versus  $\gamma$ ) being detected. An understanding of the system's limitations may insure that the detectors are used correctly and that the results are viable.

Table 1 lists: (a) the check sources in our  $\beta$  source set, (b) their activity ( $1 \mu\text{Ci} = 2,220,000 \text{ dpm}$ ) on the day they were produced (these have such long half-lives that they have not appreciably decayed since then), and (c) the maximum energy (remember that  $\beta$  particles are emitted with a spectrum of energies ranging from essentially zero keV to the maximum energy,  $E_{\text{max}}$ , with the most likely and average energies being approximately a the maximum energy) of the emitted  $\beta$  particle. The  $^{32}\text{P}$  source is actually a  $^{90}\text{Sr}$ - $^{90}\text{Y}$  source which has equivalent energy by a 29.1 year half-life

### Energy versus Efficiency

The energy of the emitted radiation is a major factor in a counting system's efficiency. All other things being equal, efficiency is proportional to energy. To demonstrate this, we will count each check source and determine the system efficiency. The thin end-window detector is placed in a SH-3 holder and each source is placed with the mylar window facing up (the radiation cannot penetrate through the back of the source) in the center of the sample holder to assure reproducible sample geometry. Record the approximate counts per minute observed for each source in Table 2. If each of the radionuclides emits 1 beta particle for each disintegration, calculate efficiency by:  $\text{eff} = \text{cpm} / \text{dpm}$ . Obtain percent efficiency by multiplying that decimal by 100%.

Table 2. Energy versus Efficiency

Isotope	Activity <sup>1</sup> ( $\mu\text{Ci}$ )	Activity (dpm)	Energy (keV)	CPM	Efficiency
$^{14}\text{C}$	0.079	175,380	157		
$^{99}\text{Tc}$	0.019	42,180	292		
$^{36}\text{Cl}$	0.0105	22,530	709		
$^{32}\text{P}$	0.0102	23,310	1710		

<sup>1</sup>Activity is listed for  $2\pi$  which is  $\frac{1}{2}$  of the actual source activity. The reasoning for this is, only half of the radiation is being emitted out of the plane of the source, the other half is being emitted downward, away from the detector (see Figure 9).

Comparing the efficiencies, you will notice that the higher the energy of the  $\beta$  radiation, the higher the detector efficiency. The \* -graph in Figure 8 shows the relationship between maximum  $\beta$  energy and efficiency. When conducting the experiment, we actually used a

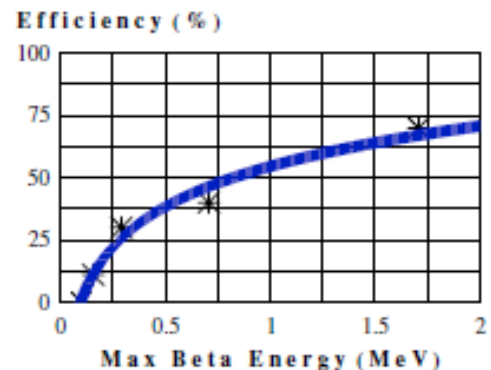


Figure 8. Beta Energy versus Detector Efficiency

90Sr source to simulate 32P. While 90Sr only emits a 540 keV  $\beta$ , it then decays to another (i.e., daughter) radioactive isotope, 90Y which emits a  $\beta$  particle with an energy of 2.281 MeV. The average energy of this combination is very nearly the average energy of 32P and can be used to simulate 32P. Thus, the graph shows that, in general, **the higher the  $\beta$  energy, the higher the efficiency of the thin-window detector**. Notice the energy-efficiency relationship is not linear. This is because the graph is based on maximum beta energy and betas are emitted in a spectrum of energies. Also, there is a point of zero (0) efficiency. For  $E_{max} < 100$  keV, the beta particle does not have enough energy to penetrate the window and be counted and therefore nuclides like 3H and 63N cannot be detected with GM tubes.

### Distance versus Efficiency

Gamma-radiation exposure from a point source followed the *inverse square law*. Although beta particles are not as penetrating as gamma-rays, for relatively short distances ( $< 5$  cm) this law may also apply. We shall consider the effect distance (geometry) has on the count rate (and consequently on the efficiency). Radiation is emitted from the source in all directions (i.e., a  $4\pi$  sphere -- Figure 9, left). When the detector is close (i.e., essentially forming a  $2\pi$  hemisphere -- Figure 9, center) to the source, nearly all of the energetic particles which are emitted in the upward direction toward the detector and penetrate the thin-window create one or more ion pairs and, consequently, produce a pulse which is counted by the meter. As the detector is moved away from the source of radiation (Figure 9, right), many beta particles are emitted at angles which allow them to miss the detector. In this case, the number of particles in-line with the detector is reduced from the  $2\pi$  situation, resulting in a much smaller count rate.

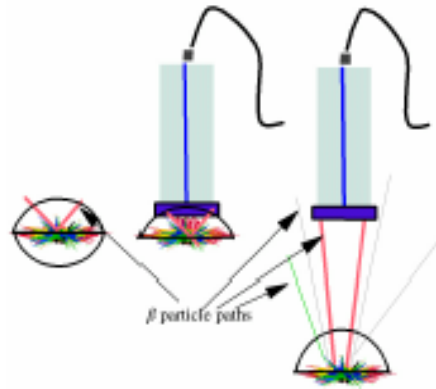


Figure 9. Geometry

To demonstrate the effect of geometry, we will use a high activity source and slowly increase the distance from the tube while listening to the count-rate on the meter's speaker. In such a manner, you can hear the effect of geometry on count-rate and observe that there is a point at which efficiency is 0% (i.e., count rate is background).

To graphically show this point, we plotted the data from our 3 check sources which emit only a single beta particle per decay. The graph in Figure 10 illustrates two concepts. Regardless of the distance, the higher the maximum beta energy, the higher the efficiency (see Figure 8);

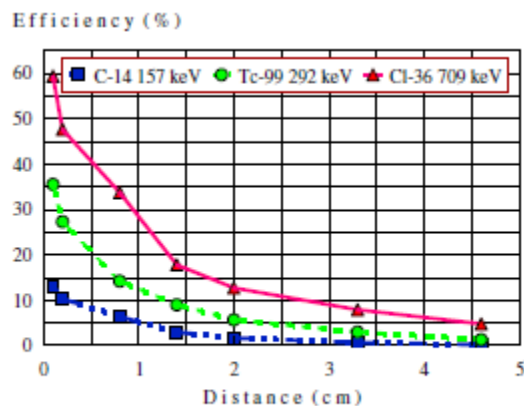


Figure 10. Detector Distance versus Percent Efficiency



however, at distances greater than 3 cm, the efficiency is less than 10%. Secondly, at distances less than 1 cm, even  $^{14}\text{C}$  has relatively good detection efficiencies. Thus, the farther the detector is from the source of contamination when doing a survey, the less likely it will be able to detect radioactivity. When doing a contamination survey, the detector should be within approximately 1 cm of the surface. Even at 1 cm the system efficiency (taking into consideration the attenuating effects of the probes protective cover, etc.) for a low energy beta (e.g.,  $^{14}\text{C}$ ,  $^{35}\text{S}$ ), is likely to be between 1 and 3% (depending upon detector used).

### Sensitivity of Detector

In radiation detection, the term *sensitivity* means the ability of a detector to detect the type of radiation at the levels of interest. One example of a system that is not sensitive to low-energy beta radiation is a **compensated GM**. This system cannot detect low energy  $\beta$ -particles because the particles are unable to penetrate the wall and enter the detector tube. Thin-window GM detectors are sensitive to  $\beta$ -particles with maximum energies ( $E_{\text{max}}$ ) greater than 100 keV. Workers using quantities of  $\beta$ -emitting isotopes (i.e.,  $^{125}\text{I}$ ,  $^{51}\text{Cr}$ ) in excess of 3.7 MBq (0.1 mCi) are required to also have scintillation detectors (see 7.4) to measure the low energy x- /  $\beta$ -rays emitted from these isotopes. A scintillation detector uses a crystal of sodium-iodide (NaI) which has a density of 3.67 gm/cm<sup>3</sup> (much denser than the GM tube gas). Low-energy gamma-rays are easily absorbed in this crystal producing light pulses.

To demonstrate the need for a special detector, we will use an  $^{129}\text{I}$  check source. Iodine-129 decays by the emission of a  $\beta$  particle with a maximum energy of 153 keV. The beta energy is absorbed by the plastic of the source housing and does not penetrate. There are also  $\beta$ -rays and characteristic x-rays accompanying this decay. These x-rays have energies between 29 and 39 keV and for each beta decay there is approximately 0.78 x- and -rays emitted. With the source being used there are approximately 200,000  $\beta$ -rays per minute being emitted. We will look at a thin-window GM response to these  $\beta$ -rays by first the source. Then we will count the source on a low-energy gamma (i.e., scintillation) detector. Note that when you count the  $^{129}\text{I}$  source on the GM, you get essentially background but when you use the low-energy gamma probe, the count rate is significant and noticeably high. You can see how a person using the wrong meter may misinterpret the results.

You may wonder why there is such a dramatic difference between the GM (first) and low-energy gamma (second) counts when there are just as many gamma rays getting to the detector. Gamma rays are more penetrating and they don't interact as often as beta-particles interact (i.e., the probability of an ionizing interaction is much less per millimeter of path [cf., 1.2.f] than for beta-particles). Most of the counts seen in the GM result from interactions that occurred in the metal wall of the GM knocking ionized electrons into the gas which are then counted. A thin window GM is **not** sensitive to gamma rays and should not be used to measure or detect such radiation. These meters are meant to survey for a  $\beta$  emitter and beta contamination, with the cpm response indicative of the quantity of contamination. When these meters are sent to the Safety

Department for annual calibration, their response to beta particles is measured and they are adjusted so the cpm scale accurately reflects the number of particles incident on the sensitive volume.

Scintillation detectors are normally used for detection of gamma and x-rays and/or high-energy beta radiation. The type and energy of radiation detected depends on the type and thickness of the scintillator used. Low energy Gamma (LEG) probes are highly efficient for low-energy gamma rays in the 20 to 70 keV range. They normally use NaI crystals approximately 0.04" to 0.08" thick. Figure 11 is a graph of the response of one such LEG detector. Because higher energy gamma rays are more penetrating, scintillation detectors designed to detect and measure photons with energies between 100 keV and 2 MeV are thicker, often more than 1" thick. However, the very thickness of the detector limits its usefulness at the lower energies because the light produced cannot penetrate through the crystal. In recent years, progress has been made in the field of plastic scintillators for detecting beta particles. These substances are like encapsulating liquid scintillation cocktail in a probe. The detectors are often very thin, usually about 0.01" (0.025 mm) thick. Some manufacturers also couple plastic scintillators with thin (0.04" - 0.08") NaI crystals to produce a portable system sensitive to both low energy gamma-rays and beta particles with  $E_{max} > 67$  keV.

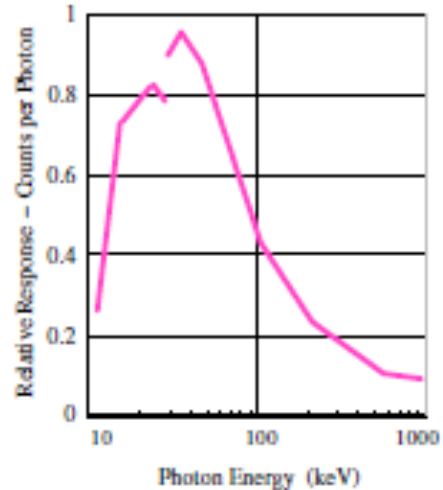


Figure 11. LEG Energy Response

Scintillation detectors can have very high efficiencies. Figure 11 graphs the relative response of a LEG detector in counts per photon. Again notice that the efficiency is highly energy dependent; but in the region that this system is designed to operate, very high efficiencies are possible. For example, using a LEG detector to survey for  $^{125}\text{I}$ , photon energy = 35.5 keV, expect efficiencies between 40% to more than 90% depending upon the type of probe and the scintillator thickness. Systems which couple gamma and beta scintillators in the same probe have advertised efficiencies of 16% for  $^{14}\text{C}$  and 38% for  $^{125}\text{I}$ .

It should be noted that the high gamma-ray sensitivity comes with a penalty. The background on these detectors is often several hundred counts per minute. The advertised background of the LEG detector in Figure 11 is 160 - 200 cpm. If a lab is considering buying a portable scintillation system, contact the Safety Office for information on a proper system for your situation.

## Liquid Scintillation Counters (LSC)

### Liquid Scintillation Cocktail

Liquid scintillation counting is a method of assaying radioactive samples by dissolving each radioactive sample in a liquid scintillation cocktail composed of a solvent (e.g., toluene, xylene, or an alkyl benzene (biodegradable) solvent), an emulsifier (a detergent type molecule which ensures proper mixing of aqueous samples in the organic solvent), and a fluor or fluorescent solute. The purpose of the scintillation cocktail is to convert the energy of the radioactive decay particle into visible light which can be detected by the scintillation counter.

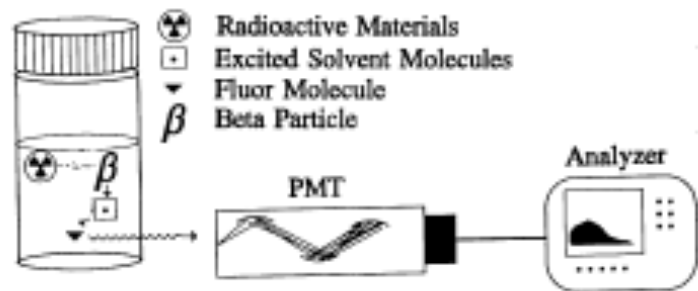


Figure 12. Liquid Scintillation Counting

The process of converting the radiation energy to visible light follows three steps. First, the kinetic energy of a single radioactive decay particle is absorbed in the cocktail by many solvent molecules causing many of them to become **excited**. The excited molecules return to their ground states by emitting this excitation energy as either heat or light. The solvent tends to lose most of this energy as heat while the light that is emitted is in the UV region. Ultraviolet light is not easily detected by the liquid scintillation counter's electronics. Thus, the second step in making cocktails is the addition of fluor molecules to the cocktail. Some of the excitation energy of the solvent molecules is then transferred to fluor molecules causing the fluors to become excited. In the third step, the fluor molecules return to ground state by emitting light, the frequency of which is dependent solely upon the fluor used (e.g., PPO generates light in the blue region [i.e., 1370 nm, 13 eV] of the spectrum). The aim of the cocktail manufacturers is to develop a cocktail which emits light of the proper frequency for the LSC electronics to detect.

The amount of light emitted by the liquid scintillation cocktail is directly proportional to the energy of the particle, i.e., the higher the energy of a radioactive particle, the more solvent molecules are excited, and the more light is generated (Figure 13). Thus, for example, while the absorption of a beta particle from  $^3\text{H}$ , which has a maximum possible beta energy of 18.6 keV and a most probable energy of approximately 6 keV (a  $\frac{1}{3}$  of 18.6 keV), might produce a maximum of 30 light photons. The absorption of a beta particle from  $^{32}\text{P}$ , which has a maximum possible beta energy of 1710 keV, might produce a maximum of 3300 light photons. Thus, the conversion of energy to light appears to be linear, 100 times the energy, 100 times the light yield.

Just as with a light bulb, the light emitted by fluors in the liquid scintillation cocktail is emitted in all directions. However, it is "directed" into two photomultiplier tubes (PMT) by surrounding the cocktail vial with mirrored surfaces everywhere except where the PMTs are located. PMTs are electronic tubes consisting of two components; a photocathode and a series (usually 13) of anodes and cathodes (called dynodes) at increasingly higher voltages. When blue light from the

fluors strikes the photocathode, electrons are ejected, attracted to the dynodes and their number multiplied at each stage (Figure 12). The PMT thus converts the light which it collects into an electrical pulse and the pulse height at the output of the PMT is proportional to the amount of light energy that was collected (Figure 13).

**Pulse (Signal) Processing** When liquid scintillation counters were first developed, the PMTs were found to generate a lot of random noise pulses. For a 2-inch PMT (i.e., diameter of the face), this background of noise was greater than 10,000 cpm. This noise normally appeared in the region 0 - 6 keV where the majority of  $^3\text{H}$  counts also appeared. Obviously, a system background of 10,000 cpm (especially for  $^3\text{H}$ ) would be useless for sample analysis. To reduce noise, coincidence circuits were introduced.

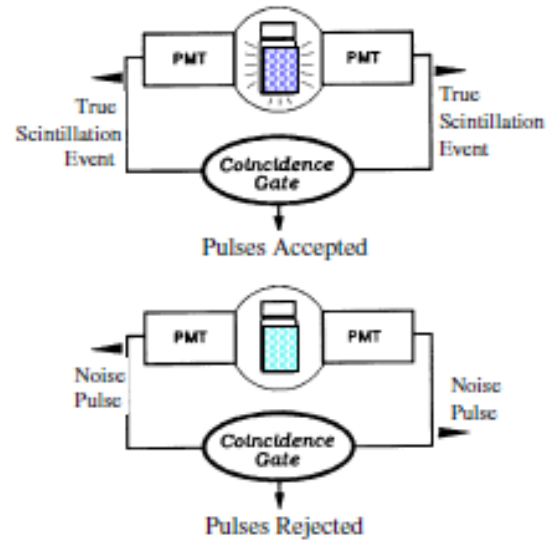


Figure 15. Coincidence Circuit

A coincidence circuit (Figure 15) is able to discriminate between noise pulses and pulses from radiation-produced scintillation events. In a "real" scintillation event, many light photons are emitted in all directions. This light will strike both photocathodes simultaneously (actually within 10 - 30 nsec, 0.000 000 01 sec). When this occurs, each PMT will generate a pulse simultaneously. Only when the coincidence circuit detects a pulse from each PMT simultaneously will the counter register that a beta decay occurred. Because noise pulses are generated randomly from each PMT, the chance of a noise pulse being emitted from both PMTs simultaneously is very small. If the coincidence circuit detects a pulse from one PMT and not the other (within 40 nsec), the analyzer will disregard the pulse. This coincidence circuit insures that the liquid scintillation counter's background will be low (about 20 - 40 cpm).

The pulses from the coincidence circuit are digitized and stored in a 1000 - to 4000-channel multichannel analyzer (MCA) system where each channel (cf., 7.6.i) corresponds to a small energy interval (i.e., in a 4000-channel system, each channel is 0.5 keV wide and the system can measure 0 - 2000 keV). This sorting can be most easily likened to the process of sorting apples. In an apple sorter, the apples pass over a series of holes, each hole increasingly larger than the previous one. As the apples pass over the sieve, they fall through the first hole which is larger than the apple's diameter. The apples are then collected in baskets.

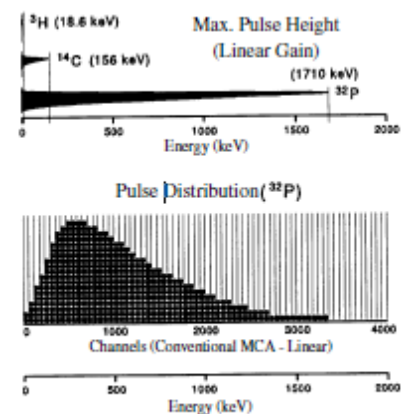


Figure 16. Pulse Analysis and Storage

Similarly, the pulses from the coincidence circuit are sieved. Rather than collecting apples in baskets, each channel has a scaler (i.e., a counter) which is incremented for each pulse of corresponding energy (e.g., tells the user how many apples in each basket). The LSC also has the capability of changing the sieve, or window, size. Users often set windows to sort pulses based on the radiation energy they are most interested in, setting the tritium ( $^3\text{H}$ ) window to collect all pulses above background but less than approximately 19 keV. Similarly, the  $^{14}\text{C}$  window would be set to collect all pulses above 0 keV but less than 160 keV (or above 19 keV but less than 160 keV if a mixed  $^3\text{H} / ^{14}\text{C}$  sample were being counted), and the  $^{32}\text{P}$  window may be set to collect all pulses with energies greater than 2 keV but less than 1710 keV. A tip for counting low activity (i.e., environmental samples) of beta emitters like  $^{14}\text{C}$ ,  $^3\text{H}$ , etc. -- Noise can be reduced by setting the lower window above the noise level which usually stops by 2 keV (cf. 7.6.1).

**Q 1.** If the window settings are used to discriminate pulses based on their amplitude, what would be the window settings (i.e., Lower Level Discriminator [LLD] and Upper Level Discriminator [ULD]) for counting a sample containing  $^{32}\text{P}$  with a maximum energy of 1710 keV?

If you were counting both  $^3\text{H}$  and  $^{14}\text{C}$ , what LLD and ULD would you set?

Thus, liquid scintillation counters can be used to quantify radioactivity and to measure radioactive contamination. They are ideal for counting radionuclides that decay by beta emission (e.g.,  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{32}\text{P}$ ,  $^{35}\text{S}$ ,  $^{36}\text{Cl}$ , etc.), they may also be used to measure low energy gamma emitters (e.g.  $^{125}\text{I}$ ). Although both  $^{125}\text{I}$  and  $^{125}\text{I}$  decay by electron capture with the emission of a gamma ray, these gamma rays sometimes interact with orbital electrons of the decaying atom, transferring their energy to an electron and ejecting it from the atom. The vacancy is filled by an electron from a higher shell resulting in the production of x-rays and Auger electrons (cf., 1.2.a.4). These conversion and Auger electrons are readily detected by the LSC. For appropriately chosen windows, the system efficiency can be very high. Table 3 shows a typical relationship between radiation energy and efficiency.

Table 3. Energy versus (unquenched) Efficiency

Isotope	Radiation	$\beta / e$ Energy $E_{\text{max}}$	Efficiency
$^3\text{H}$	$\beta$	18.6 keV	60%
$^{14}\text{C}$	$\beta$	156 keV	90%
$^{32}\text{P}$	$\beta$	1710 keV	95%
$^{35}\text{S}$	$\beta$	160 keV	90%
$^{51}\text{Cr}$	$\gamma - e$	5 keV	35%
$^{125}\text{I}$	$\gamma - e$	4 & 30 keV	80%

to

and

$^{51}\text{Cr}$

**Q 2.** The CPM of a 3.7 kBq (0.1  $\mu\text{Ci}$ ) of  $^3\text{H}$  sample is 80,000, what is the counter efficiency?

The CPM of a 3.7 kBq (0.1  $\mu\text{Ci}$ ) of an unknown sample with a  $\beta$  yield of 50% (i.e., 1.85 kBq [0.05  $\mu\text{Ci}$ ] of  $\beta$ ) is 80,000, what is the counter efficiency?

## Quench

Almost anything added to a counting vial by an investigator as a result of sample processing (e.g., solvents, filters) can lower the efficiency of the scintillation process by reducing the number of blue light photons reaching the PMT. This reduction in counting efficiency is called quench. There are two basic types of quench. **Chemical** quenching occurs when chemical agents added to the cocktail interfere with the transfer of radiation energy between the solvent and the fluor (i.e., absorbs beta energy better than the cocktail so it does not excite as many cocktail molecules) resulting in a reduction and loss of light and consequent lowered efficiency. For example, carbon tetrachloride absorbs beta energy and radiates infrared light. **Color** quenching arises when (1 3 eV) blue light photons from the fluors are absorbed by colored components in the cocktail and counting vial (i.e., red [1.9 eV], yellow [2.1 eV] and green [2.4 eV] colors in the counting vial absorb the blue light emitted from the fluor) resulting in reduced blue light pulses. Additionally, low energy  $\beta$  radiation may be absorbed in the sample medium itself (i.e., self-absorption) and never get out to excite a solvent molecule.

Because quench absorbs a portion of energy from each decay, quenching results in two effects (Figure 17): (1) a shift in the pulse spectrum to a lower energy region, and (2) a reduction in the measured sample cpm (especially low energy emitters -- Figure 18). Regardless of the type, quench results in a reduction of the number of counts registered, and reduces efficiency. All laboratory samples are quenched to some degree. To properly analyze data, a researcher often needs results which are independent of quench. Because of quench, the researcher cannot simply convert cpm to dpm by using the efficiencies listed in Table 3 (e.g.,  $dpm = cpm / \text{eff}$ ). Rather the effect of quench must be factored into the conversion if the researchers is interested in the true activity in the vial.

When properly set, the LSC can report the amount of quench in a sample. All manufacturers determine the sample's quench in the same ways; but they designate the amount of quench present differently. For example,

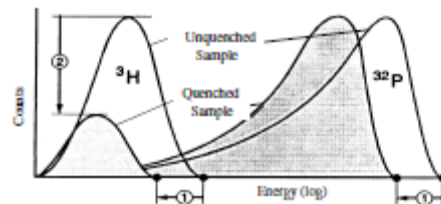


Figure 17. Effects of Quench

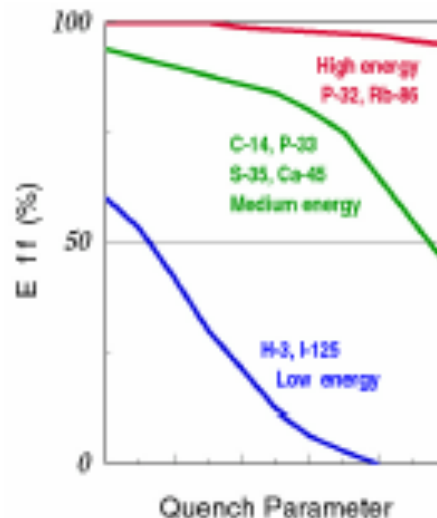


Figure 18. Quench vs Energy

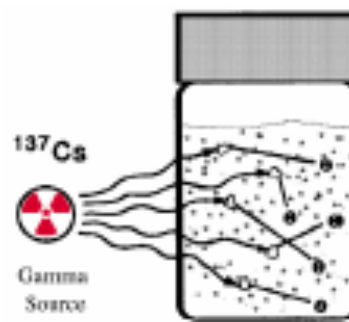


Figure 19. External Standard



Beckman uses an external source of  $^{137}\text{Cs}$  (or  $^{133}\text{Ba}$  or  $^{226}\text{Ra}$ ) to determine the sample's H-Number. Cesium gamma-rays interact with the cocktail and eject (Compton) electrons. The Compton electrons produce a spectrum in the quenched sample that is compared to the Compton spectrum of a theoretically unquenched sample. The shift in channels (i.e., the difference between the channel that an unquenched standard's inflection point occurs and the channel that the quenched standard's inflection point occurs) is the sample's **H-Number**. For a Beckman LSC, the greater the H-Number, the greater the amount of quench present and the lower the efficiency.

Packard Instruments uses slightly different terminology to describe quench. They still utilize an external ( $^{133}\text{Ba}$  or  $^{137}\text{Cs}$ ) standard which bombards the sample with high energy gamma-rays and the system analyzes the resultant Compton spectrum. Sample quench shifts this Compton spectrum and Packard calculates a **transformed Spectral Index of the External (tSIE)** standard to determine the Quench Indicating Parameter (QIP). On Safety's Packard system, 3H quenched standards with tSIE ranging between 1000 and 50 give efficiencies of 60% to 3.3%, respectively (see Figure 7-27 or Figure 23).

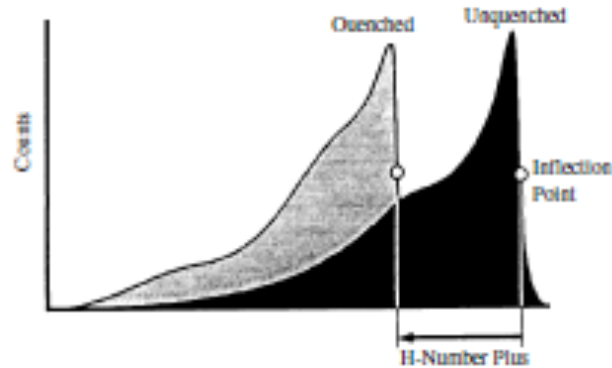


Figure 20. Beckman's H-Number

Figure 21 shows these two manufacturer's Quench versus Efficiency curves. Notice that they are different. Other manufacturers use different quench numbers (e.g., the QIP on some Wallac LSC systems varies from 0 - 22), but all LSC systems relate quench with efficiency. If you want to extrapolate your data taking into account the quench, you must know the shape of the quench curve.

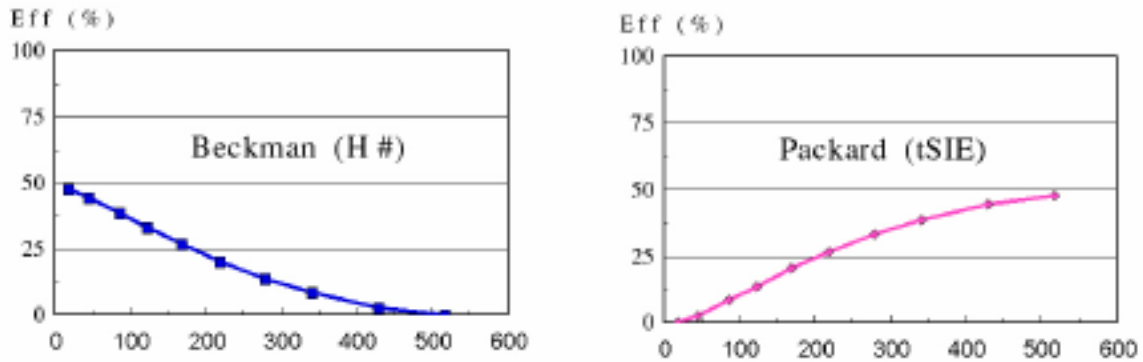


Figure 21. Quench Representations

**Q 3.** A sample has a tSIE quench parameter of 1000. Referring to the description of quench value ranges for Packard systems (Figure 21, right), is this sample quenched or unquenched?

### Quench Calibration

Most of the information about quench is found in the manufacturer's literature. However, users can determine the relationship between quench and counter efficiency manually. This method uses an external standard, Packard's Quench Indicating Parameter (QIP), and a set of "Quenched" standards.

A quenched standard set usually consists of 10 vials each of which contains the same radioactivity (dpm) but each with differing amounts of the quenching agent, nitro methane, added. The more quench in the sample, the fewer counts that will be detected. The quenched standard set is loaded into the LSC. If necessary, the LLD, ULD and Gain are set for the radionuclide and counting is begun. The number of counts registered for each standard vial as well as the quench parameter is determined by the counter. Because all the standards contain the same amount of radioactivity, the efficiency ( $\text{eff} = \text{cpm} / \text{dpm}$ ) of the counter at various levels of quenching can be plotted.

**Q 4.** Can you use a tritium quench curve to estimate the activity of  $^{32}\text{P}$  samples? Can you use a tritium quench curve to estimate the activity of  $^{63}\text{Ni}$  sample? Performing a calibration as a practical exercise, count a  $^3\text{H}$  quenched standard set. Each of the standards has an activity of 194,433 dpm (about 0.088  $\mu\text{Ci}$ ). If counted in a Packard LSC with the "window" (or counting region A) Lab 1 -- Radiation Detection and Measurement 291 Figure 21. Quench Representations Figure 22. Set of  $^3\text{H}$  Quenched Standards set to sort energies between 0 keV and 18.6 keV (i.e., the tritium window), calculate the efficiency of each standard and correlate it to the quench indicating parameter (tSIE). Figure 23 summarizes the quench standard calibration results, listing the cpm and the tSIE for each of the standards. The efficiency for each sample is calculated by using the equation,  $\text{eff} = \text{cpm} / \text{dpm}$ . Plotting the efficiency (y-axis) versus the

tSIE (x-axis) results in the graph. From Figures 17, 18 and 21, we see that quenching has its greatest effect on low energy (e.g., 3H, 63Ni, etc.) samples. This should be obvious when reviewing Figure 17 where you see that, depending upon type, quench both reduces the counts (absorbs energy and re-radiates it as heat) and reduces the energy (absorbs some of the light). Because low energy emitters are already at the threshold of detection, this attenuation is more severe than for higher energy emitters (e.g., 14C, 33P, 35S, 32P, etc.) which suffer only slight degradation in efficiency. To apply quench correction by converting a sample's cpm result into dpm activity using the counter's quench parameter, simply interpret the graph. For example, Table 4 lists several 3H (E<sub>max</sub> = 18.6 keV) sample results along with the quench of each sample. To calculate the true activity (in units of dpm) of the samples, use the QIP to find the counter's efficiency from Figure 23, then calculate the dpm activity using the equation: **dpm = cpm / eff**.  
 Table 4. 3H DPM Determination 427 45 2,847 175 5,476 500 47% 11,651 cpm tSIE eff (%)  
 Activity (dpm)

**References** Burns, P.D., and Steiner, R. *Bulletin No. 7885, Advanced Technology Guide for LS 6000 Series Scintillation Counters*, Beckman Instruments, Inc., April 1991 Hawkins, E.F., and Steiner, R. *Bulletin No. 7884, Scintillation Supplies and Sample Preparation Guide*, Beckman Instruments, Inc., April 1991 Packard Instruments Company, *Basic Liquid Scintillation Counting* Packard Instruments Company, *Tri-Carb Liquid Scintillation Analyzer, Model 1900 CA, Operations Manual* 292 Radiation Safety for Radiation Workers Figure 23. 3H Quench Curve  
 0 100 200 300 400 500 600 tSIE 0 10 20 30 40 50 60 % Efficiency Ch A Ch A H-3 Efficiency vs  
 tSIE 518 430 341 279 219 169 123 86.3 45.2 17.9 48 45 39 33 27 20 14 9 3 0 Ch A -- 0.0 - 18.6  
 keV tSIE