Course Title: **Radiological Control Technician**
Module Title: **Counting Errors and Statistics**
Module Number: **2.03**

Objectives :

2.03.01. Identify five general types of errors that can occur when analyzing radioactive samples, and describe the effect of each source of error on sample measurements.

2.03.02. State two applications of counting statistics in sample analysis.

2.03.03. Define the following terms:
a. mode
b. median
c. mean

2.03.04. Given a series of data, determine the mode, median, or mean.

2.03.05. Define the following terms:
a. variance
b. standard deviation

2.03.06. Given the formula and a set of data, calculate the standard deviation.

2.03.07. State the purpose of a Chi-squared test.

⇒ 2.03.08. State the criteria for acceptable Chi-squared values at your site.

2.03.09. State the purpose of creating quality control (QC) charts.

⇒ 2.03.10. State the requirements for maintenance and review of QC charts at your site.

2.03.11. State the purpose of calculating warning and control limits.

2.03.12. State the purpose of determining efficiencies and correction factors.

2.03.13. Given counting data and source assay information, calculate efficiencies and correction factors.

2.03.14. State the meaning of counting data reported as $x \pm y$.

2.03.15. Given counting results and appropriate formulas, report results to desired confidence level.

2.03.16. State the purpose of determining background.

⇒ 2.03.17. State the method and requirements for determining background for counting systems at your site.

2.03.18. State the purpose of performing sample planchet maintenance.

⇒ 2.03.19. State the method and requirements for performing planchet maintenance for counting systems at your site.

2.03.20. Explain methods to improve the statistical validity of sample measurements.

2.03.21. Define "detection limit," and explain the purpose of using detection limits in the analysis of radioactive samples.

⇒ 2.03.22. Given the formula and necessary information, calculate detection limit values for counting systems at your site.

2.03.23. State the purpose and method of determining crosstalk.

⇒ 2.03.24. State the criteria for acceptable values of crosstalk for counting systems at your site.

2.03.25. State the purpose of performing a voltage plateau.

⇒ 2.03.26. State the method of performing a voltage plateau on counting systems at your site.

INTRODUCTION

Radiological sample analysis involves observation of a random process, one that may or may not occur, and estimation of the amount of radioactive material present based on that observation. All over the country radiation protection personnel are using activity measurements to make decisions that may affect the health and safety of workers at those facilities and their surrounding environments.

This unit presents an overview of measurement processes, and statistical evaluation of both measurements and equipment performance. In addition, this unit addresses some of the actions to take to minimize the sources of error in count room operations.

References:

1. "Advanced Health Physics Course Prestudy Guide," United States Nuclear Regulatory Commission, General Physics Corporation.
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6. Moe, Harold, "Operational Health Physics Training," ANL-88-26; DOE; Argonne National Laboratory, Chicago, 1988.
7. "Introduction to Low-background Counting Systems," Oxford-Tennelec Instruments.
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2.03.01	*Identify five general types of errors that can occur when analyzing radioactive samples, and describe the effect of each source of error on sample measurements.*

GENERAL SOURCES OF ERROR

Assuming the counting system is calibrated correctly, there are five general sources of error associated with **counting** a sample:

1. *Self-absorption*
2. *Backscatter*
3. *Resolving time*
4. *Geometry*
5. *Random disintegration* of radioactive atoms (statistical variations).

Self-Absorption

When a sample has an abnormally large amount of material on the sample media, it could introduce a counting error due to *self-absorption*, which is the absorption of the emitted radiation by the sample material itself. Self-absorption could occur for:

- Liquid samples with a high solid content
- Air samples from a high dust area
- Use of improper filter paper may introduce a type of self-absorption, especially in alpha counting (i.e., absorption by the media, or filter).

Personnel counting samples should ensure the correct sample media is used, and that the sample does not become too heavily loaded with sample material. Count room personnel should be routinely checking samples for improper media or heavily loaded samples.

Backscatter

Counting errors due to *backscatter* occur when the emitted radiation traveling away from the detector is reflected, or scattered back, to the detector by the material in back of the sample. The amount of radiation that is scattered back will depend upon the type and energy of the radiation and the type of backing material (reflector). The amount of backscattered radiation increases as the energy of the radiation increases and as the atomic number of the backing material increases. Generally, backscatter error is only a consideration for particulate radiation, such as alpha and beta particles. Because beta particles are more penetrating than alpha particles, backscatter error will be more pronounced for beta radiation. The ratio of measured activity of a beta source counted with a reflector compared to counting the same source without a reflector is called the *backscatter factor* (BF).

(Equation 1)

$$BF = \frac{countsw/reflector}{countsw/outreflector}$$

Normally, backscatter error is accounted for in the efficiency or conversion factor of the instrument. However, if different reflector materials, such as aluminum and stainless steel, are used in calibration and operation, an additional unaccounted error is introduced. (This additional error will be about 6% for stainless steel versus aluminum.) Count room personnel must be aware of the reflector material used during calibration of the counting equipment. Any deviation from that reflector material will introduce an unaccounted error and reduce confidence in the analysis results.

Resolving Time

Resolving time is the time interval which must elapse after a detector pulse is counted before another full-size pulse can be counted. Any radiation entering the detector during the resolving time will not be recorded as a full size pulse; therefore, the information on that radiation interaction is lost. As the activity, or decay rate, of the sample increases, the amount of information lost during the resolving time of the detector is increased. As the losses from resolving time increase, an additional error in the measurement is introduced. Typical resolving time losses are shown in Table 1.

Count rate (cpm)	GM Tube[1]	Proportional[2]	Scintillation[3]
20,000	1.7%	< 1%	< 1%
40,000	3.3%	< 1%	< 1%
60,000	5.0%	< 1%	< 1%
100,000	8.3%	< 1%	1.0%
300,000	25.0%	< 1%	3.5%
500,000	42.0%	1.5%	5.8%

[1] GM tube: 50µs resolving time
[2] Proportional detector: 2µs resolving time
[3] Scintillation detector: 7µs resolving time

Resolving time losses can be corrected by using the equation:

(Equation 2) $$R = \frac{R_o}{1 - R_o\tau}$$

where: R = "true" count rate, in cpm
R_o = observed count rate, in cpm
τ = resolving time of the detector, in minutes ("tau")

Count room personnel should be aware of the limitations for sample count rate, based upon procedures and the type of detector in use, to prevent the introduction of additional resolving time losses. This is especially true for counting equipment that uses GM detectors.

Geometry

Geometry related counting errors result from the positioning of the sample in relation to the detector. Normally, only a fraction of the radiation emitted by a sample is emitted in the direction of the detector because the detector does not surround the sample. If the distance between the sample and the detector is varied, then the fraction of emitted radiation which hits the detector will change. This fraction will also change if the orientation of the sample under the detector (i.e., side-to-side) is varied.

An error in the measurement can be introduced if the geometry of the sample and detector is varied from the geometry used during instrument calibration. This is especially critical for alpha counting, where any change in the sample-to-detector distance also increases (or decreases) the chance of attenuation of the alpha particles by the air between the sample and detector.

Common sources examples of geometry-related errors include:

- Piling smears and/or filters on top of each other in the same sample holder (moves the top sample closer to the detector and varies the calibration geometry).
- Using deeper or shallower sample holders than those used during calibration (changes the sample-to-detector distance).
- Adjusting movable bases in the counting equipment sliding drawer (changes the sample-to-detector distance).
- Using too many or inappropriate sample holders or planchets (changes the sample-to-detector distance). Sources not fixed in position can change can change geometry and reduce reproducibility.
- Plexiglass shelving in counting chamber is improperly set.

Random Disintegration

The fifth source of general counting error is the *random disintegration* of the radioactive atoms and constitutes the remainder of the lesson.

STATISTICS

Statistics is a branch of mathematics that deals with the organization, analysis, collection, and interpretation of statistical data. No definition of *statistical data* is given. However, Webster's does define a statistic as "an estimate of a variable, as an average or a mean, made on the basis of a sample taken from a larger set of data."

This last definition is applicable to our discussion of counting statistics. After all, when we take samples, we use the data derived from analysis of those samples to make determinations about conditions in an area, in water, or in air, etc., assuming that the sample is representative.

So, we have estimated conditions (a variable) on the basis of a sample (our smear, water sample, air sample) taken from a larger set of data.

Over the years, various methods and observations have identified three models which can be applied to observations of events that have two possible outcomes (binary processes). Luckily, we can define most observations in terms of two possible outcomes. For example, look at the following table:

Trial	Definition of Success	Probability of Success
Tossing a coin	"heads"	1/2
Rolling a die	"a six"	1/6
observing a given radioactive nucleus for a time, *t*	*The nucleus decays during the observation*	$1-e^{-\lambda t}$

For each of the processes that we want to study, we have defined a *trial* (our test), a *success* and a *failure* (two possible outcomes), and have determined the *probability* of observing our defined success.

Now, to study these processes, we can use proven, statistical models to evaluate our observations for error. Consider the possibilities when throwing two dice. There are 36 possible outcomes when throwing two dice, as indicated in Table 3.

Table 3. Possibilities in Rolling Dice

Result	Possibilities	No. of Possibilities
2	1&1	1
3	1&2,2&1	2
4	1&3,2&2,3&1	3
5	1&4,2&3,4&1,3&2	4
6	1&5,2&4,3&3,4&2,5&1	5
7	1&6,2&5,3&4,4&3,5&2,6&1	6
8	2&6,3&5,4&4,5&3,6&2	5
9	3&6,4&5,5&4,6&3	4
10	4&6,5&5,6&4	3
11	5&6,6&5	2
12	6&6	1

If, in our study of this process, we define a success as throwing a number between 2 and 12, the outcome is academic. All trials will be successful, and we can describe the probabilities of throwing any individual number between the range of 2 and 12 inclusive would add up to 1.

If we define a success as throwing a particular number, we can define the probability of our success in terms of the number of possible outcomes that would give us that number in comparison to the total number of possible outcomes.

If we were to take two dice, roll the dice a large number of times, and graph the results in the same manner, we would expect these results to produce a curve such as the one shown in Figure 1.

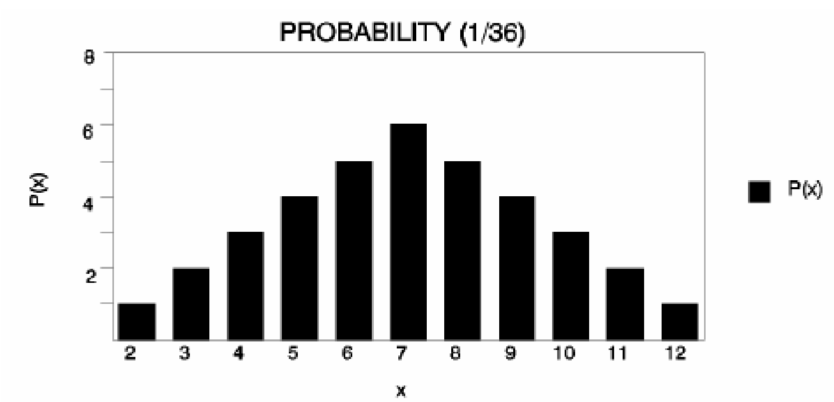

Figure 1. Probability in a Binary Process

The area under the curve can be mathematically determined and would correspond to the probability of success of a particular outcome. For example, to determine the probability of throwing a particular number between 2 and 12 we would calculate the area under the curve between 2 and 12. The results of that calculation would be 36.

This is what statistics is all about; random *binomial* processes that should produce results in certain patterns that have been proven over the years. The three models that are used are distribution functions of binomial processes with different governing parameters. These functions and their restrictions are:

- **Binomial Distribution**

This is the most general of the statistical models and is widely applicable to all processes with a constant probability. It is not widely used in nuclear applications because the mathematics are too complex.

- **Poisson Distribution**

A simplified version of binomial distribution is the *Poisson* (pronounced "pwusówn") distribution, which is **valid when the probability of success, P(*x*), is small**. If we graphed a Poisson distribution function, we would expect to see the predicted number of successes at the lower end of the curve, with successes over the entire range if sufficient trials were attempted. Thus, the curve would appear as seen in Figure 2.

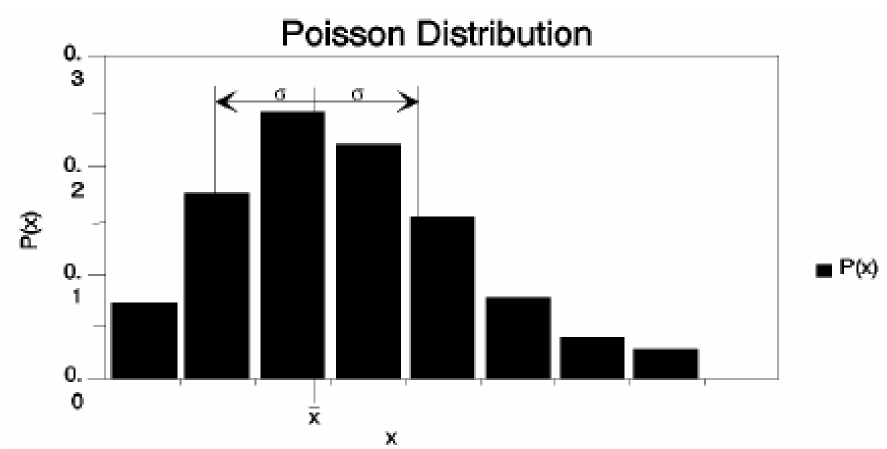

Figure 2. Predicted Successes for Poisson

The Poisson model is used mainly for applications involving counting system background and detection limits, where the population (i.e., number of counts) is small. This will be discussed in greater detail later.

- **Gaussian Distribution**

Also called the "normal distribution," the *Gaussian* (pronounced "Gowziun") distribution is a further simplification which is **applicable if the average number of successes is relatively large, but the probability of success is still low**. A graph of a Gaussian distribution function is shown in Figure 3.

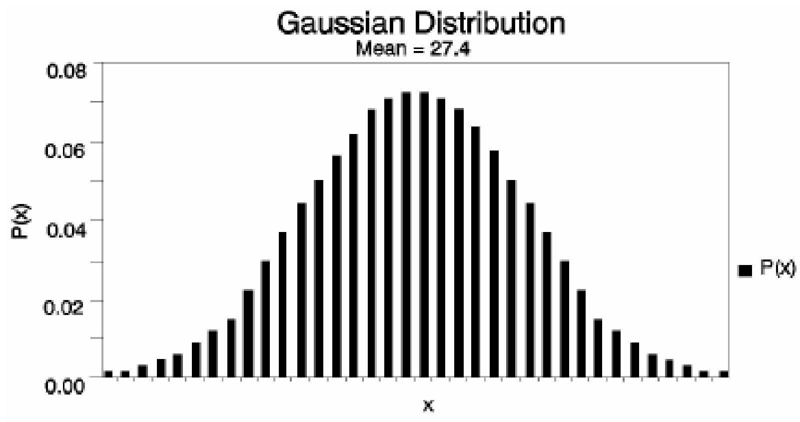

Figure 3. Predicted Successes for Gaussian

Note that the highest number of successes is at the center of the curve, the curve is a bell shaped curve, and the relative change in success from one point to the adjacent is small. Also note that the mean, or average number of successes, is at the highest point, or at the center of the curve.

The Gaussian, or normal, distribution is applied to counting applications where the mean success is expected to be greater than 20. It is used for counting system calibrations and operational checks, as well as for normal samples containing activity. It may or may not include environmental samples (i.e., samples with very low activity).

2.03.02	*State the two purposes for statistical analysis of count room operations.*

APPLICATION OF STATISTICAL MODELS

Application of specific statistical methods and models to nuclear counting operations is termed *counting statistics* and is essentially used to do two things:

- **Predict the inherent statistical uncertainty associated with a single measurement**, thus allowing us to estimate the precision associated with that measurement.
- **Serve as a check** on the normal function of nuclear counting equipment.

2.03.03	*Define the following terms:* *a. mode* *b. median* *c. mean*

DEFINITIONS

Mode An individual data point that is repeated the most in a particular data set.

Median The center value in a data set arranged in ascending order.

Mean The average value of all the values in a data set.

2.03.04	*Given a series of data, calculate mode, median, or mean.*

Student	Test Score
Susan	80
Richard	82
Greg	86
Peter	88
Andrew	90
Wanda	92
Randy	95
Jennifer	95
Sarah	95

Figure 4. Sample Data Set

DETERMINATION OF MODE, MEDIAN, AND MEAN

- Determination of the Mode: In the set of test scores above, a score of 95 occurs (i.e., is repeated) more often than any other score.

- Determination of the Median: In the same set of test scores, this is the score in the middle - where one half of the scores are below, and the other half are above the median. The median for the test scores in Figure 4 is 90.

- Determination of the Mean: This is found by adding all of the values in the set together, and dividing by the number of values in the set. The mean of the nine test scores is 89.

Mean determination is often expressed using special symbols, as illustrated in the following equation:

(Equation 3)
$$\bar{x} = \frac{\Sigma x_i}{n}$$

where:
- $\bar{x}$ = mean (sometimes pronounced "x bar")
- x_i = data point with index i
- n = number of data points
- Σ = summation symbol $\Rightarrow \sum_{i=1}^{n} x_i = x_1 + x_2 + x_3 + \cdots + x_n$

2.03.05	*Define the following terms:*	
	a.	*variance*
	b.	*standard deviation*
2.03.06	*Given the formula and a set of data calculate the standard deviation.*	

VARIANCE AND STANDARD DEVIATION

Using the Gaussian distribution model depicted in Figure 4 (below) we need to define the terms "variance" and "standard deviation," which are both used as descriptors of the spread of the population (or the data set) in a normal distribution.

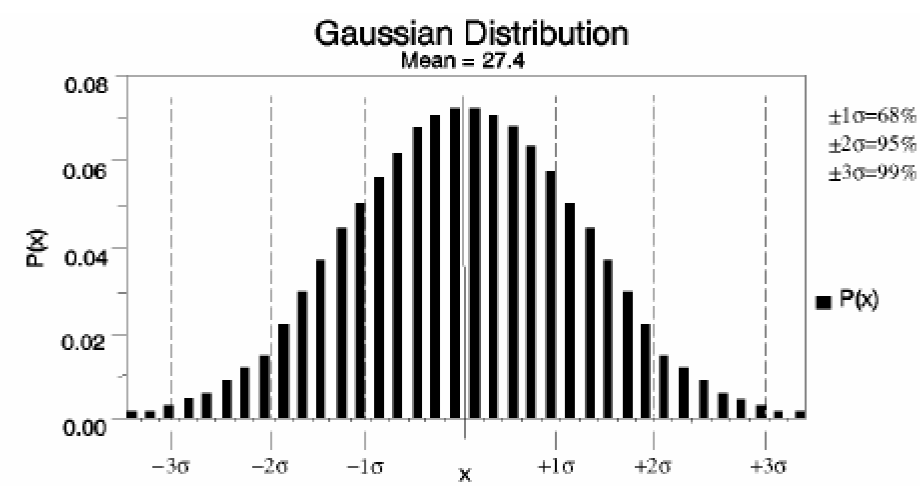

Figure 5. Gaussian Distribution with Standard Deviations

Variance

The amount of scatter of data points around the mean is defined as the sample *variance*. In other words, it tells how much the data "varies" from the mean.

Standard Deviation

Mathematically, a the normal distribution, the standard deviation is **the square root of the variance**. A term more precise than the variance is *standard deviation*, represented by a σ (pronounced "sigma"). The standard deviation of a population is defined mathematically as:

(Equation 4)

$$\sigma = \sqrt{\frac{\Sigma\left(x_i - \bar{x}\right)^2}{n}}$$

where: σ = biased standard deviation of the population
x_i = sample counts for each data point
= mean
n = number of data points

If most of the data points are located close to the mean, the curve will be tall and steep and have a low numerical value for a standard deviation. If data points are scattered, the curve will be lower and not as steep and have a larger numerical value for a standard deviation.

In a Gaussian distribution, it has been determined mathematically that 68.2% of the area under the curve falls within the data point located at the mean ± (plus or minus) one standard deviation (1σ); 95.4% of the area under the curve falls between the data point located at ± two standard deviations (2σ), etc. What this means to us in terms of counting processes is that if the distribution (as depicted in Figure 5) is representative of a counting function with a mean observable success >20 (Gaussian distribution):

- 68.2% of the time the observed successes (or counts) will be within ±1 standard deviation of the mean.
- 95.4% of the time the observed successes (or counts) will be within ±2 standard deviations of the mean.
- 99.97% of the time the observed successes (or counts) will be within ±3 standard deviations of the mean.

Remember, the area of the curve represents the probability of success in a random process. In radiation protection this random process is the decay of a radioactive sample.

The known statistical distribution is used in radiation protection when setting up a counting system and in evaluating its operation by means of daily pre-operational source checks. In performing the calibration of the system, a radioactive source with a known activity is counted twenty times for one minute each time. Using the data from the twenty counts, the mean and standard deviation can be calculated. The mean can then be used to determine the efficiency of the system while allowing for a certain number of standard deviations during operation. The twenty counts can also be used to perform another required test of the system's performance, the chi-squared test (see below).

Example 2.03-1

Calculate the mean and sample standard deviation for the following data set:
{151, 161, 143, 145, 121, 150, 135, 142, 135, 146}.

Using a table or spreadsheet we can arrange the data points and determine the required statistical values:

n	x	$(x - \bar{x})^2$
1	151	65.61
2	161	327.61
3	143	0.01
4	145	4.41
5	121	479.61
6	150	50.41
7	135	62.41
8	142	0.81
9	135	62.41
10	146	9.61

2.03.07	*State the purpose of a Chi-squared test.*

CHI-SQUARED TEST

The *Chi-squared test* (pronounced "ki") is used to determine the *precision* of a counting system. Precision is a measure of exactly how a result is determined without regard to its *accuracy*. It is a measure of the *reproducibility* of a result, or in other words, how often that result can be repeated, or how often a "success" can be obtained.

This test results in a numerical value, called the Chi-squared value (X^2), which is then compared to a range of values for a specified number of observations or trials. This range represents the expected (or predicted) probability for the chosen distribution. If the X^2 value is lower than the expected range, this tells us that there is not a sufficient degree of randomness in the observed data. If the value is too high, it tells us that there is too much randomness in the observed data.

The Chi-squared test is often referred to as a "goodness-of-fit" test. It answers the question: How well does this data fit a Poisson distribution curve? If it does NOT fit a curve indicating sufficient randomness, then the counting instrument may be malfunctioning.

The Chi-squared value is calculated as follows:

(Equation 5)

$$X^2 = \frac{\sum\left(x_i - \bar{x}\right)^2}{\bar{x}}$$

Example 2.03-2

Using the data from Example 2.03-1, determine the Chi-squared value for the data set.

2.03.08	*State the criteria for acceptable Chi-squared values at your site.*

(Insert site-specific information here.)

Assuming a given set of data passes the Chi-squared test, the data can then be used to prepare quality control charts for use in verifying the consistent performance of the counting system.

2.03.09	*State the purpose of creating quality control (QC) charts.*
2.03.10	*State the requirements for maintenance and review of QC charts at*

QUALITY CONTROL CHARTS

Quality control charts are prepared using source counting data obtained during system calibration. The source used for daily checks should be identical to the one used during system calibration. Obviously since this test verifies that the equipment is still operating within an expected range of response, we cannot change the conditions of the test in mid-stream. QC charts, then, enable us to track the performance of the system while in use.

Data that can be used for quality control charts include gross counts, counts per unit time, and efficiency. Most nuclear laboratories use a set counting time corresponding to the normal counting time for the sample geometry being tested. If smears are counted for one minute, then all statistical analysis should be based on one-minute counts.

When the system is calibrated and the initial calculations performed, the numerical values of the mean ± 1, 2, and 3 standard deviations are also determined.

Using standard graph paper, paper designed specifically for this purpose, or a computer graphing software, lines are drawn all the way across the paper at those points corresponding to the mean, the mean plus 1, 2, and 3 standard deviations, and the mean minus 1, 2, and 3 standard deviations. The mean is the center line of the paper.

Quality control charts should be maintained in the area of the radioactivity counting system such that they will be readily accessible to those who operate the system. These charts can then be used by operators to determine if routine, periodic checks (typically daily) have been completed before system use.

(Insert site-specific information here.)

2.03.11	*State the purpose of calculating warning and control limits.*

SYSTEM OPERATING LIMITS

The values corresponding to ±2 and ±3 standard deviations are called the upper and lower *warning* and *control limits*, respectively. The results of the daily source counts are graphed daily in many countrooms. Most of the time our results will lie between the lines corresponding to ±1 standard deviation (68.2%). We also know that 95.4% of the time our count will be between ±2 standard deviations and that 99.97% of the time our count will be between ±3 standard deviations.

Counts that fall outside the warning limit ($\pm 2\sigma$) are not necessarily incorrect. Statistical distribution models say that we should get some counts in that area. Counts outside the warning limits indicate that something MAY be wrong. The same models say that we will also get some outside the control limits ($\pm 3\sigma$). However, not very many measurements will be outside those limits. We use 3σ as the *control* – a standard for acceptable performance. In doing so we say that values outside of $\pm 3\sigma$ indicate unacceptable performance, even though those values may be statistically valid.

True randomness also requires that there be no patterns in the data that are obtained; some will be higher than the mean, some will be lower, and some will be right on the mean.

When patterns do show up in quality control charts, they are usually indicators of systematic error. For example:

- Multiple points outside two sigma
- Repetitive points (*n* out of *n*) outside one sigma
- Multiple points, in a row, on the same side of the mean

- Multiple points, in a row, going up or down.

The assumption is made that systematic error is present in our measurements, and that our statistical analysis has some potential for identifying its presence. However, industry assumption is that systematic error that is present is very small in comparison to random error.

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2.03.12	*State the purpose of determining efficiencies and correction factors.*
2.03.13	*Given counting data and source assay information, calculate efficiencies and correction factors.*

COUNTER EFFICIENCY

A detector intercepts and registers only a fraction of the total number of radiations emitted by a radioactive source. The major factors determining the fraction of radiations emitted by a source that are detected include:

- The fraction of radiations emitted by the source which travel in the direction of the detector window
- The fraction emitted in the direction of the detector window which actually reach the window
- The fraction of radiations incident on the window which actually pass through the window and produce an ionization
- The fraction scattered into the detector window

All radiation detectors will, in principle, produce an output pulse for each particle or photon which interacts within its active volume. The detector then would be said to be 100 percent "efficient," because 100 percent of the activity was detected and reported. In practice, because of the factors outlined above, the actual (or total) activity emitted from the source is not detected. Therefore, there is only a certain fraction of the disintegrations occurring that results in counts reported by the detector. Using a calibrated source with a known activity, a precise figure can be determined for this fraction. This value can then be used as a ratio in order to relate the number of pulses counted to the number of particles and/or photons incident on the detector. This ratio is called the *efficiency*. It can also be referred to as the *detector yield*, since the detector yields a certain percentage of the actual counts.

The detector efficiency gives us the fraction of counts detected per disintegration, or c/d. Since activity is the number of disintegrations per unit time, and the number of counts are detected in a finite time, the two rates can be used to determine the efficiency if both rates are in the same units of time. Counts per minute (cpm) and disintegrations per minute (dpm) are the most common.

Thus, the efficiency, ***E***, can be determined as shown in Equation 6. Used in this manner the time units will cancel, resulting in counts/disintegration (c/d).

(Equation 6)

$$E = \frac{cpm}{dpm} = \frac{c}{d}$$

The efficiency obtained in the formula above will be in fractional or decimal form. To calculate the *percent efficiency*, the fraction can be multiplied by 100. For example, an efficiency of 0.25 would mean 0.25 × 100, or 25%.

Example 2.03-3

A source is counted and yields 2840 counts per minute. If the source activity is known to be 12,500 dpm calculate the efficiency and percent efficiency.

By algebraic manipulation, Equation 6 can be solved for the disintegration rate (see Equation 7). The system efficiency is determined as part of the calibration. When analyzing samples, a count rate is reported by the counting system. Using Equation 7, the activity, (***A***), of the sample can then be determined in dpm, and then converted to any other units of activity (e.g., Ci, Bq).

(Equation 7)

$$dpm = \frac{cpm}{E} \longrightarrow A_{dpm} = \frac{cpm}{E}$$

Example 2.03-4

A sample is counted on a system with a 30% efficiency. If the detector reports 4325 net counts per minute what is the activity of the sample in dpm?

As seen in Equation 7 above, the net count rate is divided by the efficiency. A *correction factor* (CF), which is simply **the inverse of the efficiency**, is used by multiplying it by the net count rate to determine the activity, as in Equation 8.

(Equation 7)

$$CF = \frac{1}{E}$$

Example 2.03-5

An instrument has an efficiency of 18%. What is the correction factor?

This <u>count-rate correction factor</u> should not to confused with a <u>geometry correction factor</u> used with some radiation instruments, such as the beta correction factor for a Cutie Pie (RO-3C).

2.03.14 State the meaning of counting data reported as x.xx ± yy.

2.03.15 Given counting results and appropriate formulas, report results to desired confidence level.

ERROR CALCULATIONS

The error present in a measurement governed by a statistical model can be calculated using known parameters of that model. Nuclear laboratories are expected to operate at a high degree of precision and accuracy. However, since we know that there is some error in our measurements, we are tasked with reporting measurements to outside agencies in a format that identifies that potential error. The format that is used should specify the activity units and a range in which the number must fall. In other words, the results would be reported as a given activity plus or minus the error in the measurement. Since nuclear laboratories prefer to be right more than they are wrong, counting results are usually reported in a range that would be correct 95% of the time, or at a 95% *confidence level*.

In order to do this, the reported result should be in the format:

(Equation 9)

$$x.xx \pm yy\ (K\sigma)$$

where:	**x.xx**	=	measured activity, in units of dpm, Ci, or Bq
	yy	=	associated potential (or possible) error in the measurement
	K	=	multiple of counting error
	σ	=	standard deviation at stated confidence level (CL)

Note: Use of Kσ is only required for confidence levels other than 68% (see Table 4). Therefore:

σ	$= 1\times \sigma$	68% CL	(optional)
1.64σ	$= 1.64 \times \sigma$	90% CL	(sometimes used)
2σ	. $1.96 \times \sigma$	95% CL	(normally used)

For example, a measurement of **150 ± 34 dpm (2σ)** indicates the activity as 150 dpm; however, it could be as little as 116 dpm or as much as 184 dpm with 95% confidence (at 2σ).

The calculations of the actual range of error is based on the standard deviation for the distribution. In the normal (or Gaussian) distribution, the standard deviation of a single count is defined as the square root of the mean, or $\sigma = \sqrt{x}$. The error, e, present in a single count is some multiplier, K, multiplied by the square root of that mean, i.e., some multiple times the standard deviation, Kσ. The value of K used is based on the confidence level that is desired, and is derived from the area of the curve included at that confidence level (see Figure 5). Common values for K include:

Table 4. Counting Error Multiples

Error	**Confidence Level**	**K**
Probable	50%	0.6745
Standard	68%	1.0000
9/10	90%	1.6449
95/100	95%	1.9600
99/100	99%	2.5750

To calculate the range to the point at which you would expect to be right 95% of the time, you would multiply the standard deviation by 1.96, and report the results of the measurement as *x.xx* dpm ± *yy* dpm (2Φ). Note that using a 68% or 50% confidence level introduces an expected error a large percentage of the time. Therefore, for reasonable accuracy a higher confidence level must be used.

The simple standard deviation (σ) of the single count (***x***) is usually determined as a count rate (counts per unit time). This is done by dividing the count rate (***R***) by the count time (***T***). Subscripts can be applied to distinguish sample count rates from background count rates.

(Equation 10) $$\sigma = K\sqrt{\frac{R}{T}}$$

Example 2.03-6

The count rate for a sample was 250 cpm. Assume 10 minute counting time, zero background counts and a 25% efficiency. Report sample activity at a 95% C.L.

2.03.16	*State the purpose of determining background.*

BACKGROUND

Determination of Background

Radioactivity measurements cannot be made without consideration of the background. *Background*, or background radiation, is the radiation that enters the detector concurrently with the radiation emitted from the sample being analyzed. This radiation can be from natural sources, either external to the detector (i.e., cosmic or terrestrial) or radiation originating inside the detector chamber that is not part of the sample.

In practice, the total counts are recorded by the counter. This total includes the counts contributed by both the sample and the background. Therefore, the contribution of the background will produce an error in radioactivity measurements unless the background count rate is determined by a separate operation and subtracted from the total activity, or *gross count rate*. The difference between the gross and the background rates is called the *net count rate* (sometimes given units of **ccpm**, or corrected counts per minute). This relationship is seen in the following equation:

(Equation 11)
$$R_S = R_{S+B} - R_B$$

where:

R_S	=	net sample count rate (cpm)
R_{S+B}	=	gross sample count rate (cpm)
R_B	=	background count rate (cpm)

The background is determined as part of the system calibration by counting a background (empty) planchet for a given time. The background count rate is determined in the same way as any count rate, where the gross counts are divided by the count time, as seen in Equation 12 below.

(Equation 12)
$$R_B = \frac{N_B}{T_B}$$

where:

R_B	=	background count rate (counts per time, i.e., cpm)
N_B	=	gross counts, background
T_B	=	background count time

For low-background counting systems two background values must be determined: one for alpha and one for beta-gamma. These two values are used to determine background alpha and beta-gamma sample count rates, respectively, during calibration and when analyzing samples.

In practice, background values should be kept as low as possible. As a guideline, background on automatic counting systems should not be allowed to exceed 0.5 cpm alpha and 1 cpm beta-gamma. If system background is above this limit the detector should be cleaned or replaced.

Reducing Background

Typically, the lower the system background the more reliable the analysis of samples will be. In low-background counting systems the detector housing is surrounded by lead shielding so as to reduce the background. Nonetheless, some background still manages to reach the detector. Obviously, little can be done to reduce the actual source of background due to natural sources. On many systems a second detector is incorporated to detect penetrating background radiation. When a sample is analyzed the counts detected by this second detector during the same time period are internally subtracted from the gross counts for the sample.

Background originating inside the detector chamber can be, for the most part, more easily controlled. The main contributors of this type of background are:

- Radiation emitted from detector materials
- Radioactive material on inside detector surfaces
- Radioactive material on the sample slide assembly
- Contamination in or on the sample planchet or planchet carrier

There are, unfortunately, trace amounts of radioisotopes in the materials of which detectors and their housings are made. This is simply a fact of life in the atomic age. However, the contribution to background from this source is negligible, but should nonetheless be acknowledged.

Radioactive material can be transferred from contaminated samples to the inside surfaces of the detector chamber during counting. This usually occurs when samples having gross amounts of material on them are counted in a lowbackground system. During the insertion and withdrawal of the sample into the detector chamber, loose material can be spread into the chamber. In order to prevent this, these samples should be counted using a field survey instrument or a mini-scaler. Low-background systems are designed for counting lower-activity samples. Counting of a high-activity sample on these systems should be avoided unless it is a sealed radioactive source.

Radioactive material can also be transferred from contaminated samples to the slide assembly upon which samples are inserted into, and withdrawn from, the detector chamber.

This can be prevented in the same way as stated above. In addition, when loading and stacking samples for counting, ensure that the slide assembly cover is in place. The slide assembly should also be cleaned on a routine basis (i.e., weekly).

When loading and unloading samples into and from planchets, material from the samples can be spread to the planchet and/or the carrier. Most smears and air samples are 47-mm diameter and are counted in a planchet that is almost the same size. The planchet is placed in a carrier which surrounds and supports the planchet and allows for automatic sample exchange by the counting system. When a sample is counted, the entire carrier is placed under the detector window inside the detector chamber. Any contamination on the carrier (or in the planchet) is counted with, and attributed to, the sample.

A paper disc can be placed in the bottom of the planchet as a step in preventing transfer of material from samples to the planchet. Care should be taken when loading and unloading samples such that material remains on the sample media.

2.03.17	*State the method and requirements for determining background for counting systems at your site.*

(Insert site-specific information here.)

2.03.18	*State the purpose of performing planchet maintenance.*

PLANCHET MAINTENANCE

Planchets and carriers should be inspected, cleaned, and counted on a routine basis. All in-use planchets and carriers must read less than established site limits. Planchets exceeding these limits should be decontaminated and recounted as necessary.

By maintaining planchets clean and as free from contamination as possible, sample result reliability will be increased because the amount of error introduced in the sample analysis will be reduced.

2.03.19	*State the method and requirements for performing planchet maintenance for counting systems at your site.*

PROPAGATION OF ERROR

The error present in a measurement includes the error present in the sample count, which contains both sample and background, and the error present in the background count. Rules for propagation of error preclude merely adding the two errors together. The total error in the measurement is calculated by squaring the error in the background and adding that to the square of the error in the sample count, and taking the square root of the sum, as shown in Equation 13.

(Equation 13)

$$e_S = \sqrt{e_{S+B}^2 + e_B^2}$$

where:

e_S	=	error present in the measurement (sample)
e_{S+B}	=	error in sample count (sample plus background)
e_B	=	error present in background count

Since we normally use this equation in terms of a count rate, the formula is slightly modified as follows, and the error stated as the *sample standard deviation* (σ_S):

(Equation 14)

$$K\sigma_S = K\sqrt{\frac{R_{S+B}}{T_S} + \frac{R_B}{T_B}}$$

where:

R_{S+B}	=	gross sample count rate (sample plus background)
R_B	=	background count rate
T_S	=	sample count time
T_B	=	background count time
K	=	confidence level multiple (see Table 4)

The error in the sample count is the standard deviation of the count, which is the square root of that count (see Equation 13 above). If we square a square root we get the number we started with.

Example 2.03-7

An air sample is counted and yields 3500 counts for a 2-minute count period. The system background is 10 cpm determined over a 50-minute count time. Determine the error in the sample and report the net count rate to 95% confidence level.

If the sample counting time and the background counting time is the same, the formula can be simplified even more to:

(Equation 15)

$$K\sigma_s = K\sqrt{\frac{R_{S+B} + R_B}{T}}$$

Example 2.03-8

A long-lived sample is counted for one minute and gives a total of 562 counts. A one minute background gives 62 counts. Report net sample count rate to 95% CL.

2.03.20	*Explain the methods used to improve the statistical validity of count room measurements.*

IMPROVING STATISTICAL VALIDITY OF COUNT ROOM MEASUREMENTS

Minimizing the statistical error present in a single sample count is limited to several options. If we look at the factors present in the calculation below (same as Equation 14), we can see that there are varying degrees of control over these factors. The standard deviation is calculated here in terms of count rate.

$$\sigma rate = \sqrt{\frac{R_{S+B}}{T_S} + \frac{R_B}{T_B}}$$

R_{S+B} is the sample count rate. <u>We really have no control over this</u>.

R_B is the background count rate. <u>We **do** have some control over this</u>. On any counting equipment the **background should be maintained as low as possible**. In most of our counting applications, however, the relative magnitude of the background count rate should be extremely small in comparison to the sample count rate if proper procedures are followed. This really becomes an issue when counting samples for free release or environmental samples. However, **some reduction in error can be obtained by increasing the background counting time**, as discussed below.

T_B and T_S are the background and sample counting times, respectively. These are the factors that we have absolute control over. In the previous section we talked about the reliability of the count itself. We have been able to state that a count under given circumstances may be reproduced with a certain confidence level, and that the larger the number of counts the greater the reliability. The condition we have been assuming is that our count is taken within a given time. In order to get more precise results, many counts must be observed. Therefore, if we have low count rates, the counting time must be increased in order to obtain many counts, thereby making the result more precise (or reproducible).

The total counting time required depends upon both the sample and background count rates. For high sample activities the sample count time can be relatively short compared to the background count time. For medium count rates we must increase the sample count time in order to increase precision. As the sample activity gets even lower, we approach the case where we must devote equal time to the background and source counts. In other words, **by counting low activity samples for the same amount of time as that of the background determination**, we increase the precision of our sample result. However, we must never count a sample for a period of time longer than that of the system background.

In summary, by minimizing the potential error present, we improve statistical validity of our measurements.

2.03.21	*Define "detection limit," and explain the purpose of using detection limits in the analysis of radioactive samples.*

DETECTION LIMITS

The *detection limit* of a measurement system refers to the statistically determined quantity of radioactive material (or radiation) that can be measured (or detected) at a preselected confidence level. This limit is a factor of both the instrumentation and technique/procedure being used.

The two parameters of interest for a detector system with a background response greater than zero are (see Figure 6):

L_C Critical detection level: the response level at which the detector output can be considered "above background"

L_D Minimum significant activity level, i.e., the activity level that can be seen with a detector with a fixed level of certainty

These detection levels can be calculated by the use of Poisson statistics, assuming random errors and systematic errors are separately accounted for, and that there is a background response. For these calculations, two types of statistical counting errors must be considered quantitatively in order to define acceptable probabilities for each type of error:

Type I - occurs when a detector response is considered above background when in fact it is not (associated with L_C)

Type II - occurs when a detector response is considered to be background when in fact it is greater than background (associated with L_D)

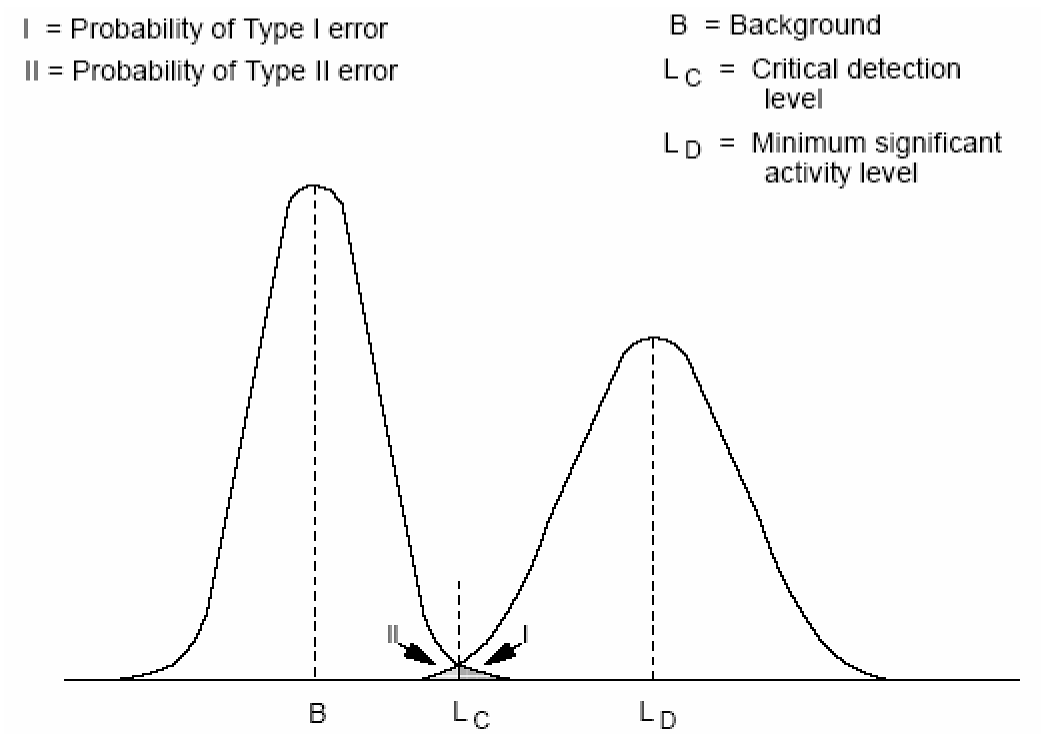


Figure 6. Errors in Detection Sensitivity

If the two probabilities (areas labeled **I** and **II** in Figure 6) are assumed to be equal, and the background of the counting system is not well-known, then the critical detection level (L_C) and the minimum significant activity level (L_D) can be calculated. The two values would be derived using the equations $L_C = k\sigma_B$ and $L_D = k^2 + 2k\sigma_B$, respectively. If 5% false positives (Type I error) and 5% false negatives (Type II error) are selected to be acceptable levels, i.e., 95% confidence level, then k = 1.645 and the two equations can be written as:

(Equation 16) $$L_C = 1.645\sqrt{\frac{R_B}{T_B} + \frac{R_B}{T_S}}$$

(Equation 17) $$L_D = 2.71 + 3.29\sqrt{\frac{R_B}{T_B} + \frac{R_B}{T_S}}$$

where:	L_C	=	Critical detection level
	L_D	=	*a priori* detection limit [minimum significant activity level
	k	=	Poisson probability sum for **I** and **II** (assuming **I** and **II** probabilities are equal)
	R_B	=	background count rate
	T_B	=	background count time
	T_S	=	sample count time

The minimum significant activity level, L_D, is the *a priori* (before the fact) activity level that an instrument can be expected to detect 95% of the time. In other words, it is the smallest amount of activity that can be detected at a 95% confidence level. When stating the detection capability of an instrument, this value should be used.

The critical detection level, L_C, is the lower bound on the 95% detection interval defined for L_D, and is the level at which there is a 5% chance of calling a background value "greater than background." This value (L_C) should be used when actually counting samples or making direct radiation measurements. Any response above this level should be counted as positive and reported as valid data. This will ensure 95% detection capability for L_D.

If the sample count time (T_S) is the same as the background count time (T_B), then equations 16 and 17 can be simplified as follows:

(Equation 18) $$L_C = 2.32\sqrt{\frac{R_B}{T}}$$

(Equation 19) $$L_D = 2.71 + 4.65\sqrt{\frac{R_B}{T}}$$

where:	L_C	=	Critical detection level (count rate)
	L_D	=	Minimum significant activity level (count rate)
	k	=	same as above; 1.645 for 95% CL
	R_B	=	background count rate
	T	=	count time (sample and background)

Therefore, the full equations for L_C and L_D must be used for samples with count times differing from the background determination time (95% CL used). These equations assume that the standard deviation of the sample planchet/carrier background during the sample count (the planchet/carrier assumed to be 0 activity) is equal to the standard deviation of the system background (determined using the background planchet/carrier).

The critical detection level, L_C, is used when reporting survey results. It is used to say that at a 95% confidence level, samples above this value are radioactive. This presupposes, then, that 5% of the time clean samples will be considered radioactive.

The minimum significant activity level, L_D, [also referred to as the LLD (Lower Limit of Detection) in some texts] is calculated prior to counting samples. This value is used to determine minimum count times based on release limits and airborne radioactivity levels. In using this value we are saying that at a 95% CL, samples counted for at least the minimum count time calculated using the L_D that are positive will indeed be radioactive (above the L_C). This presupposes, then, that 5% of the time samples considered clean will actually be radioactive.

Example 2.03-9

A background planchet is counted for 50 minutes and yields 16 counts. Calculate the critical detection level and the minimum significant activity level for a 0.5 minute sample count time.

2.03.22 Given the formula and necessary information, calculate detection limit values for counting systems at your site.

(Insert site-specific information here.)

2.03.23 State the purpose and method of determining crosstalk.

CROSSTALK

<u>Discrimination</u>

Crosstalk is a phenomenon that occurs on proportional counting systems (such as a Tennelec) that employ electronic, pulse-height discrimination, thereby allowing the simultaneous analysis for alpha and beta-gamma activity. Discrimination is accomplished by establishing two thresholds, or *windows*, which can be set in accordance with the radiation energies of the isotopes of concern. Recall that the pulses generated by alpha radiation will be much larger than those generated by beta or gamma. This makes the discrimination between alpha and beta-gamma possible. Beta and gamma events are difficult to distinguish; hence, they are considered as one and the same type by such counting systems.

In practice, the lower window is set such that electronic noise and ultra-low-energy photon events are filtered out. Any pulse generated whose size is greater than the setting for the lower window is considered an event, or a *count*. The upper window is then set such that any pulses which surpass the upper discriminator setting will be considered an alpha count (see Figure 7).

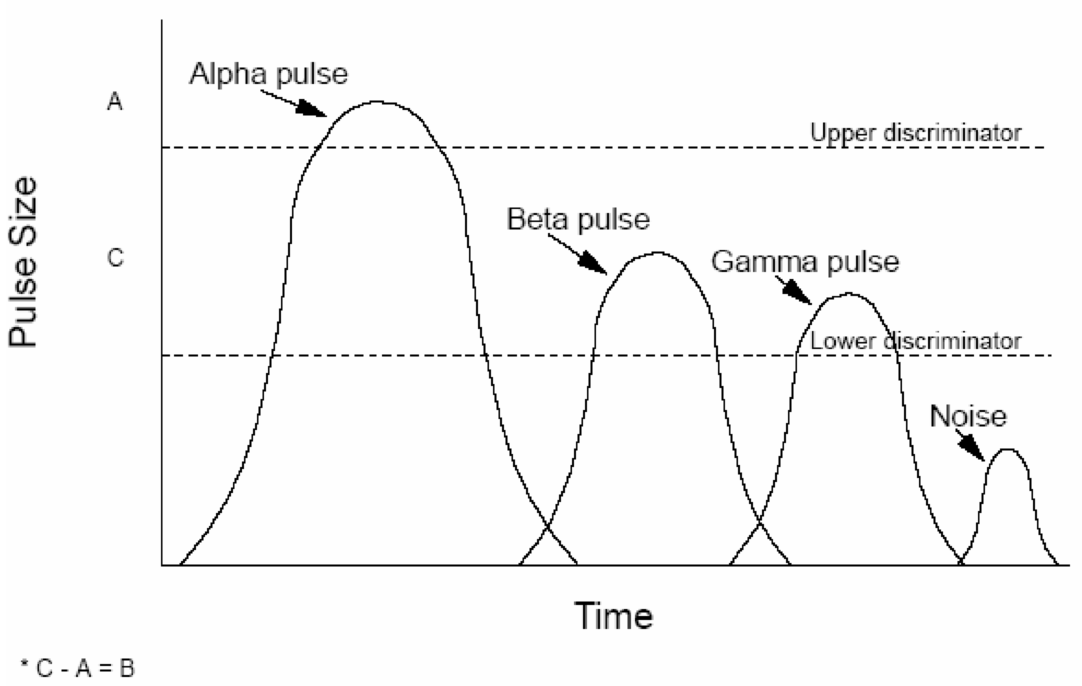


Figure 7. Pulse-height Discrimination

For output purposes, the system routes each count to a series of *channels* which simply keep a total of the counts routed to them. Channel A is for alpha counts, Channel B is beta-gamma counts, and Channel C is total counts. As a sample is being counted, all valid counts registered (i.e., those which surpass the lower discriminator setting) are routed to the C-channel. In addition, if the count was considered an alpha count (i.e., it surpassed the upper discriminator setting) it is routed to the A-channel; else it is tallied in the B-channel. In effect, what occurs is that the number of beta-gamma counts (Channel B) are determined by subtracting the number of alpha counts (Channel A) from the total counts (Channel C), or $\boldsymbol{B = C - A}$.

Origin of Crosstalk

Now that we understand the process involved, there is a dilemma that stems from the fact that events are identified by the system as either alpha or beta-gamma according to the size of the pulse generated inside the detector. The system cannot really tell what type of radiation has generated the pulse. Rather, the pulse is labeled as "alpha" or "beta-gamma" by comparing the size of the pulse to the discriminator setting. It is the setting of the discriminator that poses the dilemma.

Alpha particles entering the detector chamber generally are attenuated by the detector fill-gas because of their high LET, thereby producing a large pulse. Low-energy beta particles and photons will also lose all their energy within the detector gas, but nevertheless produce a smaller pulse because of their lower energies. High energy beta particles can still retain some of their energy even after having produced a pulse while traversing the detector volume. Rather than leaving the detector, as would a photon, the beta is reflected off of the detector wall and reenters the volume of gas, causing ionizations and generating a second pulse. These two pulses can be so close together that the detector sees them as one large pulse. Because of the large pulse size it can surpass the upper discriminator setting and is, therefore, counted as an alpha, and not as a beta. The result is that alpha activity can be reported for a sample when in fact there was little or no alpha present. Conversely, if a true alpha-generated pulse is not large enough so as to exceed the upper discriminator, it would be counted as a beta-gamma event. This is *crosstalk*.

The solution is not a simple one. The setting of the upper discriminator depends on the radiations and energies of the sources and samples being analyzed. If high energy beta radiations are involved, a significant portion of them could be counted as alpha events if the setting is too low. If the setting is too high, lower-energy alpha events could be counted as beta-gamma. Typically, the setting of the discriminator will usually be some "happy medium." A discussion of how this can be dealt with is in order.

Calibration Sources and Crosstalk

For calibrations of Tennelec counting systems, the manufacturer provides the following general recommendations for discriminator settings: First, using a Strontium-90 beta source, set the upper (∀) discriminator such that there is 1% beta-to-alpha crosstalk.

Then, using a Polonium-210 alpha source, set the ∀+∃ discriminator such that there is less than 3% alpha-to-beta crosstalk.

Energies of sources used to calibrate counting systems should be the same as, or as close as possible to, the energies of isotopes in the samples analyzed. Wherever possible they should be a pure emitter of the radiation of concern.

For beta-gamma sources the most popular isotope in radiation protection is Sr-90. It has a relatively long half-life of 29.1 years, but emits betas of only 546 keV. However, Sr-90 decays to Yttrium-90, another beta emitter which has a short half-life of only 2.67 days and emits a 2.281 MeV beta. Y-90 decays to Zirconium-90m which emits a 2.186 Mev gamma almost instantaneously to become stable. The daughters reach equilibrium with the strontium parent within a number of hours after source assay. Hence, for every Sr beta emitted a Y beta is also emitted, thereby doubling the activity. These sources are often listed as **Sr/Y-90** for obvious reasons. This makes Sr/Y-90 sources an excellent choice and are used by many sites for calibrations and performance testing.

Po-210 is essentially a pure alpha emitter. This is primarily the reason why it is recommended for calibrations and performance testing. It yields a strong alpha, but it also has a short half-life. A comparison of some alpha emitters is given in Table 5.

Table 5. Alpha Emitters

Isotope	**Half-Life**	**Energy (MeV)**
Po-210	138.38 days	5.3044
Pu-239	2.4E4 years	5.156, 5.143, 5.105
Ra-226	1.60E3 years	4.78, 4.602
Th-230	7.54E4 years	4.688, 4.621
Natural U	4.4E9 years (avg.)	4.2 (avg.)

2.03.24 State the criteria for acceptable values of crosstalk for counting systems at your site.

(Insert site-specific information here.)

2.03.24	*State the criteria for acceptable values of crosstalk for counting systems at your site.*

VOLTAGE PLATEAUS

Very simply put, a *voltage plateau* is a graph that indicates a detector's response to an isotope with variations of high voltage. The x-axis represents the high voltage and the y-axis the response (i.e., counts). The resulting curve gives an indication of detector quality, and can indicate problems with the counting gas should they be present. The curve can also be used to determine the optimum operating high voltage for the system.

Most automatic low-background counting systems provide several different analysis modes. These modes count samples at certain pre-determined voltages. Counting systems generally provide three analysis modes:

- ALPHA ONLY
- ALPHA THEN BETA
- ALPHA AND BETA (SIMULTANEOUS)

There are usually two voltage settings used in conjunction with these analysis modes:

- **Alpha** voltage (lower)
- [Alpha plus] **Beta** voltage (higher)

Recall that in a proportional counter the amount of voltage determines the amount of gas multiplication. Because of the high LET of alpha radiation, at a lower voltage, even though the gas amplification will be lower, alpha pulses will still surpass the lower discriminator and some will even pass the upper discriminator. Because of the lower gas amplification beta-gamma pulses will not be large enough to be seen. Therefore, any counts reported for the sample will be alpha counts.

In the ALPHA ONLY mode, the sample is counted once, at the alpha voltage. Counts may appear in either the A or B channels. Upon output, the A and B channels will be added together and placed in Channel A and, therefore, reported as alpha counts; the B channel will be cleared to zero, thereby resulting in no beta-gamma counts.

In the ALPHA THEN BETA mode, the sample is counted twice. The first count interval determines the alpha counts using the alpha voltage. The second count is done at the beta voltage. The determination of alpha and beta-gamma counts in this mode is based strictly on the operating characteristics of the detector at the different voltages. For this reason, the A and B counts are summed during both counting intervals to attain the total counts. The separation of alpha and beta-gamma counts is then calculated and reported according to the following formula:

(Equation 20)

$$\alpha = \frac{A_1 + B_1}{CF_\alpha}$$

$$\beta = \left(A_2 - B_2\right) - \alpha$$

where:

α	=	reported gross alpha counts
β	=	reported gross beta-gamma counts
A_1,B_1	=	accumulated channel counts respectively, 1st interval
A_2,B_2	=	accumulated channel counts respectively, 2nd interval
CF_α	=	alpha correction factor (ratio of alpha efficiency at alpha voltage to efficiency at beta voltage)

In the ALPHA AND BETA (SIMULTANEOUS) mode, the sample is counted once using the beta voltage. Alpha events are reported in the A channel, while beta-gamma counts are reported in the B channel. This is the mode used most often.

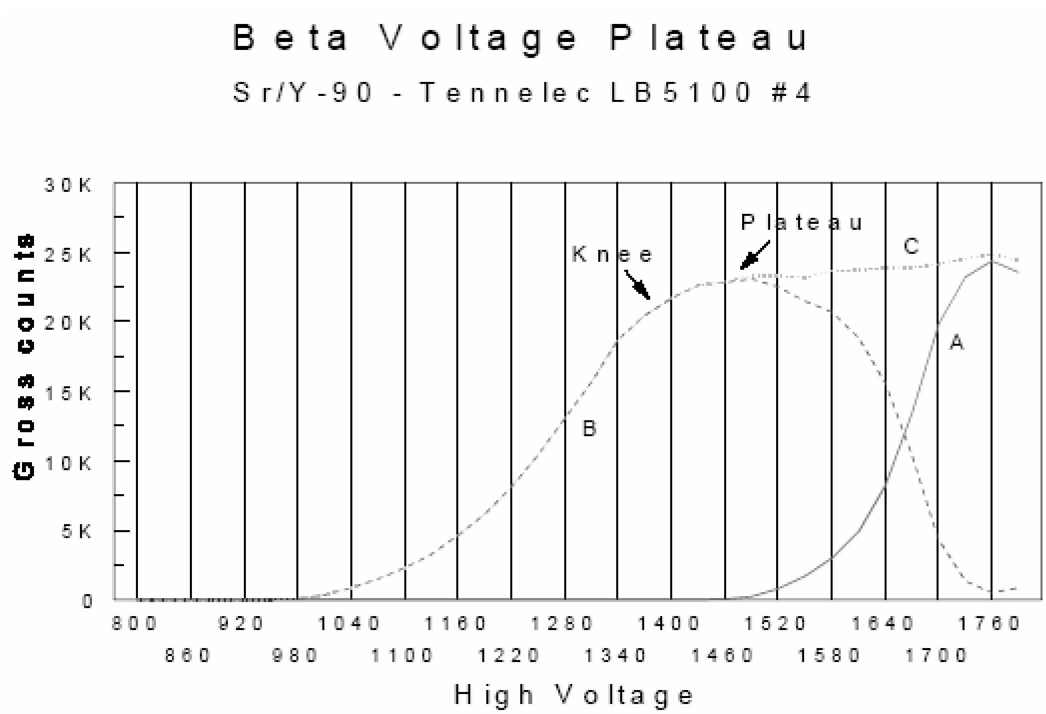
As can be seen, the setting of the two voltages will have a direct impact on the number of counts reported for a given sample. The determination of what these voltage settings should be must be done such that the optimum performance of the detector is obtained for those voltage regions. This is the purpose of a plateau.

2.03.26 State the method of performing a voltage plateau on counting systems at your site.

(Insert site-specific information here.)

In conjunction with initial system setup and calibration by the vendor, two voltages plateaus are performed--alpha voltage and beta voltage. For P-10 gas the alpha plateau is started at about 400 volts and the beta plateau at about 900 volts. Alpha and beta plateaus are defined by the isotope being used and not by the channel being used to accumulate the counts. More appropriately, the gross counts are accumulated and plotted for each type of isotope. Each time that a count is completed, the high voltage is incremented a specific amount, typically 25 to 50 volts, and another count is accumulated. This is repeated until the end of the range is reached, typically about 1800 volts.

With the high voltage set at the starting point, few or no counts are observed because of insufficient ion production within the detector. As the voltage is increased, a greater number of pulses are produced with sufficient amplitude to exceed the discriminator threshold, and are then accumulated in the counter. There will be a high voltage setting where the increase in counts levels off (see Figure 8). This area is the detector plateau. Further increases in high voltage result in little change in the overall count rate. The plateau should remain flat for at least 200 volts using a Sr/Y-90 source, and this indicates the plateau length. Between 1750 and 1850 volts the count rate will start to increase dramatically. This is the avalanche region, and the high voltage should not be increased any further.



The region where the counts level off is called the *knee* of the plateau. The operating voltage is chosen by viewing the plateau curve and selecting a point 50 to 75 volts above the knee and where the slope per 100 volts is less than 2.5%. This ensures that minor changes in high voltage will have negligible effects on the sample count. Poor counting gas or separation of the methane and argon in P-10 can result in a very high slope of the plateau. Upon initial system setup and calibration the vendor determines and sets the optimum operating voltages for the system. Thereafter, plateaus should be generated each time the counting gas is changed.

SUMMARY

This lesson addressed the measures used to minimize error and the fundamentals of binomial statistics, as well as the application of these fundamentals in a nuclear counting environment. Completion of the unit does not qualify the student to perform any tasks independently.

EXAMPLE PROBLEM SOLUTIONS

2.03-1

σ	$\bar{x}$	$\Sigma\left(x-\bar{x}\right)^2$
10.31	142.9	1062.9

Therefore, the mean of the set is found to be 142.9, and the standard deviation is 10.31.

2.03-2

$$\mathrm{X}^2 = \frac{1062.9}{142.9} = 7.44$$

2.03-3

$$E = \frac{2840}{12500}$$
$$E = 0.2272$$
$$0.2272 \times 100 = 22.72\%$$

2.03-4

$$A = \frac{4325}{0.3} = 14416.7 dpm$$

2.03-5

$$CF = \frac{1}{0.18} = 5.\bar{5}$$

2.03-6

$$2\sigma = 1.26\sqrt{\frac{250}{10}} = 1.96\sqrt{25}$$
$$2\sigma = 1.96(5) = 9.8$$
$$\frac{250cpm}{0.25cld} = 1000dpm$$
$$\frac{9.8cpm}{0.25cld} = 39dpm$$

2.03-7

$$\frac{3500counts}{2minutes} = 1750 - 10 = 1740cpm$$
$$\sigma_5 = \sqrt{\frac{1750}{2} + \frac{0.2}{50}} = 29.6$$
$$2\sigma_5 = 29.6 \times 1.96 = 58$$

$$R_{S+B} = \frac{3500counts}{2minutes} = 1750cpm$$
$$R_B = \frac{10counts}{50\min utes} = 0.2cpm$$
$$R_S = 1749.8cpm$$
$$T_S = 2minutes$$
$$T_B = 50minutes$$

Therefore, the net count rate should be reported as:

$$500 \pm 49cpm(2\sigma)$$

2.03-8

$$2\sigma_5 = 1.96\sqrt{\frac{562+62}{1}}$$
$$2\sigma_5 = 1.96\sqrt{624}$$
$$2\sigma_5 = 1.96(24.98)$$
$$2\sigma \ = 49$$

$$R_S = 562 - 62 = 500cpm$$

Therefore, the net sample count rate and associated error is:

$$500 \pm 49\text{cpm}(2\sigma)$$

2.03-9

$$L_C = 1.645\sqrt{\frac{0.32}{50} + \frac{0.32}{0.5}}$$
$$L_C = 1.645\sqrt{0.0064 + 0.64}$$
$$L_C = 1.645\sqrt{0.6464}$$
$$L_C = 1.32cpm$$

$$L_D = 2.71 + 3.29\sqrt{\frac{0.32}{50} + \frac{0.32}{0.5}}$$
$$L_D = 2.71 + 3.29(0.804)$$
$$L_D = 5.36cpm$$