Rad Measurements Laboratory
Counting Instruments

ACADs (08-006) Covered

3.2.3.8.1 3.2.3.8.2 3.2.8.3.3 3.2.3.8.4 3.2.3.17 3.2.3.20

3.2.5.2 3.2.5.3 3.2.5.5 3.2.5.6

Keywords

Detectors, gas-filled detectors, counter-scaler scintillation detectors, count-time, voltage maximum, observed vs expected frequencies, counting efficiency, minimum detectable activity, sample radioactivity, calibration curve.

Description

This lesson addresses the general procedures for performing radiation calibration, calculating efficiency and calculating a plotted curve.

Supporting Material

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I. PROGRAM: Radiological Protection Technician Initial Training

II. COURSE: Specialty Area Training – Instrumentation and Respiratory Protection

III. TITLE: Laboratory Instrumentation

IV. LENGTH OF LESSON: 16 hours

V. TRAINING OBJECTIVES

A. Terminal Objective

Upon completion of this module, participants will demonstrate knowledge of the radiation counting instrumentation used in site Radcon laboratories. A score of $\geq$ 80% must be achieved on a written examination.

B. Enabling Objectives

Standards and conditions apply to all enabling objectives. They include the training participant's ability to utilize, under the examination ground rules (i.e. without the use of training materials or outside assistance), the information presented in this lesson plan.

1. Name the two types of detectors primarily used for counter-scalers in Radcon laboratories.
2. Identify the three types of gas-filled detectors.
3. Name the two materials generally used in laboratory counter-scaler scintillation detectors.
4. Identify the radioisotopes used for beta and alpha sources, respectively, in reliability testing Radcon laboratory counter-scalers.
5. State the maximum voltage which should be applied to GM and scintillation detectors and tell why these levels should not be exceeded.
6. State the count time generally used to determine laboratory counter-scaler background.
7. Name the test used to test whether the observed frequencies differ significantly from the expected frequency for laboratory counter-scaler instruments.
8. Identify the equation used in evaluating the statistical test for determining if the observed frequencies differ significantly from the expected frequency.
9. State the expected value for χ^2 when the predicted and observed values are not equal.
10. Define counting efficiency.
11. Define Minimum Detectable Activity.

12. Identify the conditions that indicate the presence of radioactivity on a sample.

VI. TRAINING AIDS

A. Whiteboard with markers.
B. Projector and Screen
C. Power Point Presentation of Key Points
D. Laser Pointer (optional)
E. Counter-Scalers, Ludlum 2200, or equivalent, with detectors.
F. Radiation sources for use with the scalers.
G. Computers with Power Point and Excel capability.

TRAINING MATERIALS:

A. Appendices
  1. Handouts
    a. HO-1 – Enabling Objectives.
    b. HO-2 – Voltage Plateau and Slope Determination Data.
    c. HO-3 – Chi-Square Test and Efficiency Determination Data.
    d. HO-4 – Source Check Limit Determination Worksheet.
    e. HO-5 – Minimum Detectable Count/Activity Worksheet.
    f. HO-6 – Voltage Plateau and Slope Determination Worksheet.
    g. HO-7 – Chi-Square Test and Efficiency Determination Worksheet.

  2. Voltage Plateau and Slope Determination Answer Sheet.
  3. Chi-Square Test and Efficiency Determination Answer Sheet.
  4. Source Check Limit Determination Answer Sheet.
  5. Minimum Detectable Count/Activity Answer Sheet.

B. Attachments
  1. Power Point Slide show Laboratory Instrumentation
  2. OE14467, "Abnormal Failure Rate of Geiger Mueller Radiation Detectors, Three Mile Island Unit 1, August 20, 2002. C:\WINDOWS\Temp\InpoReader747053.htm.

VIII. REFERENCES:

A. ACAD 93-008, "Guidelines for Training and Qualification of Radiological Protection Technicians," National Academy For Nuclear Training, August 1993.

B. Code of Federal Regulations, Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," U.S. Government Printing Office, Washington, 2003.
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E. "Measurement of Low-Level Radioactivity," ICRU Report 22, International Commission on Radiation Units and Measurements, Washington, DC, June 1, 1972.
F. NUREG/CR-4007. "Lower Limit of Detection: Definition and Elaboration of a Proposed Position for Radiological Effluent and Environmental Measurements." Washington, D.C.: Nuclear Regulatory Commission. 1984
G. Browns Ferry Nuclear Plant Radiological Control Instruction, RCI-11.1, INST-IP-10, "Radiation Protection Instrument Program Implementing Procedure No. 10, Counting Equipment Performance Tests," Revision 59, July 21, 2004.
H. Sequoyah Nuclear Plant Radiological Control Instruction, RCI-5, Attachment-04, Revision 35, June 18, 2002.
I. Watts Bar Nuclear Plant Radiological Control Instruction RCI-110, "Calibration of Radiological Control Laboratory Scaler/Counters," Revision 7, July 14, 2000.
J. Title 10, Code of Federal Regulation, Part 20, "Standards for Protection Against Radiation," January 1, 2003.

INSTRUCTOR NOTES

IX INTRODUCTION:

TP-1, 2, 3, & 4

HO-1

Laboratory radiation detection counter-scaler instruments are used to evaluate radioactivity and contamination conditions in the plants. Radiation calibration must be performed often enough to prevent errors in measurements with an otherwise operable instrument. The instruments are calibrated by counting the radioactivity given off by a radiation source with known activity. The measured count rate is then compared with the known activity and an efficiency calculated or a calibration curve plotted. The efficiency can then be applied to counts from samples and the activity calculated. For the majority of counter-scaler instruments, this calibration is performed every 6 months.

In addition to the calibration of the instruments, other checks are performed to establish the operating characteristics of the instruments and to ensure that they are operating properly. These checks include tests to determine the operating voltage, the background, and the minimum detectable activity, and other statistical tests to validate the proper operation of the instruments. This lesson will address the general procedures for performing these checks.

A. Radiation Detection and Measurement

1. Radiation detection is based on the principle that radiation causes ionization and excitation in matter.
2. Detection equipment is designed to measure the amount of ionization and excitation produced by responding to the charged particles which are produced when radiation interacts with matter.
3. The basic difference between various radiation detection devices is the medium in which the interactions occur.
4. Types of Detection Devices used in Radcon laboratory counter-scalers.

Objective 1, TP-5

This is a brief review of the detectors. Detailed descriptions of the detector characteristics and functions are presented in Lesson Plan HPT001.021, "Radiation Detection Principles."

   a. Gas Filled Detectors.

      (1) The primary method of detecting radiation is when radiation ionizes the gas in a filled chamber. The gas used in the detector can be almost any gaseous mixture which will ionize, including air. Some ionization detectors, particularly ionization chambers use only air, while other detectors use gas mixtures that ionize more readily to obtain the desired detector response.

Most widely used method of radiation detection.

      (2) This ionization can result in either pulses representing individual interactions or a current value which is an averaging of many interactions.

      (3) Detectors which utilize this principle include:

Objective 2, TP-6

         (a) Ionization chambers;
         (b) Gas proportional detectors;

        (c) Geiger-Mueller (G-M) detectors. **TP-7**

b. Scintillation Detectors. **Objective 1**

    (1) The scintillation material converts radiation energy to a visible light output by excitation of the material. Very effective and very efficient.

    (2) Scintillation detectors generally in use at power plants include: **Objective 3, TP-8**

        (a) Sodium Iodide (Thallium) [NaI (Tl)]for gamma counting;
        (b) Zinc Sulfide (ZnS) for alpha counting. **TP-9**

5. Counter-Scalers currently in use at NUCLEAR POWER PLANTS typically utilize
   G-M detectors for beta-gamma counting and ZnS detectors for alpha counting. In addition, NaI detectors may be employed when the presence of radioiodine is known or suspected.

B. Requirements and Prerequisites.

1. Sources used for calibration and system reliability checks (i.e., **Tc-99** (beta) and **Th-230** (alpha)) shall be traceable to the National Institute of Standards and Technology (**NIST**). **Objective 4, TP-10**

    a. **Tc-99** the isotope of choice for determining **beta** efficiency for the alpha/beta counters. Desirable characteristics of the isotope which make it a good calibration source include: **TP-11**

        (1) Long half-life (211,000 years)
        (2) Average beta energy of 0.085 MeV with a maximum beta energy of 0.295 MeV. These energies are lower than those of most fission and corrosion products of health physics concern in a nuclear power plant. Therefore, the efficiency obtained with Tc-99 will be conservative with respect to the types of radionuclides to be sampled.
        (3) Decays via beta emission only (no gamma) to a

stable radionuclide, Ru-99. There is no radioactive daughter in-growth to alter the beta spectrum emitted.

b. **Th-230** the isotope generally used for determining **alpha** efficiency for the alpha/beta counters. Desirable characteristics which make it a good calibration source include: **TP-12**
   (1) Long half-life (75,400 years).
   (2) Emits alpha particles of 4.68 MeV and 4.62 MeV. These energies are comparable to those of U-235 and U-238 (the radioactive material found in new fuel) and less than those of Pu-234, Pu-240, and Pu-241 (products found in irradiated fuel). The efficiency obtained with Th-230 is appropriate for calibrating the counters for alpha counting. **TP-13**

2. Sources must be used in accordance with applicable source handling procedures.
3. Sources used for source checks should be the same sources as those used to establish source check limits for a given instrument.
4. If any test or check result does not meet the applicable acceptance criteria, the affected instrument will be placed out of service immediately.

Error Prevention Tools
Two Minute Rule
Follow procedures
Self-Checking:
S top
T hink
A ct
R eview
Have a Questioning Attitude.

C. Determination of Operating Voltage.

For counter-scalers, the optimum operating voltage can vary for each counter-detector combination, and can vary over time for any individual counter-detector combination. Consequently, the optimum operating voltage must be determined periodically for each instrument. This operation is performed at least semiannually, and may be performed more frequently if circumstances or site procedures dictate.

What circumstances could require more frequent determination of operating voltages?

Response: Instrument repair or calibration;

change of counter-detector combination.

1. The operating voltage is determined by first establishing a voltage plateau.

   a. Set the detector HV adjustment to the **lowest** possible setting.

   TP-14, 15

   CAUTION! ADJUST DETECTOR VOLTAGE SLOWLY. RAPID HIGH VOLTAGE TRANSIENTS CAN DAMAGE DETECTORS.

   Focus on the Four: Equipment Reliability! Take care not to damage any equipment!

   b. Place the source in the established counting configuration for the instrument being used.

   Always **Practice *ALARA*** and **Follow Procedures** when handling radioactive materials!

   c. Begin counting the source and slowly increase the HV until counts begin to register, then reduce the voltage to the nearest convenient 50 or100-volt increment. Enter this value as the starting voltage in the appropriate plant-specific form similar to the one presented in Handout 2.

   HO-2, TP-16

   This handout contains data from a voltage plateau determination. Have the students complete the blanks on this worksheet as you go through the discussion. **Self-Checking! Attention to Detail!**

   d. Acquire counts for **one minute** at the starting voltage. Enter counts for the voltage in the the appropriate space beside the voltage entry on the form.

   e. Slowly increase the high voltage in 50-volt increments and perform a 1-minute count at each increment. Record the results on the appropriate form. Continue until the number of counts begins to rise dramatically, or until the maximum recommended detector voltage is reached.

CAUTION! EXCESSIVE APPLIED DETECTOR VOLTAGE MAY RESULT IN DETECTOR DAMAGE. DO NOT EXCEED THE VALUES LISTED BELOW.

Reemphasize Equipment Care!

Objective 5, TP-17

Gas proportional counters:	- 1900 volts
GM counters:	- 1600 volts
Scintillation counters:	- 1500 volts

f. Tabulate the data on an Excel spreadsheet and plot the counts obtained versus the voltage on a semi-log scale.

g. Select an operating voltage at approximately one-half of the plateau starting at V_1 of the plateau (see note on Handout 2).

Guide the students in creating the graph and in selecting the proper value for the operating voltage. Follow the guidelines in Handout 2.

2. Calculate percent slope as described on Handout 2 and record the results in the appropriate sections of the form. If the slope falls within the established range, it demonstrates that the selected operating is indeed on a relatively flat plateau.

TP-18

Go over the calculation of the slope per Handout 2.

D. Background determination.

TP-19

1. The operating voltage must be determined **prior** to establishing background.
2. Instrument background is determined daily**,** when performing detector efficiency determinations, and/or when sample chamber contamination is suspected.
3. Ensure that the instrument is set at the proper operating voltage for the type of radiation to be detected.
4. Place a clean empty planchet or blank sample into the detector chamber. Use the same configuration as used for the efficiency checks.
5. Acquire a 10-minute count (or longer if required for alpha or other circumstances) and calculate the count rate.

Objective 6

6. If the background determination is for performing a calibration or efficiency determination, enter the results in the appropriate space on Handout 3 (or equivalent).
7. If the background determination is for performing a daily check, record the results on the appropriate plant form.

E. The Chi-Square (χ^2) test.

Objective 7

χ^2 is a statistic performed to test whether the observed frequencies differ significantly from the expected frequency. For our application, the observed frequency is the individual observed count rates (x) and the expected frequency is the mean (x-bar). The equation defining χ^2 is given by:

For simplicity the term $\bar{x}$ (mean) is written as 'x-bar'.

Objective 8

$$\chi^2 = \frac{\sum (x_i - \text{x-bar})^2}{\text{x-bar}}$$

where: x_i = Observed count rate
x-bar = Mean of the count rates

The numerator of the equation is a measure of the spread of the observations and the denominator is a measure of the expected spread. If the observed values agree exactly with the expected value, then $\chi^2 = 0$. For any physical experiment where the predicted and observed values are not equal, we would expect a value of $(\chi^2) \approx n$, where n = the number of observations.

Objective 9
(Emphasize!)

1. Conducting the χ^2 test.
   χ^2 tests are not performed at all nuclear power plants. The data generated in the conduct of the χ^2 test may also be used in the calculation of the source check limit determination (or vice versa).

TP-20

HO-3

This handout contains data from a χ^2 test determination. Have the students complete the blanks on this worksheet as you go through the discussion. Handout 3 is a general form similar to the ones in use at the sites. For purposes of this exercise, we will use this

   a. An operating voltage and background determination shall have been completed prior to performing this test.

form.

b. Ensure that the instrument is set at the proper operating voltage for the type of radiation to be detected.

c. Place the source in the established counting configuration for the instrument being used.

Emphasize **ALARA** and **Following Procedures!**

d. Acquire approximately 20 sequential 1-minute counts and enter the results of each gross count in column A of Handout 3.

e. Perform the following calculations:

TP-21

Demonstrate the performance of these calculations on the student's calculators. Have the students Perform the calculations and enter the results in the appropriate blanks on the worksheet. Complete the remainder of the worksheet as you go through the discussion.

(1) Compute the average of one minute count values (x_i). This value is the mean (x-bar). Record the mean in the blank for the average at the bottom of column A of Handout 3.

(2) Square each individual one minute count and record the value in column B of Handout 3 beside the corresponding observed value.

(3) Subtract the mean (x-bar) from each of the one count values in column A (x_i). Enter the results on the corresponding line in column C (x_i – x-bar).

(4) Square each entry in column C (x_i – x-bar) and enter the result on the corresponding line in column D $(x_i - \text{x-bar})^2$.

(5) Sum the values in columns B and D and record the totals in the 'Total' line at the bottom of the corresponding column.

TP-22

(6) Divide the total in column D ($\sum(x_i - \text{x-bar})^2$) by the mean (x-bar) from the bottom of column A and record the result in the appropriate space on Handout 3.

2. Verify the X^2 result is within the acceptance criteria shown on Handout 3.

F. Determination of source check limits.

1. A source check limit determination may be performed in conjunction with a chi-square test.
2. An operating voltage and background determination must

HO-4, **TP-23**

be completed prior to setting these limits.

3. If a chi-square test has been conducted, use the data generated in this test to calculate the source check limits in accordance with the applicable portions of the worksheet in Handout 4.

Using data from the χ^2 test, perform the calculations and fill in the blanks on Handout 4.

4. If a chi-square test has not been conducted, perform the steps presented in Section D above and use this data to calculate the source check limits in accordance with the applicable portions of Handout 4.
5. Record the lower and upper source check limits in the appropriate spaces on Handout 4.

G. Counting Efficiency

1. Radiation detectors seldom detect all of the radiation emitted from a source, therefore, we must have a means of relating the amount that is detected (number of counts) to the amount that was released (number of disintegrations). This relationship is called the counting efficiency and is given by the equation:

Objective 10

2. Efficiency (ε) = Number of pulses recorded (cpm)/ Number of radiation quanta emitted by the source (dpm).

TP-24

3. The efficiency is normally given as a fraction (cpm/dpm) or a percent [(cpm x 100)/dpm]. The activity from the counting of a sample could then be determined by dividing the count rate produced by the sample (cpm) by the efficiency (cpm/dpm).

The number of pulses recorded may also be related to the activity in other units, such as mCi, mCi/cc, etc.

4. Sometimes it is desirable to establish an efficiency factor. The efficiency factor is simply the inverse of the efficiency (1/ε) with units of dpm/cpm. The activity from a sample would then be calculated by multiplying the count rate from the sample (cpm) by the efficiency factor (dpm/cpm).

5. Efficiency determination for counter-scalers.
   a. Operating voltage, background, source check limits and chi square results (if required) shall be complete prior to calculating the efficiency.
   b. Efficiency is normally calculated after calibration or after performing chi-square and/or source check limit determinations. The efficiency calculated may be used

as long as the daily source check falls within specified limits.

c. Data for calculating the efficiency may be obtained in one of two ways.

Using the data on Handout 3, calculate the counter efficiency and record the results on the form.

  (1). Perform a 10-minute count of a known source.

    (a) Obtain a standard source appropriate for the counter-scaler used and its configuration.
    (b) Place the source in the normal counting configuration for the instrument being calibrated.
    (c) Count the standard source for ten minutes and determine the gross source count rate in cpm.
    (d) Record the results in the appropriate section of Handout 3.
    OR:

  (2) Use the average of the gross counts **(x-bar)** from the chi-square/source check limit determination to calculate the efficiency count rate.

d. Subtract the previously determined background from the efficiency count rate and calculate the efficiency in accordance with the equation given in Handout 3.

6. Efficiency determination for the Ludlum 2200 and Bicron Analyst iodine and noble gas screening systems using NaI detectors.
   a. The Ludlum 2200 and Bicron Analyst NaI screening counters are calibrated at the Western Area Radiological Laboratory (WARL). The efficiencies are located on the side of the instruments.
   b. The source check limits are also determined by the WARL and are located on the side of the instruments.
   c. Specific instructions regarding the use of these instruments is included in lesson plan HPT001.003, “Radiological Environs Monitoring Van - Radiological Emergency Response.”

H. Minimum Detectable Count Rate/Minimum Detectable Activity determination.

1. Minimum Detectable Activity (MDA) is defined as that activity

Objective 11, TP-25

of a radionuclide which, in a given counting time, increases the reading of the instrument by an amount equal to three times the standard deviation of the background recorded in that time.

2. Another form of the MDA is the Minimum Detectable Count (MDC) which is the number of counts produced in a given time that increases the reading of the instrument by an amount equal to three times the standard deviation of the background recorded in that time. The MDC may also be expressed as the Minimum Detectable Count Rate (MDCR) by dividing the MFC by the count time, or by calculating the MDCR directly. The MDA may be calculated from the MDC.
3. The most straightforward method for calculating the MDCR is by the equation:

   SQN RCI-5, Att 04

   HO-5

   $$MDCR = 3\sqrt{Bkg}$$

   where Bkg is expressed as cpm

   The MDA may then be calculated by dividing the MDCR by the efficiency, or

   $$MDA = MDCR/\varepsilon$$

   Using the background from Handout 3 and the equations from Handout 5, calculate the MDC/MDA using the three techniques and record the results on the Handout 5 worksheet.

4. The equation given in NUREG/CR-4007 for the MDC is:

   BFN RCI-11.1,
   INST-IP-10

   $$MDC = 2.71 + 3.3\sqrt{B(t_b + t_s)/t_b}$$

   where:

   MDC = Minimum Detectable Counts

   B = Background counts

   t_b = Background counting time, minutes

   t_s = Sample counting time, minutes.

   and

   $$MDCR = MDC/t_s$$

5. An equation for calculating the MDCR directly is given by:

WBN RCI-110

$$MDCR = 3.29\sqrt{(R_b/t_b) + (R_b/t_s)}$$

where:

R_b = Background count rate, cpm

t_b = Background count time, minutes

t_s = Sample count time, minutes.

and

MDA = MDCR/ε

6. Record the MDCR/MDA results on the appropriate form.

Objective 12

   a. Sample count rates greater than Background plus the MDCR indicate the presence of radioactivity on the sample.
   b. Sample count rates less than Background minus the MDCR indicate probable instrument malfunction which should be investigated.
   c. Sample count rates within Background ± MDCR indicate statistically valid fluctuations in the background.
7. Minimum Detectable Count Rate or Minimum Detectable Activity values are determined daily when instruments are in use and/or before being put back into service following calibration or maintenance. Background counts are normally accumulated for 10 minutes and sample counts for 1 minute.
8. Handout 5 is a worksheet for documenting the determination of MDA/MDCR using each of the techniques discussed above.

I. Source checks

Review OE14467, Abnormal Failure Rate of Geiger Mueller Radiation Detectors: Detector window seal failure.

1. Source checks shall be performed **daily** when instruments are in use and upon return to service following calibration, repair or maintenance.

2. Background must be determined prior to performing a source check.
3. Ensure the operating voltage is set at the proper voltage for the type of radiation to be detected.
4. Place the source in the normal counting configuration for the instrument being used.
5. Count the standard source for one minute to obtain the gross counts.
6. Subtract the background count rate from the gross count rate to obtain the net count rate.
7. Record the results on the appropriate form and ensure that they fall with the appropriate limits (Handout 4).

Emphasize **ALARA** and **Following Procedures!**

J. Timing Circuit Test or 60-Cycle Test

1. For those instruments equipped with an internal timing circuit test mode (ie. the Eberline MS-2 Miniscaler), the 60-cycle test is performed daily when the instrument is in use.
2. To perform the test, place the instrument in the test mode and acquire a one minute count.
3. The count rate should be 3600 ± 2 cpm. Record the results on the appropriate form.

HO-6 & 7

K. Practical Exercise.

Using a laboratory scaler and a provided check source, perform the following tests and/or calculations and record the results on the appropriate form:

Also hand out additional copies of Handouts 4 and 5 for use in performing this exercise.

Emphasize the proper handling of radioactive materials when using calibration sources.

1. Voltage Plateau.
   a. Acquire the voltage plateau data;

   b. Plot the voltage vs. counts;

   c. Establish the voltage plateau;
   d. Determine the operating voltage.
2. Calculate the Percent Slope.
3. Perform the χ^2 test.
   a. Acquire the data;
   b. Calculate:

(1) $\sum x_i$;

(2) x-bar

(3) $(x_i)^2$ for each x_i;

(4) $\sum (x_i)^2$;

(5) x_i – x-bar for each x_i

(6) (x_i – x-bar$)^2$ for each x_i;

(7) $\sum$(x_i – x-bar$)^2$.

c. Calculate χ^2 and enter the results.

4. Determine the background and enter the results on Handout 7.

5. Determine the source check limits.

   Using the data generated in the χ^2 test, calculate the source check limits employing each of the three techniques on Handout 4and enter the results on the handout.

6. Calculate the counter efficiency and record the results on Handout 7.

If the activities of the sources being used are know, have the students determine the counter efficiency with the source. If the activities are not known, have them use the x-bar data from the χ^2 and source check limit data.

7. Using the background determined in section 4 above, calculate the MDC/MDA in accordance with the equations presented in Handout 5 and record the results on the handout.

8. Perform a source check and check the results against the limits calculated on Handout 4.

INSTRUCTOR NOTES

XI. SUMMARY

TP-26

Routine checks are performed on RadCon laboratory counter-scaler instruments to establish the operating characteristics of the instruments and to ensure that they are operating properly. These checks include tests to determine the operating voltage, the background, efficiency, and the minimum detectable activity, and Chi-square and other statistical tests to validate the proper operation of the instruments. In this lesson we have looked at the various tests performed on the equipment, the characteristics of the detectors and sources, and performed exercises to practice the conduct of tests.

Handout 2

Voltage Plateau and Slope Determination Data

Voltage Plateau and Slope Determination

Voltage	Counts
700	52
750	840
800	1150
850	1180
900	1324
950	1362
1000	1348
1050	1414
1100	1552

set

V_1 = __________ volts

V_2 = __________ volts

C_1 = __________ counts

C_2 = __________ counts

Operating Voltage set at __________ volts

Note: Manufacturer recommends that the operating voltage for the Ludlum 2200 be at approximately 900 volts.

Slope Determination:

$$\%\ \text{slope}/100\text{v} = \frac{(2 \times 10^4)(C_2 - C_1)}{(C_1 + C_2)(V_2 - V_1)} = \frac{(2 \times 10^4)(\underline{\qquad\quad} - \underline{\qquad\quad})}{(\underline{\qquad} + \underline{\qquad})(\underline{\qquad} - \underline{\qquad})}$$

$$\%\ \text{slope}/100\ \text{v} = \frac{(\underline{\qquad\qquad\qquad})}{(\qquad\qquad\qquad)} = \underline{\qquad\qquad\qquad}\%$$

In general, the slope should be less than 10 %. Consult plant-specific procedures for differences.

Where: C_1 = cpm at applied voltage V_1.

C_2 = cpm at applied voltage V_2.

V_1 = Voltage at the base of the plateau (past the first knee of the response curve).

V_2 = Voltage at the end (top) of the plateau.

Note: V_2 must be at least 150 volts greater than V_1.

Handout 3

Chi-Square Test and Efficiency Determination Data

Chi-Square Test (χ^2)/Source Limit Determination Data

	A	B	C	D
Trial Number, n	Counts per Minute, x_i	$(x_i)^2$	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
1	1433			
2	1333			
3	1361			
4	1397			
5	1307			
6	1360			
7	1319			
8	1393			
9	1398			
10	1384			
11	1339			
12	1304			
13	1333			
14	1381			
15	1304			
16	1385			
17	1364			
18	1314			
19	1339			
20	1381			
21	1372			
Total			N/A	
Average, $\bar{x}$		N/A	N/A	N/A

χ^2 Acceptable if $\chi^2 \geq \sim 10$ and $\leq \sim 30$

(See plant procedures for specific criteria.)

χ^2 Satisfactory? ☐ Yes ☐ No

Average Count Rate ($\bar{x}$) Determination

Average cpm ($\bar{x}$) = $\frac{\text{Total Column A}}{n}$

$\bar{x} = \frac{\text{\_\_\_\_\_\_\_\_\_\_}}{n}$ = __________ cpm

Where n = number of observations

Detector Efficiency Determination

Net Count Rate (cpm) = Average Count Rate (cpm) – Bkg Count Rate

Average count Rate ($\bar{x}$) = _________cpm

Bkg. Count Rate = ___24_____cpm

Net Count Rate = __________cpm

% Efficiency = $\frac{\text{Net Count Rate (cpm) x 100}}{\text{Source Activity (dpm)}}$

% Efficiency = $\frac{(\text{\_\_\_\_\_\_\_\_\_\_\_\_})\text{ cpm x 100}}{(\quad 15700 \quad)\text{ dpm}}$

% Efficiency = _______________%

χ^2 Determination

$\chi^2 = \frac{\text{Total, Column D}}{\bar{x}} = \frac{(\text{\_\_\_\_\_\_\_\_\_\_})}{\bar{x}}$

$\chi^2 = \frac{(\text{\_\_\_\_\_\_\_\_\_\_})}{(\qquad)}$ = __________

Handout 4

Source Check Limit Determination Worksheet

There are three different methods used to determine source check limits. Even though the methods are different, similar results are produced by each technique. All three utilize data generated for the χ^2 test, therefore, we will use the data table in Handout 3 in these calculations.

1. Calculate the range of two standard deviations using the equation:

$$\text{Limits} = \pm 2 \sqrt{\frac{\sum(x_i - \text{x-bar})^2}{n-1}}$$

Where: $\sum(x_i - \text{x-bar})^2$ = Total from Handout 3, Column D
n = Number of observations

$$\text{Limits} = \pm 2 \sqrt{(\qquad\qquad)/(n-1)} = \pm 2 \sqrt{(\qquad\qquad)} = \pm$$ __________cpm

When x-bar = __________, Limits = _______________ to _______________ cpm

2. Calculate the range of two standard deviations using the equation:

$$\text{Limits} = \pm 2 \sqrt{\frac{\sum x_i^2 - n(\text{x-bar})^2}{n-1}}$$

Where" $\sum x_i^2$ = Sum of the square of each count = Total from Handout 3, Column B
x-bar = Mean net counts per minute = Average from Handout 3, Column A
n = Number of observations.

$$\text{Limits} = \pm 2 \sqrt{(\qquad\qquad) - (\qquad\qquad)/(n-1)} = \pm 2 \sqrt{(\qquad\qquad)} = \pm$$ ________

When x-bar = __________, Limits = _______________ to _______________ cpm.

3. Approximate the lower and upper limits by multiplying the mean count rate (x-bar, Handout 3, Column A) by 0.9 and 1.1, respectively. When x-bar = __________cpm;

Lower limit = 0.9(x-bar) = _______________ cpm

Upper limit = 1.1(x-bar) = _______________ cpm.

Handout 5

Minimum Detectable Count/Activity Worksheet

At least three different techniques are used to determine the minimum detectable activity for laboratory counter/scalers. This worksheet provides guidelines for performing each calculation.

1. Basic method

MDCR = $3\sqrt{\text{Bkg}}$ = $3\sqrt{(\qquad\qquad \text{cpm})}$ = 3(   ) =____________cpm

and

MDA = MDCR/ε = (________________)/(________________) = ________________dpm

---

2. NUREG/CR-4007 methodology

MDC = 2.71 + $3.3\sqrt{B(t_b + t_s)/t_b}$

= 2.71 + 3.3 $\sqrt{(\underline{\hspace{2cm}}\text{cts})[(\underline{\hspace{1.5cm}}\text{min}) + (\underline{\hspace{1.5cm}}\text{min})]/(\underline{\hspace{1.5cm}}\text{min})}$

= 2.71 + 3.3 $\sqrt{(\underline{\hspace{3cm}})}$ = 2.71 + 3.3(________________)

MDC = __________ and MCDR = MDC/t_s = (_______)/(_______) = _________cpm

---

3. Determination of MDCR directly

MDCR = $3.29\sqrt{(R_b/t_b) + (R_b/t_s)}$

= $3.29\sqrt{[(\underline{\hspace{2cm}}\text{cpm})/(\underline{\hspace{2cm}}\text{min}) + (\underline{\hspace{2cm}}\text{cpm})/(\underline{\hspace{2cm}}\text{min})}$

= $3.29\sqrt{(\underline{\hspace{3cm}}) + (\underline{\hspace{3cm}})}$

= $3.29\sqrt{\underline{\hspace{3cm}}}$ = 3.29 x ________________

= ________________cpm.

MDA = MDCR/ε = (________________)/(________________) = ______________dpm.

Handout 6

Voltage Plateau and Slope Determination Worksheet

Voltage Plateau and Slope Determination

Voltage	Counts

set

V_1 = __________ volts

V_2 = __________ volts

C_1 = __________ counts

C_2 = __________ counts

Operating Voltage set at __________ volts

Note: Manufacturer recommends that the operating voltage for the Ludlum 2200 be at approximately 900 volts.

Slope Determination:

$$\% \text{ slope/100v} = \frac{(2 \times 10^4)(C_2 - C_1)}{(C_1 + C_2)(V_2 - V_1)} = \frac{(2 \times 10^4)(\_\_\_\_\_\_\_\_\_\_ - \_\_\_\_\_\_\_\_\_\_)}{(\_\_\_\_\_\_\_ + \_\_\_\_\_\_)(\_\_\_\_\_\_ - \_\_\_\_\_\_)}$$

$$\% \text{ slope/100 v} = \frac{(\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_)}{(\qquad\qquad)} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\%$$

In general, the slope should be less than 10 %. Consult plant-specific procedures for differences.

Where:

C_1 = cpm at applied voltage V_1.

C_2 = cpm at applied voltage V_2.

V_1 = Voltage at the base of the plateau (past the first knee of the response curve).

V_2 = Voltage at the end (top) of the plateau.

Note: V_2 must be at least 150 volts greater than V_1.

Handout 7

Chi-Square Test and Efficiency Determination Worksheet

Chi-Square Test (χ^2)/Source Limit Determination Data

	A	B	C	D
Trial Number, n	Counts per Minute, x_i	$(x_i)^2$	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				
Total			N/A	
Average, $\bar{x}$		N/A	N/A	N/A

Average Count Rate ($\bar{x}$) Determination

$$\text{Average cpm } (\bar{x}) = \frac{\text{Total Column A}}{n}$$

$$\bar{x} = \frac{\_\_\_\_\_\_\_\_\_\_}{n} = \_\_\_\_\_\_\_\_\_\_ \text{ cpm}$$

Where n = number of observations

Detector Efficiency Determination

Net Count Rate (cpm) =
Average Count Rate (cpm) – Bkg Count Rate

Average count Rate ($\bar{x}$) = __________cpm

Bkg. Count Rate = __________cpm

Net Count Rate = __________cpm

$$\text{\% Efficiency} = \frac{\text{Net Count Rate (cpm) x 100}}{\text{Source Activity (dpm)}}$$

$$\text{\% Efficiency} = \frac{(\_\_\_\_\_\_\_\_\_\_\_\_)\text{ cpm x 100}}{(\qquad\qquad)\text{ dpm}}$$

% Efficiency = _______________%

χ^2 Determination

$$\chi^2 = \frac{\text{Total, Column D}}{\bar{x}} = \frac{(\_\_\_\_\_\_\_\_\_\_)}{\bar{x}}$$

$$\chi^2 = \frac{(\_\_\_\_\_\_\_\_\_\_)}{(\qquad\quad)} = \_\_\_\_\_\_\_\_\_\_$$

χ^2 Acceptable if $\chi^2 \geq$ ~10 and $\leq$ ~30

(See plant procedures for specific criteria.)

χ^2 Satisfactory? ☐ Yes ☐ No

Appendix 2

Voltage Plateau and Slope Determination Answer Sheet

Voltage Plateau and Slope Determination

Voltage	Counts
700	52
750	840
800	1150
850	1180
900	1324
950	1362
1000	1348
1050	1414
1100	1552

set

V_1 = $\underline{\quad 900 \quad}$ volts

V_2 = $\underline{\quad 1050 \quad}$ volts

C_1 = $\underline{\quad 1324 \quad}$ counts

C_2 = $\underline{\quad 1414 \quad}$ counts

Operating Voltage set at $\underline{\quad 950 \quad}$ volts

Note: Manufacturer recommends that the operating voltage for the Ludlum 2200 be at approximately 900 volts.

Slope Determination:

% slope/100v = $\dfrac{(2 \times 10^4)(C_2 - C_1)}{(C_1 + C_2)(V_2 - V_1)}$ = $\dfrac{(2 \times 10^4)(\underline{\ 1414\ } - \underline{\ 1324\ })}{(\underline{\ 1324\ } + \underline{\ 1414\ })(\underline{\ 1050\ } - \underline{\ 900\ })}$

% slope/100 v = $\dfrac{(\underline{\ 1,800,000\ })}{(\ 410,700\ )}$ = $\underline{\quad 4.4 \quad}$%

In general, the slope should be less than 10 %. Consult plant-specific procedures for differences.

Where: C_1 = cpm at applied voltage V_1.

C_2 = cpm at applied voltage V_2.

V_1 = Voltage at the base of the plateau (past the first knee of the response curve).

V_2 = Voltage at the end (top) of the plateau.

Note: V_2 must be at least 150 volts greater than V_1.

Appendix 3

Chi-Square Test and Efficiency Determination Answer Sheet

Chi-Square Test (χ^2)/Source Limit Determination Data

	A	B	C	D
Trial Number, n	Counts per Minute, x_i	$(x_i)^2$	$x_i - \bar{x}$	$(x_i - \bar{x})^2$
1	1433	2053489	76	5776
2	1333	1776889	-24	576
3	1361	1852321	4	16
4	1397	1951609	40	1600
5	1307	1708249	-50	2500
6	1360	1849600	3	9
7	1319	1739761	-38	1444
8	1393	1940449	36	1296
9	1398	1954404	41	1681
10	1384	1915456	27	729
11	1339	1792921	-18	324
12	1304	1700416	-53	2809
13	1333	1776889	-24	576
14	1381	1907161	24	576
15	1304	1700416	-53	2809
16	1385	1918225	28	784
17	1364	1860496	7	49
18	1314	1726596	-43	1849
19	1339	1792921	-18	324
20	1381	1907161	24	576
21	1372	1882384	15	225
Total	28501	38707813	N/A	26528
Average, $\bar{x}$	1357	N/A	N/A	N/A

χ^2 Acceptable if $\chi^2 \geq$ ~10 and $\leq$ ~30
(See plant procedures for specific criteria.)
χ^2 Satisfactory? X Yes ☐ No

Average Count Rate ($\bar{x}$) Determination

Average cpm ($\bar{x}$) = Total Column A / n

$\bar{x}$ = 28501 / n = 1357 cpm

Where n = number of observations

Detector Efficiency Determination

Net Count Rate (cpm) =
Average Count Rate (cpm) – Bkg Count Rate

Average count Rate ($\bar{x}$) = 1357 cpm

Bkg. Count Rate = 24 cpm

Net Count Rate = 1333 cpm

% Efficiency = Net Count Rate (cpm) x 100 / Source Activity (dpm)

% Efficiency = (1333) cpm x 100 / (15700) dpm

% Efficiency = 8.5 %

χ^2 Determination

χ^2 = Total, Column D / $\bar{x}$ = (26528) / $\bar{x}$

χ^2 = (26528) / (1357) = 19.5

Appendix-4

Source Check Limit Determination Answer Sheet

There are three different methods used to determine source check limits. Even though the methods are different, similar results are produced by each technique. All three utilize data generated for the χ^2 test, therefore, we will use the data table in Handout 3 in these calculations.

1. Calculate the range of two standard deviations using the equation:

$$\text{Limits} = \pm 2\sqrt{\frac{\sum(x_i - \text{x-bar})^2}{n-1}}$$

Where: $\sum(x_i - \text{x-bar})^2$ = Total from Handout 3, Column D
n = Number of observations

$$\text{Limits} = \pm 2\sqrt{(\ 26528\ )/(n-1)} = \pm 2\sqrt{(\ 1326\ )} = \pm \underline{\ 73\ }$$

When x-bar = __1357___, Limits = ____1284_______ to ______1430_____ cpm

2. Calculate the range of two standard deviations using the equation:

$$\text{Limits} = \pm 2\sqrt{\frac{\sum x_i^2 - n(\text{x-bar})^2}{n-1}}$$

Where” $\sum x_i^2$ = Sum of the square of each count = Total from Handout 3, Column B
x-bar = Mean net counts per minute = Average from Handout 3, Column A
n = Number of observations.

$$\text{Limits} = \pm 2\sqrt{(\ 38707813\ ) - (\ 38670429\ )/(n-1)} = \pm 2\sqrt{(\ 1869\ )} = \pm \underline{\ 86\ }$$

When x-bar = ___1357___, Limits = ____1271_______ to _____1443______ cpm.

3. Approximate the lower and upper limits by multiplying the mean count rate (x-bar, Handout 3, Column A) by 0.9 and 1.1, respectively. When x-bar = __1357__cpm;

Lower limit = 0.9(x-bar) = ____1221______ cpm

Upper limit = 1.1(x-bar) = _____1493______ cpm.

Appendix-5

Minimum Detectable Count/Activity Answer Sheet

At least three different techniques are used to determine the minimum detectable activity for laboratory counter/scalers. This worksheet provides guidelines for performing each calculation.

1. Basic method

MDCR = $3\sqrt{\text{Bkg}}$ = $3\sqrt{(\ 24\ \text{cpm})}$ = 3(4.9) = $\underline{\ \ 14.7\ \ \ \ }$cpm

and

MDA = MDCR/ε = ($\underline{\ \ \ \ 14.7\ \ \ \ }$)/($\underline{\ \ \ \ 0.085\ \ \ \ }$) = $\underline{\ \ \ \ 173\ \ \ \ \ \ }$dpm

2. NUREG/CR-4007 methodology

MDC = $2.71 + 3.3\sqrt{B(t_b + t_s)}/t_b$

$= 2.71 + 3.3\sqrt{(\underline{\ \ 240\ \ }\text{cts})[(\underline{\ \ 10\ \ }\text{min}) + (\underline{\ \ 1\ \ }\text{min})]/(\underline{\ \ 10\ \ }\text{min})}$

$= 2.71 + 3.3\sqrt{(\underline{\ \ 264\ \ \ \ \ \ \ \ })}$ $= 2.71 + 3.3(\underline{\ \ 16.2\ \ \ \ \ \ })$

MDC = $\underline{\ \ 56.3\ \ }$, and MCDR = MDC/t_s = ($\underline{\ \ 56.3\ \ }$)/($\underline{\ \ 1\ \ }$) = $\underline{\ \ 56.3\ \ }$cpm

3. Determination of MDCR directly

MDCR = $3.29\sqrt{(R_b/t_b) + (R_b/t_s)}$

$= 3.29\sqrt{[(\underline{\ \ 24\ \ }\text{cpm})/(\underline{\ \ 10\ \ }\text{min}) + (\underline{\ \ 24\ \ }\text{cpm})/(\underline{\ \ 1\ \ }\text{min})}$

$= 3.29\sqrt{(\underline{\ \ 2.4\ \ \ \ }) + (\underline{\ \ 24\ \ \ \ })}$

$= 3.29\sqrt{\underline{\ \ 26.4\ \ \ \ \ \ }}$ $= 3.29 \times \underline{\ \ 5.14\ \ \ \ \ \ }$

$= \underline{\ \ 16.9\ \ \ \ }$cpm.

MDA = MDCR/ε = ($\underline{\ \ 16.9\ \ \ \ }$)/($\underline{\ \ 0.085\ \ \ \ }$) = $\underline{\ \ 199\ \ \ \ }$dpm