PRINCIPLES OF NUCLEAR RADIATION DETECTION

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LABORATORY MANUAL

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PREFACE

Radiation detection is essentially a tool in research, in medical dosimetry and in the monitoring of radiation levels in industrial facilities, yet it incorporates some fairly sophisticated scientific principles and its proper use and application in many areas still require considerable expertise and skill. For this reason no course in radiation detection is complete without a laboratory in which the student gets some individual, hands-on experience in the use of detection equipment and has the opportunity to familiarize himself with many of the practical aspects of setting up, calibrating and operating representative units. Appreciation for the problems of selecting the most appropriate detector and sample geometry and for the best methods for evaluating and displaying count results can only be obtained by practical experience.

The present manual has been designed as a companion volume to our textbook "Principles of Nuclear Radiation Detection." For this reason, the theoretical introduction to most experiments is kept brief, and the student is referred to the textbook for further details. Nevertheless, enough details are provided to supply the necessary explanations for the objectives of the experiments and the procedure to be followed.

To avoid undue obsolescence no reference is made to specific commercial equipment; however, the type of electronic units required is specified. This will make it fairly easy in most cases to select a matching commercial unit.

No originality is claimed for any of the experiments. They represent a fairly conventional evolution of a long-term program of detector courses and special short courses in Radiation Detection and Radiation Protection held at Georgia Tech and many other institutions over the past two decades. The need for such a manual has arisen mainly from the technical developments in that time that have superseded many of the earlier types of equipment, shifted the emphasis to detectors capable of more rapid response and led to increasing use of online computer evaluation of experimental data.

It is hoped that this manual will fill this need and will contribute to the effective training of health physicists, nuclear engineers, medical technologists and research personnel in the physical and biological sciences.

We are greatly indebted to Dr. J. Narl Davidson for permission to use many of the laboratory outlines that he has developed, to Dr. Bernd Kahn for providing material for Experiments 11 and 32, Mr. Robert M. Boyd for Experiment 33 and Dr. John L. Russell for Experiment 27. We are also grateful to Mrs. Julia H. Rankin for her patience and care in preparing the typescript.

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CHAPTER 1. GENERAL LABORATORY SKILLS

INTRODUCTION

Radiation detection involves the localization and identification of "invisible" nuclear radiations, both particular or electromagnetic in nature, by means of readily amplified and recorded processes through a variety of physical interaction mechanisms in a suitable medium (see text, Chapters 1 and 2 for details). A fairly wide range of usable interaction processes is available, but for a specific purpose or type of radiation the choice of the best detection method or procedure may be quite narrow. This choice may be dictated by the type of information required, the radiation intensity existing, the geometry and configuration attainable and the equipment available. With some experience the most logical approach will appear simple in most cases and it is the purpose of a laboratory course to provide such experience and to facilitate an insight on how detector systems work and what pitfalls must be avoided.

Except for such detectors as photographic emulsions, most detector systems involve a combination of a possibly rather delicate detector and an often complicated-looking electronic system. There are many possibilities for damaging the detector through improper handling and for damage of the electronic unit by incorrect connections, insufficient grounding or operation at inappropriate voltages. In addition, many detectors employ high voltages, and poor procedures or badly maintained components can result in severe electric shocks to the experimenter. For this reason, the user should familiarize himself with all components and read the procedural outline before handling any of the equipment or turning on any electronic unit. When in doubt, read the manual or consult the instructor! It is generally not satisfactory to try all switches or controls to see what happens and you may just completely spoil a carefully set up operating condition. Some detectors have thin walls or thin mica windows and must be handled with great care to avoid damage.

The use of radioactive materials as sources requires careful procedures and proper record-keeping; this will be discussed further below. In general, cleanliness and care are essential qualities in any radioactive laboratory to avoid contamination of detectors, persons and facilities, changes in background counts and the introduction of erratic and unaccountable errors into the measurements. This is particularly important for very low-level measurements, such as for environmental samples, where background counts may represent a large fraction of the total counts obtained.

REPORTS AND RECORD-KEEPING

Part of the training obtained through a laboratory course pertains to the maintenance of a complete and comprehensible set of laboratory notes and records. From the beginning the student should make it a rule to write up the objectives and basic procedural steps as he does the experiment and record his results in a format that makes evaluation simple. In the following outlines, formats are suggested for recording data for many experiments and it will be convenient to stick to that presentation in most cases.

No results should be discarded without valid reasons and such matters should be recorded, too, until the completion of the test runs. In a teaching laboratory it is also usually important to show intermediate steps in calculations to ensure a clear, logical development. In industrial and medical laboratories complete maintenance of records is often also a legal requirement and it is good practice to get into this habit from the start.

USE OF GRAPH PAPERS

While many counting results are obtained in digital form and most readily displayed in tables, in many experiments the main interest lies in the change in source activity with time, a change in dose or intensity with position or with absorber thickness. In all these cases it is much simpler to see trends and to interpolate intermediate points on a graph plotted on appropriate graph paper.

The clarity of graphs is often enhanced by the choice of special graph papers. Of these, the ones most commonly encountered are *linear*, *semi-log* , *logarithmic* and *polar* coordinate papers. These are illustrated in Fig. 1. By supplying the coordinates already in the special scale, detailed numerical conversion of all measurement points becomes unnecessary.

A graphical plot is intended to show relationship, that is how variable y changes with change in parameter x. If the relationship is linear, or nearly so, i.e., $y = mx + c$, the results of such a measurement are most conveniently displayed on linear graph paper. The unit dimension or pitch of the paper should be chosen to make plotting of all points easy

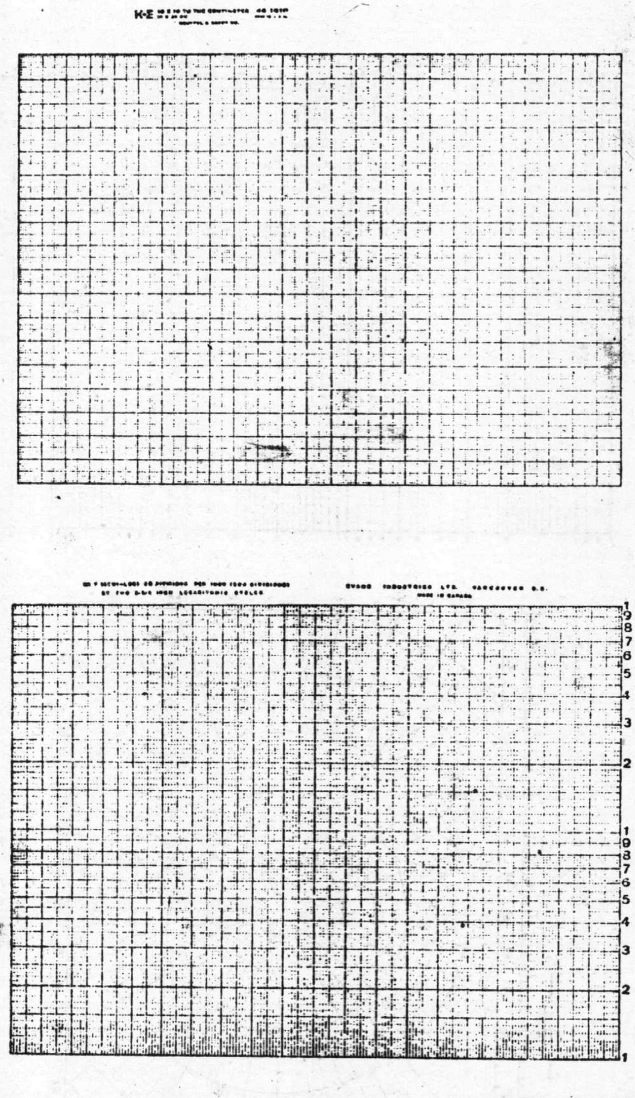
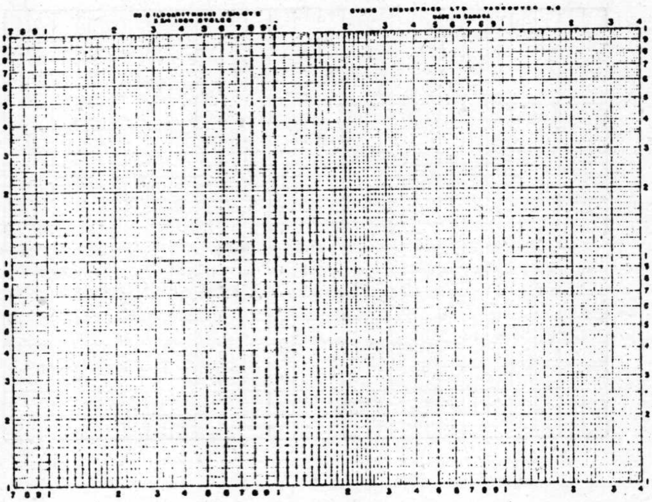


Fig. 1. Examples of graph papers (reduced in size)
a (upper): Linear, millimeter square
b (lower): Semilog, 2 cycles upward



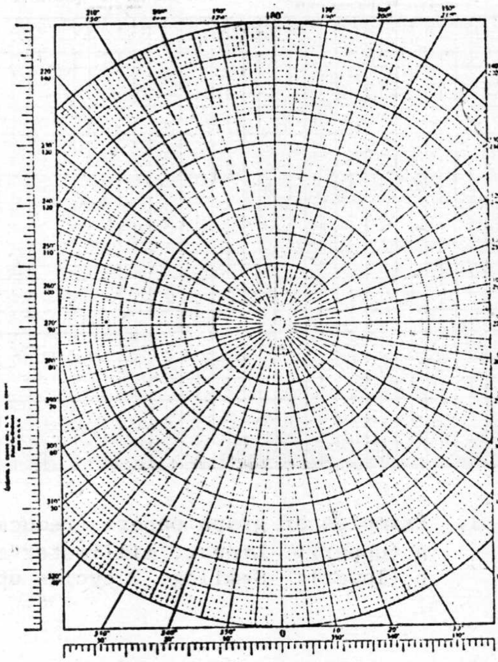


Fig.1-c (upper): Log-log, 2 cycles by $2\frac{3}{4}$ cycles
-d (lower): Polar coordinates

without either crowding points in one small area or requiring awkward conversion of numbers; for instance, it is obviously inconvenient to use 3 unit spaces per ten units.

If the relationship is exponential, e.g., $x = A e^{-\lambda t}$, semilog paper should be used since $\log x = C \lambda t$, where C includes a logarithm conversion for $\log_{10} e$. By plotting x along the logarithmic scale against a linear t a straight line results from which the slope λ, or in half life measurements, the half life can be easily deduced. The number of logarithmic cycles must be chosen to match the number of decades through which the variable x is measured.

Semilog paper is equally useful to display calibrations or measurements running through several powers of ten, though in such cases the plot would not necessarily be linear. Such a plot would, however, retain data of comparable accuracy, whereas on a linear graph appreciable clustering and distortion would arise if one tried to display points over a wide range of values.

Where both parameters cover several decades, fully logarithmic graph paper may be employed, (Fig. 1-c). Such graph papers are available in various cycles, 1 by 2, 2 by 3 and 3 by 5 being particularly common.

For displaying angular or directional dependence, e.g., the variation of radiation intensity in a horizontal or vertical plane, polar coordinate paper, as shown in Fig. 1-d, is very useful. It is widely used to show isodose contours and meteorological data such as wind roses and plume dispersion data. Radial distance from the center represents one variable, angular position from a selected base line the other.

Intelligent use of appropriate graph paper thus is a valuable aid in displaying experimental data, fitting curves and evaluating slopes and calibration constants.

RADIATION SAFETY

Radiation detection laboratories involve measurements on radiations emitted by radiation sources, either radioactive sources or machines, such as X-ray machines, high-voltage generators or nuclear reactors. Particularly in the latter cases it cannot always be assumed that radiation exposures are low and suitable precautions must be taken.

In general all operations involving radiation fields and radioactive sources require scrupulous attention to radiation safety precautions under three headings:

Personnel Protection and Monitoring
Source Handling and Storage
Clean Laboratory Procedures

Personal Protection and Monitoring

Even though the sources handled in the laboratory may be low in activity and license-exempt (typically less than 1 μCi [< 37 kBq] in activity (Table 1)), it is always advisable to take basic precautions as a matter of good practice. This includes personal cleanliness, no smoking, drinking or eating in any laboratory containing radioactive materials, washing of hands after handling any radioactive material or container, wearing of smocks or laboratory coats and, preferably, wearing of individual personnel dosimeters, such as TLD's or film badges.

Areas where radiation sources are employed should be properly labeled and surveyed periodically for contamination. Disposable gloves should be worn when radioactive solutions are prepared and any chemical or physical source preparation or separation should be done in a vented fume hood or glove box. A portable monitoring instrument of appropriate type should be available for spot checks.

Source Handling and Storage

All radioactive materials not actually in use should be stored in a shielded, well-labeled location. To minimize interference with other work any radioactive material not immediately in use should be stored behind lead. All sources should be properly labeled, with identification of the type of emitter, the activity and date of preparation. This also applies to commercial reference sources which are available in sealed form or as solution sources. Any sources that have decayed below background level should be discarded and disposed of properly.

It is important to maintain proper records for all sources used or prepared, including their ultimate disposal. This includes radioactive sample solutions, such as scintillator solutions, and nuclear medicine samples or research tracer samples, including animal carcasses. All such material must be treated as contaminated waste.

Contamination of sample holders and glassware can lead to serious errors in measurements. For that reason all chemical preparations should be done over cleanable trays and all bench tops and fume hoods must be checked for contamination regularly. Re-use of planchets is often not worthwhile, particularly for alpha or beta emitters. Open, evaporated sources should be handled with forceps, never with bare fingers. Encapsulated alpha sources usually have thin windows that are easily damaged. Such sources should be smear-tested for leaks, on the back, at 6-monthly intervals.

Clean Laboratory Procedures

There are a number of cleaning solutions on the market. Trisodium phosphate and the use of ultrasonic cleaning baths are particularly effective. Many radionuclides form radiocolloids and adhere to the walls of beakers and pipets; this must be checked frequently when preparing tracer solutions.

The outside of source containers should be checked for contamination on first receipt and subsequent handling to minimize contamination of storage facilities and radiation shields ("castles"). The lab instructor should be familiar with emergency procedures and facilities existing to check any suspected contamination of staff or students using the lab.

The key to satisfactory detection results is careful adherence to laid-down procedures, cleanliness and care in handling sources, solutions and delicate detectors, and patience. Especially with weak sources, such as those from environmental samples, enough time must be allowed for counting to obtain adequate count statistics and for any radiochemical concentration procedure.

PULSE ELECTRONICS

As pointed out in the text (Chapter 1, also Chapter 11), most radiation detectors require the collection, sorting or counting of electrical impulses that arise from the collection of charge in ionization devices or from the amplification of photoelectron signals in light-emitting processes. Since these pulses frequently are small in amplitude they require electronic amplification; since they occur often in very rapid succession they require counting systems capable of rapid response, and since in many cases useful information is contained in the rise time, amplitude and duration of the pulse signals, electronic circuits must be employed capable of analyzing that information.

Each type of detection system will be found to consist of a particular combination of electronic components to accomplish its mission. For a Geiger counter this may comprise the detector tube and its supporting base and shield, a high-voltage supply and a count-rate meter or a scaler with a timer. For a Ge(Li) gamma-ray spectrometer this may be the detector proper mounted integrally with a pre-amplifier on a liquid introgen reservoir, a high-voltage supply, a main amplifier, a pulse-height multichannel analyser, a printout or display unit and, perhaps, a computer-generated system of reference spectra. In all these cases the components fulfill specific functions and should never just be treated as "black boxes" that are accepted unquestioned. For this reason it is important for the student to understand the most common circuit

Table 1. License-Exempt Quantities of Radioactive Materials (Extract from Title 10, Code of Federal Regulations)

§ 30.18 Exempt quantities.

(a) Except as provided in paragraphs (c) and (d) of this section, any person is exempt from the requirements for a license set forth in section 81 of the Act and from the regulations in Parts 30-34 of this chapter to the extent that such person receives, possesses, uses, transfers, owns, or acquires byproduct material in individual quantities each of which does not exceed the applicable quantity set forth in § 30.71, Schedule B.

(b) Any person who possesses byproduct material received or acquired prior to October 22, 1970 under the general license then provided in § 31.4 of this chapter is exempt from the requirements for a license set forth in section 81 of the Act and from the regulations in Parts 30-34 of this chapter to the extent that such person possesses, uses, transfers or owns such byproduct material.

§ 30.71 Schedule B.

Byproduct material	Microcuries
Antimony 122 (Sb 122)	100
Antimony 124 (Sb 124)	10
Antimony 125 (Sb 125)	10
Arsenic 73 (As 73)	100
Arsenic 74 (As 74)	10
Arsenic 76 (As 76)	10
Arsenic 77 (As 77)	100
Barium 131 (Ba 131)	10
Barium 140 (Ba 140)	10
Bismuth 210 (Bi 210)	1
Bromine 82 (Br 82)	10
Cadmium 109 (Cd 109)	10
Cadmium 115m (Cd 115m)	10
Cadmium 115 (Cd 115)	100
Calcium 45 (Ca 45)	10
Calcium 47 (Ca 47)	10
Carbon 14 (C 14)	100
Cerium 141 (Ce 141)	100
Cerium 143 (Ce 143)	100
Cerium 144 (Ce 144)	1
Cesium 131 (Cs 131)	1,000
Cesium 134m (Cs 134m)	100
Cesium 134 (Cs 134)	1
Cesium 135 (Cs 135)	10
Cesium 136 (Cs 136)	10
Cesium 137 (Cs 137)	10
Chlorine 36 (Cl 36)	10
Chlorine 38 (Cl 38)	10
Chromium 51 (Cr 51)	1,000
Cobalt 58m (Co 58m)	10
Cobalt 58 (Co 58)	10
Cobalt 60 (Co 60)	1
Copper 64 (Cu 64)	100
Dysprosium 165 (Dy 165)	10
Dysprosium 166 (Dy 166)	100
Erbium 169 (Er 169)	100
Erbium 171 (Er 171)	100
Europium 152 9.2 h (Eu 152 9.2 h)	100
Europium 152 13 yr (Eu 152 13 yr)	1
Europium 154 (Eu 154)	1
Europium 155 (Eu 155)	10
Fluorine 18 (F 18)	1,000
Gadolinium 153 (Gd 153)	10
Gadolinium 159 (Gd 159)	100
Gallium 72 (Ga 72)	10
Germanium 71 (Ge 71)	100
Gold 198 (Au 198)	100
Gold 199 (Au 199)	100
Hafnium 181 (Hf 181)	10
Holmium 166 (Ho 166)	100
Hydrogen 3 (H 3)	1,000
Indium 113m (In 113m)	100
Indium 114m (In 114m)	10
Indium 115m (In 115m)	100
Indium 115 (In 115)	10
Iodine 125 (I 125)	1
Iodine 126 (I 126)	1
Iodine 129 (I 129)	0.1
Iodine 131 (I 131)	1
Iodine 132 (I 132)	10
Iodine 133 (I 133)	1
Iodine 134 (I 134)	10
Iodine 135 (I 135)	10
Iridium 192 (Ir 192)	10
Iridium 194 (Ir 194)	100
Iron 55 (Fe 55)	100
Iron 59 (Fe 59)	10
Krypton 85 (Kr 85)	100
Krypton 87 (Kr 87)	10
Lanthanum 140 (La 140)	10
Lutetium 177 (Lu 177)	100
Manganese 52 (Mn 52)	10
Manganese 54 (Mn 54)	10
Manganese 56 (Mn 56)	10
Mercury 197m (Hg 197m)	100
Mercury 197 (Hg 197)	100
Mercury 203 (Hg 203)	10
Molybdenum 99 (Mo 99)	100
Neodymium 147 (Nd 147)	100
Neodymium 149 (Nd 149)	100
Nickel 59 (Ni 59)	100
Nickel 63 (Ni 63)	10
Nickel 65 (Ni 65)	100
Niobium 93m (Nb 93m)	10
Niobium 95 (Nb 95)	10
Niobium 97 (Nb 97)	10
Osmium 185 (Os 185)	10
Osmium 191m (Os 191m)	100
Osmium 191 (Os 191)	100
Osmium 193 (Os 193)	100
Palladium 103 (Pd 103)	100
Palladium 109 (Pd 109)	100
Phosphorus 32 (P 32)	10
Platinum 191 (Pt 191)	100
Platinum 193m (Pt 193m)	100

(c) This section does not authorize the production, packaging, repackaging, or import of byproduct material for purposes of commercial distribution, or the incorporation of byproduct material into products intended for commercial distribution.

(d) No person may, for purposes of commercial distribution import or transfer byproduct material in the individual quantities set forth in § 30.71 Schedule B, knowing or having reason to believe that such quantities of byproduct material will be transferred to persons exempt under this section or equivalent regulations of an Agreement State, except in accordance with a license issued under § 32.18 of this chapter, which license states that the byproduct material may be transferred by the license to persons exempt under this section or the equivalent regulations of an Agreement State.

Platinum 193 (Pt 193)	100
Platinum 197m (Pt 197m)	100
Platinum 197 (Pt 197)	100
Polonium 210 (Po 210)	0.1
Potassium 42 (K 42)	10
Praseodymium 142 (Pr 142)	100
Praseodymium 143 (Pr 143)	100
Promethium 147 (Pm 147)	10
Promethium 149 (Pm 149)	10
Rhenium 186 (Re 186)	100
Rhenium 188 (Re 188)	100
Rhodium 103m (Rh 103m)	100
Rhodium 105 (Rh 105)	100
Rubidium 86 (Rb 86)	10
Rubidium 87 (Rb 87)	10
Ruthenium 97 (Ru 97)	10
Ruthenium 103 (Ru 103)	10
Ruthenium 105 (Ru 105)	10
Ruthenium 106 (Ru 106)	1
Samarium 151 (Sm 151)	10
Sanarium 153 (Sm 153)	100
Scandium 46 (Sc 46)	10
Scandium 47 (Sc 47)	100
Scandium 48 (Sc 48)	10
Selenium 75 (Se 75)	10
Silicon 31 (Si 31)	100
Silver 105 (Ag 105)	10
Silver 110m (Ag 110m)	1
Silver 111 (Ag 111)	100
Sodium 24 (Na 24)	10
Strontium 85 (Sr 85)	10
Strontium 89 (Sr 89)	1
Strontium 90 (Sr 90)	0.1
Strontium 91 (Sr 91)	10
Strontium 92 (Sr 92)	10
Sulphur 35 (S 35)	100
Tantalum 182 (Ta 182)	10
Technetium 96 (Tc 96)	10
Technetium 97m (Tc 97m)	100
Technetium 97 (Te 97)	100
Technetium 99m (Tc 99m)	100
Technetium 99 (Tc 99)	10
Tellurium 125m (Te 125m)	10
Tellurium 127m (Te 127m)	10
Tellurium 127 (Te 127)	100
Tellurium 129m (Te 129m)	10
Tellurium 129 (Te 129)	100
Tellurium 131m (Te 131m)	10
Tellurium 132 (Te 132)	10
Terbium 160 (Th 160)	10
Thallium 200 (Tl 200)	100
Thallium 201 (Tl 201)	100
Thallium 202 (Tl 202)	100
Thallium 204 (Tl 204)	10
Thulium 170 (Tm 170)	10
Thulium 171 (Tm 171)	10
Tin 113 (Sn 113)	10
Tin 125 (Sn 125)	10
Tungsten 181 (W 181)	10
Tungsten 185 (W 185)	10
Tungsten 187 (W 187)	100
Vanadium 48 (V 48)	10
Xenon 131m (Xe 131m)	1,000
Xenon 133 (Xe 133)	100
Xenon 135 (Xe 135)	100
Ytterbium 175 (Yb 175)	100
Yttrium 90 (Y 90)	10
Yttrium 91 (Y 91)	10
Yttrium 92 (Y 92)	100
Yttrium 93 (Y 93)	100
Zinc 65 (Zn 65)	10
Zinc 69m (Zn 69m)	100
Zinc 69 (Zu 69)	1,000
Zirconium 93 (Zr 93)	10
Zirconium 95 (Zr 95)	10
Zirconium 97 (Zr 97)	10
Any byproduct material not listed above other than alpha emitting byproduct material	0.1
* Barium 133 (Ba 133)	10

NOTE: No more than 10 exempt quantities set forth in § 30.71, Schedule B of this chapter shall be sold or transferred in any single transaction. For purposes of this requirement, an individual exempt quantity may be composed of fractional parts of one or more of the exempt quantities in § 30.71, Schedule B, provided that the sum of such fractions shall not exceed unity.

Quantities of byproduct material in excess of the amounts specified § 30.71 Schedule B above cannot be supplied unless a copy of the customer's specific license to possess the material is on file with the supplier.

functions and to employ a cathode-ray oscilloscope to observe the effects of changing circuit parameters on signal output, or of changing pulse characteristics by varying circuit parameters. (Experiment 1).

Note that many circuit components are interconnected by cables carrying high voltages. Many components, especially semiconductors, are easily damaged by voltage transients. Whenever a circuit module is inserted or removed from a NIM bin or Power Supply or a connection is changed to a detector assembly, turn off the power or high-voltage supply. For stable operation it is also important that one point of the electronic system be connected to a reliable ground. Not all electric units have a grounded third pin on the plug and cable braiding does not provide a reliable ground return.

The following parameters are important for each of the major equipment items and must be taken into account when specifying such a unit.

A. High-voltage Power Supply

- Voltage range, e.g., 500-3000 volts, adjustable in steps or continuously
- Current output, typically 50A to 1mA
- Output polarity, positive or negative
- Voltage regulation; stability for slow variations in mains supply or for short transients
- Noise level (should be very low).

B. Preamplifier

- Amplifier gain, fixed or variable
- Supply voltage required
- Rise time
- Temperature sensitivity
- AC coupling; DC coupling usual for low-capacitance detectors only
- Noise level
- Input and output impedances.

C. Main amplifier

- Amplifier gain, fixed or adjustable
- Band width; determines rise time capability
- Pulse shaping capabilities; often in separate unit
- DC level restoration or cancellation of pulse undershoot
- Common-mode noise rejection
- Gain stability
- Gain linearity, over wide range of signal amplitudes.