RADIOLOGICAL MONITORING METHODS AND INSTRUMENTS

Handbook 51

U. S. Department of Commerce
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Radiological Monitoring Methods and Instruments

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Preface

The Advisory Committee on X-ray and Radium Protection was formed in 1929 upon the recommendation of the International Commission on Radiological Protection, under the sponsorship of the National Bureau of Standards and with the cooperation of the leading radiological organizations. The small committee functioned effectively until the advent of atomic energy, which introduced a large number of new and serious problems in the field of radiation protection.

At a meeting of this committee in December 1946, the representatives of the various participating organizations agreed that the problems in radiation protection had become so manifold that the committee should enlarge its scope and membership and should appropriately change its title to be more inclusive. Accordingly, at that time the name of the committee was changed to the National Committee on Radiation Protection. At the same time, the number of participating organizations was increased and the total membership considerably enlarged. In order to distribute the work load, eight working subcommittees were established, as listed below. Each of these subcommittees is charged with the responsibility of preparing protection recommendations in its particular field. The reports of the subcommittees are approved by the main committee before publication.

The following parent organizations and individuals comprise the main committee:

American Medical Association: H. B. Williams.
American Radium Society: E. Quimby and J. E. Wirth.
American Roentgen Ray Society: R. R. Newell and J. L. Weatherwax.
National Bureau of Standards: L. S. Taylor, Chairman.
National Electrical Manufacturers Association: E. Dale Trout.
Radiological Society of North America: G. Failla and R. S. Stone.
U. S. Air Force: W. S. Cowart, Lt. Col.
U. S. Army: D. A. York, Lt. Col.
U. S. Atomic Energy Commission: K. Z. Morgan and Shields Warren.
U. S. Navy: W. H. Sullivan.
U. S. Public Health Service: H. L. Andrews and E. G. Williams.

The following are the subcommittees and their chairmen:

Subcommittee 1. Permissible Dose from External Sources, G. Failla.
Subcommittee 2. Permissible Internal Dose, K. Z. Morgan.
Subcommittee 3. X-rays up to Two Million Volts, H. O. Wyckoff.
Subcommittee 4. Heavy Particles (Neutrons, Protons and Heavier), D. Cowie.
Subcommittee 5. Electrons, Gamma Rays and X-rays above Two Million Volts, H. W. Koch.
Subcommittee 6. Handling of Radioactive Isotopes and Fission Products, H. M. Parker.
Subcommittee 7. Monitoring Methods and Instruments, H. L. Andrews.
Subcommittee 8. Waste Disposal and Decontamination, J. H. Jensen.

With the increasing use of radioactive isotopes by industry, the medical profession, and research laboratories, it is essential that certain minimal precautions be taken to protect the users and the public. The recommendations contained in this Handbook represent what is believed to be the best available opinions on the subject as of this date. As our experience with radioisotopes broadens, we will undoubtedly be able to improve and strengthen the recommendations for their safe handling, utilization, and disposal of wastes.

This report does not endeavor to provide a complete manual on radiological instruments. It is designed, however, to indicate the types of measurements and instruments that are necessary for determining the adequacy of radiation shielding. This applies to low-voltage and high-voltage X-ray installations, radioactivity laboratories, radium handling areas, etc. The Committee on Nuclear Sciences of the National Research Council is preparing detailed reports on specific instrumentation problems and the reader is referred to these reports for more detailed information.

The present Handbook has been prepared by the Subcommittee on Monitoring Methods and Instruments. Its membership is as follows:

H. L. Andrews, Chairman.
C. B. Braestrup.
J. Healey.
R. E. Lapp.
W. H. Ray.
J. E. Rose.
E. G. Williams.

A. V. Astin, *Acting Director.*

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Radiological Monitoring Methods and Instruments

I. General

1. Scope of Report

It is imperative that users of radioactive materials and other sources of radiation take adequate measures to prevent overexposure of personnel. Any adequate radiation protection program may require a variety of types of measuring instruments, and trained personnel must be available to insure the use of suitable instruments in the proper way, to interpret the readings obtained, and to make necessary recommendations for reducing hazards. The present report represents an attempt to establish some basic guides for methods of determining radiation hazards and selecting suitable instruments for measuring them. No attempt will be made to give detailed discussions of the recommendations.

Radiation hazards arise from a wide variety of sources and the monitoring methods must vary accordingly. Sources such as X-ray units are relatively fixed in position and constitute radiation hazards only when they are in operation. Radioactive isotopes, on the other hand, are hazardous until natural decay has reduced the activity to safe levels. Furthermore, such materials may be spilled or lost during their use and become rather widely spread throughout a building or area. High-voltage accelerators represent an intermediate case, where the greatest hazard is present during operation, but where induced radioactivity may persist for some time after the equipment is shut down.

The attainable characteristics of radiation-protection instruments are dependent on technical advances in electronics and in other fields. For this reason, specific recommendations may become obsolete as new designs are introduced. The present report considers only types that have proved useful in practice.

Throughout this report a sharp distinction has been made between scanning and measuring radiation. *Scanning* is used to denote a rapid, qualitative survey, usually carried out with sensitive detecting instruments, to locate and determine the extent of a radiation source. *Measuring* refers to

the quantitative determination of the kind and amount of radiation present.

It should be emphasized that the measurement and evaluation of hazardous radiation is not generally a straightforward problem. This is particularly so in situations involving a mixture of two or more types of radiation. Such work should be done, whenever possible, by a trained health physicist who is familiar both with the instrumentation and the operational problems.

2. Definitions

Terms in this report will be used in accordance with the following brief definitions:[1]

2.1 *Shall.* Is necessary to meet currently accepted standards.

2.2 *Should.* Is recommended. Indicates advisory requirements that are to be applied when possible.

2.3 *Assay.* The determination of kind and quantity of radioactive materials present by physical or chemical measurements.

2.4 *Air-equivalent.* Descriptive of materials for walls and electrodes of ionization chambers selected to produce ionization for proton or electron measurement essentially equivalent to that in a free-air ionization chamber. This is possible only over limited ranges of photon energies.

2.5 *Dose.*[2] The radiation delivered to a specified volume or to the whole body. The unit is the roentgen.

2.6 *Dose meter.* An instrument that measures radiation dose.

2.7 *Dose rate.* The radiation dose delivered per unit time.

2.8 *Electromagnetic radiation.* For purposes of the present report, X-rays and gamma rays.

2.9 *Exposure.*[3] The total quantity of radiation at a given point, measured in air. The measurement of exposure is made at a given point in the radiation field without the presence of a scattering body.

2.10 *Exposure rate.* The amount of radiation (exposure) delivered at a given point per unit time.

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[1] For more critical definitions, see "Glossary of Terms in Nuclear Science and Technology," National Research Council.

[2, 3] The terms "dose" and "exposure" are frequently used loosely with no clear distinction between their meanings. The definitions given here do not agree with those given in the NBS Handbook 41 because of concepts developed since its publication.

2.11 *Electrometer.*[4] An instrument for measuring the difference in electric potential between two points.

2.12 *Electrometer tube.* An electronic tube specially designed and constructed to measure very small electric potentials.

2.13 *Electroscope.*[5] An instrument for detecting the presence of an electric charge on a body.

2.14 *Flux.* A rate of flow across a unit area. For example, a neutron flux is the number of neutrons that cross 1 cm^2/sec.

2.15 *Geiger-Müller counter (G-M counter).* A chamber equipped with suitable electrodes and operated at a voltage and gas pressure that will permit ionization by collision and in which the total ionization per event is independent of the amount of ionization produced by the absorption of radiation.

2.16 *Ionization.* The process whereby a neutral atom or molecule is split into positive and negative ions.

2.17 *Ionization by collision.* Ionization produced when ions already formed are accelerated as by an electric field to velocities high enough to produce more ions by collisions with neutral atoms or molecules.

2.18 *Ionization chamber.* A container with electrodes on which suitable voltages are impressed for collecting only ions formed in the gas in the chamber by the ionizing event.

2.19 *Personnel meter.* A device to be worn or carried by a person for the purpose of detecting or measuring radiation received by him.

2.20 *Proportional counter.* A chamber equipped with suitable electrodes and operated at voltages high enough to produce ionization by collision and adjusted so that the total ionization per count is substantially proportional to the ionization produced by the absorption of the radiation per event.

2.21 *Radiation.* Energy propagated through space.

2.22 *Radiation field.* Region in which radiation is propagated.

2.23 *Roentgen (r).* The international unit of quantity for both X-rays and gamma rays adopted by the Fifth International Congress of Radiology at Chicago in 1937. It was defined by the International Commission on Radiological Units in the following words:

> The International Unit of quantity or dose of X-rays or gamma rays shall be called the roentgen and shall be designated by the symbol r. The roentgen shall be the quantity of X- or gamma-

[4, 5] There is some confusion in the usages of the terms "electrometer" and "electroscope," but the definitions given suffice for this report.

radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign.

2.24 *Roentgen equivalent physical (rep).* Although not an internationally accepted unit, the rep is often a convenient shorthand notation for statements of dose of ionizing radiation not covered by the definition of the roentgen. One represents that dose which produces energy absorption of 93 ergs/g of tissue. The actual energy absorption in tissue per roentgen is a function of the tissue composition and of the wavelength of the radiation. It ranges between 60 and 100 ergs/g. For calculations of permissible exposure this variation is ignored, and a beta-ray dose of one rep is said to be physically equivalent to an X-ray dose of 1 r at a given point in the body. The numerical coefficient of the rep has been deliberately changed to 93, instead of the earlier 83, to agree with L. H. Gray's "energy-unit".

2.25 *Saturation.* Condition in an ionization chamber when the applied voltage is sufficiently high to collect all the ions formed from the absorption of radiation, but insufficient to produce ionization by collision.

2.26 *Survey.* A critical examination of the radiation near a source by or under the supervision of a qualified expert.

2.27 *Survey meter.* A device for detecting radiation fields or for measuring exposure or exposure rate.

3. General Principles of Hazard Control

3.1 Radiation injuries can be prevented if potential exposures can be forecast with sufficient accuracy to permit the application of appropriate protective measures. Basic protective measures, not all of which may be required simultaneously, follow in the next two paragraphs.

3.2 Entrance of radioactive materials into the body should be prevented by (a) enclosing all radioactive materials, (b) supplying air of assured purity to all occupied spaces, (c) maintaining effective contamination control boundaries around all sources, (d) using immaculate handling techniques, (e) decontaminating where control has failed, and (f) enforcing a rigid system of accounting for all radioactive materials.

3.3 Irradiation of any part of the body should be reduced at least to, and preferably well below, the maximum permissible dose,[6] a minimum to be sought by (a) reducing the

[6] See NBS Handbook 47, Recommendations of the International Commission on Radiological Protection and of the International Commission on Radiological Units (1950). Further reports on permissible dose are in the course of preparation by the National Committee on Radiation Protection.

time of exposure, (b) increasing the distance from the source, and (c) interposing shielding.

4. Airborne Hazards

4.1 Laboratory air and air discharged from the laboratory should be monitored for radioactivity if there is any possibility of airborne contamination at hazardous levels.

4.2 Continuous sampling of airborne particulates (section VII) can be used to determine concentrations of beta and gamma emitters provided the samples truly represent the air being breathed. Airborne contamination may remain localized and fixed instruments may fail to indicate the extent of contamination.

4.3 Assays for long-lived alpha-emitting particulates are complicated by the fact that maximum permissible concentrations may be less than the naturally occurring decay products of radon and thoron. Studies on concentrates may be required in order to evaluate the hazard properly. Any assays for airborne alpha-emitters should be supplemented by a careful analysis of the physical circumstances giving rise to the hazard. Protective measures should be instituted if there is a chance that alpha emitters may become airborne.

4.4 Radioactive, chemically active gases can be concentrated by chemical methods from a known volume of air and assayed by laboratory counting techniques.

4.5 Methods for assaying radioactive, noble gases are unsatisfactory because of the difficulty of concentrating a suitable sample. Some noble gases can be condensed with liquid air, but others require lower temperatures.

4.6 Radon and thoron present particular problems because each has a number of radioactive daughter products. Radon and thoron can be condensed with liquid air. To evaluate properly the hazard associated with these isotopes, it is necessary to know the stage of decay of the sample assayed. A curve showing the rise and fall of gamma activity from radon is shown in figure 3.

5. Surface Contamination

5.1 Quantitative measurements of surface contamination are difficult because of unknown factors such as self-absorption, geometry, and depths of penetration. Estimates made by counting wipes furnish useful information and should be made in order to determine whether or not a contaminant is likely to rub off a surface. However, these measurements are only qualitative and unreliable because of the uncertainty as to the amount of contamination removed. In general,

measurements of surface contamination are qualitative in nature.

5.2 Identification of the kinds of radiation emitted should be made to estimate the possibility of alpha-emitters becoming airborne.

5.3 In some cases measurements of alpha and low-energy beta contaminants may require the removal of surface material and a chemical separation of radioactive and inert components.

6. Determination of Hazards

6.1 The determination of the existence of a radiation hazard presupposes the presence of a radiation field. The degree of the hazard and the protection techniques to be instituted depend on the location of the source, its strength, physical form, and the kind and energy distribution of its radiations. Protective measures should be checked by measurements whenever possible.

6.2 Scanning rather than measuring instruments should be used to locate unknown sources. Scanning instruments require rapid meter response, and aural indicators are useful as they respond promptly and permit the eyes to follow the sensitive element. Shields around part of the sensitive element are desirable

6.3 All locations where a scanning survey shows an exposure rate of one-fifth or more of the permissible value are to be considered potentially hazardous. Quantitative measurements shall be made at all of these positions.

6.4 Except for alpha particles and neutrons, all measurements should be expressed in roentgens or reps (depending on the type of radiation) per unit time.

6.5 Neutron measurements may be expressed as the number of neutrons per square centimeter per second (flux density), together with any available information on the energy distribution of the neutrons.

7. Personnel Monitoring

7.1 Every person whose safety depends upon proper operating procedures rather than upon adequate shielding shall have upon his person a personnel meter at all times when exposure is possible. Personnel meters may be any one or a combination of the following types: (a) Pocket ionization chamber, (b) pocket dose meter, and (c) photographic film meter.

7.2 Under some conditions other types of personnel meters may be used. Pocket ionization chambers with an alarm actuated after a preset exposure, crystal, or chemical dose meters may be used.

7.3 It must be remembered that personnel meters measure the exposure only at the point where they are worn, which should be the part of the body expected to receive the greatest exposure.

7.4 In general, personnel meters do not respond properly to beta radiation and may give incorrect readings with low-energy electromagnetic radiation unless specially calibrated.

II. Radiation Detectors

8. Beta-and Gamma-Radiation Detectors

8.1 A detecting instrument should be used for locating sources of radiation and contamination. It shall not be used for measurement of the radiation unless it has been calibrated under appropriate conditions with radiation of approximately the same energy distribution as that being measured.

8.2 A detecting instrument should have sufficient sensitivity to show a response to normal radiation background. It should be capable of rapid response and preferably be equipped with an aural indicator.

8.3 A G-M counter may be suitable for detecting beta and gamma radiation. For beta-particle detection the G-M tube should have as thin a wall as possible. A movable shield will serve to differentiate beta from gamma radiations. The G-M tube shall not respond to visible light, and it should function properly over the maximum range of temperature in which it may be used.

8.4 For the detection of soft radiations, such as the beta particles from C^{14} and S^{38}, any absorbing material between the source and the detector shall be a minimum.

8.5 Care shall be taken to insure that the instrument is in proper operating condition by frequent tests with a known source of radiation.

9. Alpha-Particle Detectors

9.1 Proportional counters, ionization chambers, or scintillation counters should be used to detect alpha particles.

9.2 Sensitive detectors incorporating flat ionization chambers with thin windows of a material such as nylon are satisfactory. An equivalent window thickness of 0.5 mg/cm^2

is acceptable. Ionization-chamber readings measure total alpha ionization near the source and must not be interpreted as dose rate to the body.

9.3 A standard alpha-emitter should be available at all times for instrument checks.

10. Neutron Detectors

10.1 Slow (0.03 to 100 ev) and intermediate (100 ev to 0.01 Mev) neutrons can be detected with a proportional counter lined with boron carbide or filled with boron trifluoride gas. This method discriminates against other types of radiation. As detection is obtained through the alpha particle from the B^{10} (n, α) reaction, the sensitivity can be enhanced by using boron enriched in B^{10}.

10.2 A cadmium shield can be placed outside an ion chamber to detect slow neutrons through the Cd (n, γ) reaction. If gamma radiation is also present, an additional reading is needed to determine the net effect due to neutrons. For measurement of this background a similar shield of a material whose gamma absorption is the same as the cadmium, but which does not give an (n, γ) reaction, should be used.

10.3 Slow neutrons can be detected with a double chamber, one half of which is lined with boron. The instrument is differentially sensitive to neutrons and can be used in the presence of gamma radiation.

10.4 Intermediate-energy neutrons can be detected by placing a paraffin moderator around either of the instruments described in paragraphs 10.1 and 10.2. The incident neutrons will be reduced in energy by hydrogen collisions to the point where either of the above nuclear reactions becomes appreciable.

10.5 Neutrons with greater than thermal energies can be detected by placing around a boron-containing proportional counter sufficient paraffin to reduce some neutrons to thermal energies. A 3½-inch paraffin thickness will produce a maximum flux of thermals. A cadmium or boron shield outside the moderator can be used to exclude slow neutrons from the determination.

10.6 As tissue damage by fast neutrons is probably largely due to ionization from recoil protons, fast neutron hazards may be estimated from measurements with a chamber filled with a hydrogen-rich gas, such as methane. To make this measurement in the presence of gamma radiation, a second chamber of the same volume filled with a high atomic number gas can be connected differentially with the first. This

chamber must be lined with a hydrogenous material, such as paraffin, of a thickness equal to the maximum range of the recoil protons (see fig. 1) if the ionization is to be expressed in rep. If the neutron beam is smaller in cross-sectional area than the flat plate area of the chamber, correction must be made for the volume actually irradiated. If gamma radiation is present, readings should be taken with the beam passing through each chamber and the positions of the chambers reversed to estimate the effects of absorption. In some cases it may be necessary to take separate readings with each chamber.

10.7 A methane-filled proportional counter can be adjusted to be insensitive to gamma radiation and yet respond to fast neutrons through the proton recoils.

10.8 At present there is insufficient experience with neutrons with energies above 10 Mev to permit making recommendations.

10.9 The calibration of neutron detectors is difficult and not entirely satisfactory. Only a rough outline of methods can be presented here.

Boron-containing chambers can be calibrated in a neutron flux that has been established by measurement of the activity induced in indium foils.

Twin-chamber instruments for fast neutrons can be calibrated by exposing to known gamma radiation the previously matched chambers (paragraph 10.6) but now connected with additive instead of reversed polarities. After a correction is made for the absorption by the chamber walls, the ionization-per-gram of chamber gas can be calculated. One-half of this value will be the sensitivity of the reversed polarity connection for fast neutrons.

Calibrations for neutrons of energy greater than 3.5 Mev can be made from the induced radioactivity in sulfur because above this energy the cross section for the (n,p) reaction in sulfur is nearly constant at 0.5 barn.

III. Measuring Instruments

11. X- and Gamma-Radiation Measuring Instruments

11.1 Electromagnetic radiation is measured by the collection of ions formed in an air-filled ionization chamber with air-equivalent walls. The wall thickness should be at least equal to the maximum range of the secondary electrons but should not greatly exceed this value. Special care must be taken in selecting suitable chambers for photon energies below 100 kev.

11.2[7] Collection voltages shall be sufficient to produce saturation in all regions of the chamber at all intensities to be measured, but shall not be so high as to produce ionization by collision.

11.3[8] Saturation conditions must be specially investigated when chambers are used with pulsed sources where the peak radiation intensities may be very high.

11.4 The chamber should project from the body of the instrument to minimize scattering from circuit components and to permit a more accurate evaluation of the measuring geometry. This can be accomplished by detaching a charged chamber from the measuring instrument.

11.5 Instruments designed to measure more than 1 r/hr should be constructed to permit mounting of the chamber on a probe at a distance from the indicating portion of the circuit so that readings can be taken without undue exposure of the operator.

11.6 The ionization can be measured by the change in charge collected on a capacitor or by the potential developed across a resistor. Electrometer tubes and amplifiers, electroscopes, and electrometers are satisfactory for this purpose.

11.7 Calibration sources for electromagnetic radiation instruments should have essentially the same energy distribution as the radiation to be measured. The primary standard of comparison for energies up to 250 kev should be the standard free-air chamber. Above 200 kev a thimble chamber, so constructed as to be essentially energy-independent, can be used.

11.8 All instruments for general use should be checked for energy dependence with gamma radiation from Ra or Co^{60} and with X-rays. There should be not more than a 20-percent variation between 100 kev and 2 Mev.

11.9 Radium in equilibrium with its decay products and in a container with 0.5-mm platinum walls will produce a gamma-ray field given by

$$r/\text{hr}=\frac{8.4\times(\text{mg of Ra})}{d^2}$$

for all distances d (in centimeters) greater than 20 times the greatest dimension of the source. Co^{60} may be used for instrument calibration if the output of the source is known in roentgens per unit time at a given distance. In using Co^{60} for calibration, care must be taken to correct for the decay,

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[7, 8] Some instruments are deliberately designed to operate at less than saturation voltage in which case paragraph 11.2 does not apply. Paragraph 11.3 applies equally to the nonsaturation type of instrument.

which takes place with a half-life of 5.3 years. In making calibrations care must be taken to minimize scattering. The equation given above is strictly valid only if there is no scattering, and where air attenuation is negligible.

11.10 Care shall be taken to insure that the instrument is in proper operating condition by frequent tests with a known source of radiation.

12. Beta-Radiation Instruments

12.1 Beta radiation may be measured by the collection of ions produced in an air-filled ionization chamber. The reading so obtained will be lower than the actual value by an amount that depends upon the thickness and material of the chamber walls and on geometric factors. The corresponding reading may be higher under some conditions.

12.2 At least one end or side of the ionization chamber shall be provided with a window thin enough to permit the entrance of a substantial fraction of the beta particles. The window should preferably have an equivalent thickness of not more than 7 mg/cm^2. The range of beta particles in aluminum is calculated from empirical equations derived from experimental data. The range depends primarily on the mass per unit area and only secondarily on the window material. See figure 2 for a curve of beta particle ranges. In using these curves it should be remembered that the beta-particle energies commonly given represent the *maximum* energy of emission and that the average energy is in general about one-third of the maximum.

Removable absorbers of not less than 1.0 g/cm^2 should be provided to cover the thin window completely and permit the differentiation of beta from gamma radiation. The material of the absorber should be air equivalent.

12.3 Precise measurement of beta radiation from a surface is best done with an extrapolation chamber.

12.4 For monitoring purposes a thin-wall chamber of organic material may be calibrated by covering the chamber with a cap of suitable thickness and composition as specified in paragraph 11.1. With this cap the chamber becomes essentially air equivalent for X-rays or gamma rays of the proper energy, and it may be calibrated with either an X-ray, radium, or Co^{60} source. With the cap removed, a chamber reading resulting from beta radiation can be expressed in arbitrary units, roughly equivalent to rep at that thickness of material. It may be calibrated with other sources of beta particles having equivalent energies.

12.5 An alternative method uses a surface monitor calibrated with a source that has been standardized with an extrapolation chamber.

12.6 Care shall be taken to insure that the instrument is in proper operating condition by frequent tests with a known source of radiation. The size and location of the instrument with respect to the source are important factors in making measurements of the beta-ray dose, and when measurements are made these should be comparable to the conditions used during calibration of the instrument or correction made for the discrepancy.

13. Alpha-Particle Instruments

13.1 Alpha-particle measurements can be made with the instruments described in section 9, provided proper calibrations are made.

13.2 No attempt should be made to measure alpha radiation and express it in rep. Results should be given as counts per minute with a given instrument or as disintegrations per minute per square centimeter if the geometrical efficiency of the instrument is known.

13.3 Chambers measuring gross ionization should be calibrated under the same conditions of energy spectrum, absorption, and geometry as for the assay.

IV. Personnel Monitoring Instruments

14. Beta and Gamma Instruments

14.1 Gamma-ray doses can be measured by ionization chambers with walls of air-equivalent materials. Ionization chambers can be so constructed that an auxiliary electroscope or electrometer is used to measure the ionization produced. In an alternative construction (dosimeter) a quartz-fiber electroscope is built into the ion chamber, and the instrument can be read without auxiliary equipment.

14.2 Calibration should be carried out as described in paragraphs 11.6 and 11.7.

14.3 A photographic film can be used for determining beta and gamma doses. A portion of the film should be shielded with about 1 mm of a suitable metal to prevent response to beta radiation and to improve the response to higher-energy photons. Tin, silver, cadmium, or lead are commonly used for this purpose as well as to reduce the energy dependence of the film.

14.4 Beta radiation can be determined from the blackening of the unshielded portion of the film, after suitable corrections are made for gamma-ray exposure and absorption by the film wrapping. Since most of the sensitive photographic emulsions are 15 to 20 times as sensitive to gamma radiation of 50 to 100 kev as to gamma radiation of 1 Mev, it is extremely difficult to estimate what fraction of the open-window readings is due to beta and what fraction is due to soft gamma radiation if both beta and soft gamma radiation are present in unknown quantity.

14.5 The film shall be processed with great care. Fresh chemicals are to be preferred, but where this is impractical the control films will serve as a check on the processing. Constant agitation of the developer is usually recommended but quiet solutions may be used if the process is standardized. Developing temperatures shall be controlled to $\pm 1°$ F. Standard exposed films shall be processed in each batch as controls.

14.6 When visual comparison with control films exposed to known amounts of radiation and processed simultaneously indicates an exposure of more than one-fifth of the permissible value, the film densities should be measured with a quantitative densitometer.

14.7 Photographic films should be calibrated with known sources of radiation of the proper energy distribution to insure the accurate determination of the exposure.

14.8 Beta calibrations should be made under proper conditions with known sources having energy distributions similar to that of the radiation being determined and having no gamma radiation softer than 1 Mev.

14.9 Films should have identifying markings produced by a suitable X-ray exposure, by punch marks, or by other suitable means of positive identification. If X-rays are used, care must be taken to prevent fogging of the useful portions of the films.

15. Neutron Instruments

15.1 Slow neutrons can be estimated with pocket ionization chambers containing boron either in the walls or in the gas.

15.2 Calibration of these chambers can be made in accordance with paragraph 10.8.

15.3 Fast neutrons can be estimated through proton-recoil tracks in special photographic emulsions prepared to be relatively insensitive to γ radiation. The developed emulsion must be examined with a microscope.

Slow neutrons and fast neutrons can be monitored with the same photographic emulsion if a portion of the film is covered with a cadmium shield. The cadmium absorbs the slow neutrons so that the proton-recoil tracks in the shielded portion of the film will be due to the proton-recoil reaction of fast neutrons with hydrogen; and the tracks in the portion of the film that is behind the open window will be due both to the N^{14} (n, p) C^{14} reaction, which is produced by slow neutrons, and the proton-recoil reaction with hydrogen.

15.4 The photographic plates can be calibrated by a determination of the track density in similar emulsions exposed to a standard neutron source.

V. Instrument Requirements

16. General

16.1 All radiological-protection instruments should reproduce their own readings to ± 10 percent of full-scale reading at any point along the scale. Survey instruments should be provided with sensitivity adjustments capable of changing the sensitivity by a ratio of about 2 to 1 so that calibrations can be maintained. The sensitivity adjustment shall require the use of a screwdriver or other tool for operation, or it should be recessed and covered or sealed in such a way as to discourage its use except during calibration adjustment of the instrument.

16.2 Battery life should provide at least 100 hr of continuous operation, and the instrument sensitivity shall not change by more than 10 percent with 50 hr of operation. Battery connections shall be made with snap, screw, or plug terminals and not by soldering.

16.3 Weight shall be kept at a minimum.

16.4 All external surfaces shall be hard and smooth to facilitate decontamination. Cracks and joints shall be kept to a minimum. Crackle paint finishes are not acceptable.

16.5 All instruments should operate under ambient conditions of 90 percent relative humidity and over a temperature range of 20° to 125° F.

16.6 All instruments used for measuring electromagnetic radiation should have scales marked in milliroentgens or in milliroentgens per hour. Instruments used only for detecting alpha and beta particles shall have scales graduated in arbitrary units.

16.7 If multirange indicating meters exhibit only the scale corresponding to the sensitivity at which they are set,

it is recommended that they conform to the following color code:

Maximum reading (r/hr)	Color
500 and above	Fire-engine red.
50 to 499	Light magenta.
5 to 49	Orange.
0.5 to 4.9	Yellow.
0.05 to 0.49	White.
0.005 to 0.049	Green-yellow.
0.0005 to 0.0049	Light-blue.

16.8 All instruments shall be constructed according to the accepted standards of high-quality electronic instrumentation. As far as possible, standard circuit components and batteries shall be used. Wherever possible, components shall conform to Joint Army-Navy specifications. A circuit diagram should be secured inside the case to facilitate servicing.

17. Detecting Instruments

17.1 G–M tubes should have a well-defined plateau where the counting rate with a constant source of radiation should not change by more than 5 percent per 100 v.

17.2 The length of the plateau so defined should not be less than 15 percent of the voltage at the center of the plateau.

17.3 G–M tubes for general use should have an opaque coating of effective thickness not greater than 5 mg/cm^2 to prevent any discharges due to visible light when the tube is exposed to direct sunlight. The coating shall not require renewal during the life of the tube. It shall remain intact after 24 hr of immersion in water.

17.4 G–M tubes used for detecting both beta and gamma radiation (except for the beta radiation from C^{14} and S^{35}) should have an effective wall thickness not greater than 30 mg/cm^2.

17.5 G–M tubes used for detecting beta radiation from C^{14} and S^{35} should have an effective window thickness not greater than 5 mg/cm^2 and the thickness should be uniform. As this may preclude the use of an opaque coating on the window, the tube must be inherently nonphotosensitive.

17.6 Any movable shield designed to stop beta radiation should have a thickness at least equal to the maximum range of the fastest beta rays (approximately 1.0 g/cm^2). The effect of bremsstrahlung can be reduced by using mate-

rials of low atomic number on the side of the shield next to the source and high atomic number material on the other side, if necessary.

17.7 The instrument shall have a sensitivity such that a significant indication is obtained with normal, natural background radiation.

17.8 The meter should not read less than full scale when exposed to radiation intensities from 1 to 100 times that required to produce full-scale deflection.

18. Measuring Instruments

18.1 Ionization chambers designed for measuring electromagnetic radiation shall agree within ±20 percent with a standard chamber (see paragraph 11.6) for quantum energies between 100 kev and 2 Mev. Chambers with greater accuracy are available if desired.

18.2 When calibrated with the gamma radiation from Co^{60} or from radium in equilibrium with its decay products and shielded with 0.5 mm of platinum or its equivalent, the instrument shall read correctly within ±10 percent of full scale over all portions of the scale.

18.3 Whenever consistent with the wall thickness necessary for obtaining the required energy response, chambers designed for measuring only electromagnetic radiation should be hermetically sealed to withstand pressures from 1.2 to 0.6 times normal atmospheric pressure (76 cm of mercury) and should show changes of sensitivity of not more than ±10 percent over this pressure range.

18.4 Instruments designed for measuring only electromagnetic radiation should maintain calibration within 20 percent after 24 hr at 100-percent relative humidity and the usual ambient temperature.

18.5 Ionization chambers should be made as small as is consistent with the required sensitivity.

18.6 Ionization chambers designed to measure alpha particles in the presence of beta and gamma radiation shall have dimensions such that the ratio of the alpha response to the beta response is as large as possible.

18.7 Ionization-chamber instruments with electrometer-tube amplifiers should have an overall time constant such that two-thirds of final reading is attained in not more than 3 sec for ranges at 50 mr or more per hour and not more than 6 sec for more sensitive ranges.

18.8 The insulation leakage in integrating-type ionization chambers with ranges of 100 mr or greater shall be such that a charged chamber placed in a region free from all but

normal, natural background radiation shall have a discharge rate not exceeding 2 percent of full-scale reading per 24 hr.

19. Personnel Instruments

19.1 The provisions of paragraphs 16.1, 16.3, 16.4, 16.5, 16.6, 18.1, 18.2, 18.3, 18.4, 18.5, and 18.8 shall also apply to personnel instruments of the ionization chamber type.

19.2 Pocket-type instruments with built-in optical systems shall be sufficiently rigid to preserve proper alinement and focusing when the instrument is dropped in any orientation from a height of 4 ft onto a wood floor.

19.3 Electrometer-type instruments with built-in scales shall be so constructed that relative rotation of scale and fiber is impossible.

19.4 The scale reticle shall be so constructed that it is not damaged by exposure of the instrument to direct sunlight.

19.5 The scale reading of electrometer-type instruments should not change by more than 2 percent of full-scale reading with any change in orientation. If this condition cannot be met, operating instructions should include a statement about proper reading position.

19.6 Pocket ionization chambers and dosimeters should be color coded in accordance with the following code:

Range (r)	Color
500 or higher	Fire-engine red.
50 to 499	Light magenta.
5 to 49	Orange.
0.5 to 4.9	Yellow.
0.05 to 0.49	Black.

19.7 Alarm meters should be so constructed that the level of alarm may be preset to any value between 40 and 100 mr, but this adjustment shall be inaccessible to the wearer.

19.8 The standard photographic film meter should consist of sensitive film in a standard, dental size packet (approximately 1¼ by 1¾ in).

19.9 The packet should contain one film with a useful range of approximately 0.05 to 2.0 r. If desired, a second film with a useful range of approximately 1.0 to 10 r may be put in the same packet. Useful range is defined as the portion of the plot of optical density against log exposure that has a slope not less than one-half that of the essentially linear portion. The useful range will depend to some extent

on the film processing procedures used. Paragraph 28.3 lists the sensitivity ranges of some commonly used photographic emulsions.

19.10 Approximately one-half of the film area should be covered with a shield of high-atomic-number material as specified in paragraph 14.3. The shield should be so arranged that a portion of the film has a shield on both sides.

VI. Radiation-Survey Methods

The purpose of this section is to outline the recommended procedures for making surveys of X-ray units and other fixed sources of radiation and areas where radioactive materials are being handled and stored. It is more difficult to be specific when radioactive materials are involved as the source of hazard may be less sharply localized, conditions may change rapidly with time, and the hazard cannot be reduced or eliminated by turning off the power. Particular attention is directed to those radiation hazards that are frequently overlooked. These will be discussed under each type of source. Care should be taken to insure that all instruments used are suitable for the type and energy range of the radiations. Further information on survey methods can be obtained from NBS Handbook 41, section 2.

20. General Recommendations

20.1 The survey should include a study of the laboratory operating procedures, personnel habits, and the methods used in handling sources. The survey should be made under representative conditions and techniques, and under conditions where the possible hazard would be greatest.

20.2 Except where noted, a preliminary scanning is recommended with a G-M survey meter or with an instrument of similar sensitivity. Because of the wavelength and directional dependence of such instruments, scanning should be supplemented with ion-chamber readings if the preliminary tests show a dosage rate of more than one-tenth of the permissible value.

20.3 The instruments used for the survey should comply with the following requirements: (a) Proper calibration, and maintenance thereof, (b) proper sensitivity, (c) small directional effect, (d) small energy dependence in the region of interest, (e) small sensitive area, (f) saturation voltage for ionization chambers, and (g) Geiger-Müller counters not subject to blocking or falling back of the reading when in radiation fields grossly above scale.

20.4 Written records of all surveys shall be maintained. Reports of results of final surveys should be made to the person responsible for the installation.

20.5 Dosage rates at critical points should be indicated in milliroentgens per hour (or milliroentgens per 100 ma-sec for radiography). If the locations cannot be positively identified by suitable description, they should be marked on a scale drawing of the installation. If, at any of these positions the permissible dose would be exceeded in a 48-hr week, the maximum time that the personnel may remain at this position shall be indicated. These positions can be identified by numbers or letters on the scale drawing. A table can then give the dosage rates and times for each of these positions.

20.6 The report shall include recommendations as to corrections in the operational techniques, barrier thickness, mechanical restriction of the radiation beam, or any other factors that will eliminate radiation hazards in occupied positions.

20.7 If radiation hazards are found to exist, the surveyor should make a reexamination after the fault has been remedied.

20.8 Personnel monitoring should be recommended where needed, and present techniques modified if unsatisfactory.

21. Radioactive-Isotope Monitoring

21.1 In making surveys it is desirable to establish as soon as possible what isotopes are involved. This can usually be done from an operational history of the areas. If other radioactive materials are being used in nearby areas, the possibility of cross-contamination must be considered. If there is any uncertainty as to the isotopes involved, they should be determined from assays.

21.2 Airborne contamination should receive first consideration. Air samples should be taken for the type of activity anticipated. If possible, these should be taken at the breathing zone. Airborne contaminants are hazardous and may become widespread in a relatively short time.

21.3 In area surveys, the speed of search should be adjusted to the response time of the instrument used and to the limits imposed by statistical fluctuations. With aural or visual indication the response time does not impose a limit on searching speed.

21.4 Area surveys must be *thorough*. A spot that is hard to reach with an instrument may be readily accessible to contamination. All reasonably possible locations should be suspect until proved otherwise.

21.5 If contamination is found, decontamination should be started promptly. See National Bureau of Standards Handbook 48 [9] for details.

21.6 If any possibility of personnel contamination exists frequent surveys with scanning instruments should be made.

21.7 All personnel should have their hands (front and back) and shoes checked when they leave a potentially contaminated area.

21.8 All manipulative techniques should be carefully observed and dosage rates measured at the various phases of the operations. Time limits should be established for all procedures that are found to produce hazard. It should be insisted that every procedure be carefully planned and rehearsed with nonradioactive materials.

21.9 All shielding should be carefully inspected for contamination and for possible radiation leaks. This should include floors, walls, ceilings, and adjoining spaces.

21.10 Periodic surveys of the surroundings should be made. If possible, the ducts from hoods should be surveyed throughout their entire length. Sludge from sewers should be assayed for activity, and air samples taken from air duct exhausts. Careful surveys should be made and samples taken for assay from any suspect traps.

21.11 Whenever there is any possibility that radioactive isotopes have entered the body; urine samples, and breath samples if indicated, should be taken and subjected to laboratory analysis.

21.12 The ultimate disposition of radioactive wastes should be carefully checked. It should be borne in mind that decontamination procedures merely move the contaminants from one place to another.

22. Medical Installations [10]

22.1 *Dental X-ray units.* These units are usually operated at 50 to 70 kv at a current of 10 ma. Common hazards are (a) exposure to the direct beam if pointed toward occupied areas in the same or adjacent rooms, (b) scattered radiation, especially that from the patient, and (c) multiple sources particularly if several units are in the same room. The exposure rate is usually too high for G-M scanning except in adjacent rooms. An ion chamber calibrated for low-energy photons should be used at the operator's position and at other occupied regions in the room. Masonry walls

[9] Handbook 48, Control and removal of radioactive contamination in laboratories (1951).

[10] See also, National Bureau of Standards Handbook 41, Medical X-ray protection up to 2 million volts, section 2 (1949) and Handbook 50, X-ray protection design (1952).

and concrete floors and ceilings usually provide sufficient shielding for adjacent rooms.

22.2 *Fluoroscopy.* These units usually operate at voltages up to 100 kv at 3 to 5 ma. Common hazards are (a) the useful beam that may extend beyond the fluoroscopic screen and its lead glass at maximum beam size and target-screen distance, (b) scattered radiation from the patient and the undersurface of the table top, (c) absence of a cone between tube housing and table top, (d) inadequate shielding of the tube enclosure against the direct beam, (e) too short a target-table distance and omission of filter, (f) filter too thin or totally lacking.

An auxiliary fluoroscopic screen can be used to scan for useful-beam leakage, partivularly at the edges of the screen. A G-M scanning meter is usually too sensitive for use in the fluoroscopic room, but it may be useful in adjacent areas. An ion chamber can be used in front of the lead glass and at all occupied positions in the fluoroscopic room.

Measurements should be made of the dose to the patient (i. e., at table surface) at maximum operating voltage and current.

All protective materials such as gloves and aprons, should be tested to determine if they comply with the recommendations of NBS Handbook 41.

22.3 *Radiography.* Usual operating conditions are 40 to 135 kv at currents up to 500 ma. Common hazards are:

(a) Scattered radiation around or over protective screens or into control booth where no door is provided.

(b) Scattering under doors and at junctions of walls with floor and ceiling if no lead baffle is provided.

(c) Useful beam and scattered radiation passing through windows in outside walls into occupied regions nearby.

(d) Holding the patient or film during exposure.

The X-ray tube should be operated at a reduced current but at the usual operating voltage to permit sufficient time for reading survey meters without overloading the X-ray tube and to minimize the possibility of lack of saturation in ionization chambers or blocking of G-M tubes.

Scanning of adjacent rooms and the floor below should be done with a G-M survey meter or equivalent instrument. Measurements should be made with the X-ray beam pointing directly at the instrument. Ion-chamber measurements should be made at the operator's position and at other habitually occupied locations where the G-M survey-meter reading exceeds one-tenth of the permissible value. Tests should be made in processing and film storage rooms to insure that

unexposed film cannot be exposed to more than 0.3 mr during its total storage period.

22.4 *Therapy up to 400 kv.* Therapy units operate at from 10 to 400 kv, depending upon the type of equipment. Common sources of hazards are:

(a) Scattering around or over protective screens or into control booth where no door is provided.

(b) Scattering under doors and at junctions of walls with floor and ceiling if no lead baffle is provided.

(c) Useful beam and scattered radiation passing through windows in outside walls into occupied areas nearby.

(d) Scattering from nearby buildings or from the floor of the room below if the treatment-room floor is insufficiently shielded.

(e) Leakage around doors and observation windows.

The equipment should be operated at maximum field size and at maximum current and voltage, with the minimum filter used for that voltage. Measurement on the useful beam should be made (a) without a patient in place, (b) in all directions in which the beam can be used, and (c) with the beam directed toward the instrument. Measurements of scattered radiation should be made during the treatment of a patient or with a phantom.

22.5 *Therapy units above 400 kv.* These are discussed in paragraph 23.8.

23. Industrial Installations

23.1 *Television receivers.* The X-rays produced in television receiver tubes usually have energies of 15 to 25 kv and hence are almost completely absorbed in the tube face. Furthermore, many sets are provided with a plastic or glass screen in front of the viewing surface, and this further decreases the radiation hazard. However, there is a tendency toward the use of higher voltages. Projection-type tubes (which operate at above 25 kv) may have insufficient attenuation to X-rays as a thinner envelope can be used in these smaller tubes. It is essential, therefore, that each type of television tube be tested for X-ray emission.

The survey should be made at maximum anode voltage and with maximum current for the voltage. The raster size should be at least as large as the window of the ion chamber for measurements at contact. The X-ray dosage rate is approximately inversely proportional to the raster size at contact, but at ordinary viewing distances, size is not an important factor.

A G-M survey meter or equivalent should be used for

scanning to locate the source and direction of maximum radiation. Usually the emission of detectable X-radiation is limited to the face of the television picture tube.

Quantitative measurements should be made with an ion chamber that has a minimum wavelength dependence in the television voltage range as determined by calibration against a standard free-air chamber. The usual heavy-walled chambers are unsuitable for this voltage.

23.2 *Electronic tubes.* Any electronic tube operating at 1,000 v or more is a potential source of X-rays. The radiation may be soft but it may also be intense because of the relatively large currents. In most cases the tube enclosure is sufficient to attenuate the soft X-rays adequately, but this is not always the case.

The emission of X-rays from rectifier tubes may increase when a low filament temperature increases the voltage drop across the tube when it is conducting. Radiation may result from a "cold discharge" or from the presence of gas. The radiation from individual tubes, even of the same type, may therefore vary widely.

In general, radiation hazards from this type of equipment can only be determined with instruments capable of measuring very soft X-rays.

23.3 *X-ray diffraction units.* The main hazard is accidental exposure to the intense useful beam, which may have a dosage rate of more than 50,000 r/min. This hazard is particularly serious where the equipment is used for production work such as crystal orientation.

The radiation survey shall be carried out with instruments suitable for the measurement of very soft radiation in beams of small cross section. Misleading and dangerous conclusions would be reached by measurements with an ordinary ionization chamber under conditions such that the larger part of the radiation is absorbed by the chamber, or that the cross section of the beam is smaller than the cross section of the ionization chamber.

Because of the high intensity, special precautions should be taken to insure saturation of the ionization chamber.

23.4 *Electron microscopes.* The principal sources of stray radiation are the primary viewing port, the specimen port, the diffraction port, and viewing port. In older units inadequate shielding was frequently provided at these ports and the dosage rate was above the permissible level. X-ray films are very useful in locating these sources of radiation leakage. The determination of the radiation levels requires

precautions similar to those mentioned above under X-ray diffraction units.

23.5 *Fluoroscopic installations.* In some respects industrial fluoroscopy presents greater hazards than medical fluoroscopy. Industrial installations frequently are operated 8 hr a day and the object seldom covers the entire fluoroscopic screen. On the other hand, it is possible to protect the operator completely against scattered radiation. The common sources of radiation leakage are through and around the lead glass. Where no mirror is used, the useful beam is directed at the operator, and even a small crack in the shielding may cause serious injuries. Such cracks can be detected with the Geiger counter or by means of a fluoroscopic screen or X-ray films.

23.6 *Radiography.* The survey procedure is similar to that used for medical radiographic installations. The industrial installations, however, present greater hazards as the load factor is usually higher and the orientation of the useful beam less restricted. Furthermore, the X-ray tube distance to occupied areas is frequently short, especially for cabinet-type installations.

23.7 *Radiography in unprotected rooms.* This type of installation is safe only if its operation is restricted by limitations set by the protection survey. It is important, therefore, that the radiation levels be accurately determined for all operating positions of the X-ray tube and orientations of the useful beam. Because of the high radiation level, precautions should be taken to assure saturation voltage in ionization chambers. Any limitations that must be imposed should be conspicuously posted near the equipment controls.

23.8 *X-ray installations from 401 to 3,000 kv.* The survey procedures for medical and industrial installations in this voltage range are nearly identical, and this section, therefore, includes both applications.

Concrete is generally used for shielding, and it is essential to make a very complete scanning in order to detect hidden cracks and air spaces. Often the protective value of the barrier is reduced by ventilating ducts, electric pull boxes, and expansion joints. The possibility of leakage around sliding doors and observation windows should also be checked by scanning.

Another frequent source of radiation hazards is multiple scattering into occupied areas. This is especially the case with industrial installations where wide beams are used and the walls are not extended to the ceiling.

VII. Appendix

24. Air-Sampling Equipment and Methods

24.1 The concentration of radioactive materials in air is determined by a laboratory count made on suitably collected and prepared samples. Filters, electrostatic precipitators, or impingers of various designs can be used to collect the samples. Care must be taken to insure that the sampling device collects all particle sizes desired.

24.2 In a filter collector a known volume of air is drawn through a specially designed filter paper on which the particulates are deposited. The activity of the paper is determined with a suitable laboratory-type instrument

24.3 Particulates carried by a known volume of air can be deposited in an electrostatic precipitator from which the collecting electrode can be removed and either used as an electrode in a proportional counter or counted by other means.

24.4 Electrostatic precipitators should not be used where explosive fumes may be present.

24.5 Impingers collect particulates as a jet of air is directed against a glass slide or other suitable backing which is usually coated with a thin layer of oil or vaseline. The deposit from a known air volume is counted by usual methods.

24.6 Noncondensable gases shall be sampled with special equipment devised for the particular material.

24.7 The size of the air sample may vary, depending on the conditions. A sample of 10 m^3 is sufficient for practical assays of alpha contaminants down to one-tenth of the maximum permissible concentration.

24.8 Direct counting from the surfaces on which the sample has been collected is desirable. Beta and gamma radiations can be determined by using a G-M tube of known geometrical efficiency. Alpha particles can be counted in a proportional counter or an ionization chamber of known geometrical efficiency.

24.9 When alpha particles are being counted, corrections should be made for the loss due to penetration into the filter material. Such correction factors can be obtained by chemical analysis of a number of filters exposed in the same location.

25. Analysis of Water Samples

25.1 If it is known which particular isotope may be the contaminant, a specific analysis for this material may be made.

25.2 If the beta-emitting contaminant is not known or if there are several possibilities, a direct measurement of the residue from evaporation can be made. Some uncertainties result, because of unknown self-absorption and absorption in the counter window.

25.3 Results obtained by direct measurement of the residue for alpha emitters are generally qualitative in nature. Specific analyses are much more sensitive and reliable.

25.4 If the activity is of gaseous or volatile nature, again specific analyses should be made.

25.5 For obtaining a sufficiently sensitive result, it will be found that the smallest workable sample is of the order of 100 to 500 ml.

26. Beta-Particle Counting

26.1 Reasonably accurate values for most isotopes mounted on small plates can be obtained by the use of end-window Geiger counters (mica window or windowless-flow type) or by the use of proper proportional counters.

26.2 The counting rate should be corrected for the following factors for the individual isotope concerned:

(a) *Geometry.* The solid angle subtended by the counter and the source is usually not equal to the physical solid angle because of the unknown sensitive volume of the tube.

(b) *Source size.* The geometry for an extended source is smaller than for a point source because of the smaller solid angle subtended by the activity at the edge of the source. For this reason and because of the difficulty of producing a uniform coating on the plate, a large error is possible in the measurement.

(c) *Backscatter.* A fraction of the particles leaving the source in the opposite direction from the counter will be scattered into the counter by the plate on which the source is mounted. This may be measured by placing a source on thin (0.2 to 0.5 mg/cm^2) film and measuring with and without the backing. This factor is reasonably constant for the same backing material with isotopes of maximum energy above about 0.6 Mev.

Approximate values of backscatter for several materials measured with 23 percent geometry and a 3 mg/cm^2 mica window

Material	Backscatter
	Percent
Glass	22
Aluminum	28
Stainless steel (0.004 in.)	30
Platinum	70
Silver	60

(d) *Absorption in window.* Because of the continuous spectrum of particles emitted from a beta source, a fraction of the particles will be absorbed in the window of a mica-window counter and in the air between the counter and the source. As the first part of the absorption curve for a beta emitter is approximately linear on a semilogarithmic plot, this effect can be measured by counting the source with several thin absorbers and extrapolating through the thickness of the window and air to zero absorber. The slope of this line can be expressed as m in the equation $N/N_0 = e^{-mx}$ for use when the isotope is known. (N is the measured counting rate, N_0 is the extrapolated counting rate, and x is the combined effective thickness of the window and air.)

(e) *Self-absorption.* When the sample contains a large enough quantity of material, a fraction of the particles will be absorbed in the sample itself. This can be measured by preparing a series of plates with varying amounts of stable material and the same amount of an active isotope. This curve can then be used for correcting analytical results.

An approximation of the self-absorption factor can be made by use of the equation

$$\frac{N}{N_0}=\frac{1}{mx}(1-e^{-mx}),$$

where N is the measured counting rate, N_0 is the true counting rate, m is the absorption coefficient as measured in (*d*) and x is the thickness of the sample.

(f) *Coincidence losses.* With high counting rates some loss will occur because of a second particle arriving while the counter is inoperative from a previous discharge. A correction factor for coincidence losses can be obtained by counting several low activity sources individually and together.

26.3 Individual counters may be calibrated by the use of standards available from the National Bureau of Standards. Direct comparison of results can be made only when the isotope being measured is the same as that used for the standard. If other isotopes are to be measured, the standard may be used to obtain the geometry by correcting for the factors given in paragraph 26.2 and the measurements of the samples can then be corrected by the appropriate factors. This method gives only an approximately correct value as geometry, absorption, and backscatter depend upon the energy of the particles.

26.4 Air samples collected on filter paper or with an electrostatic precipitator can be counted by wrapping the paper around a thin-window cylindrical counter. Calibrations may be made by preparing sources with known amounts of activity as measured with end-window counters and comparing with the sample. Correction should be made from the radon and thoron daughters collected, which can be estimated from decay curves of the samples.

27. Alpha-Particle Counting

27.1 Alpha emitters can be measured with pulse counters, proportional counters, or scintillation counters of the proper design.

27.2 Characteristics of the measurement which may introduce inaccuracies are:

(a) *Self-absorption.* Because of the short range of the alpha particle, the self-absorption is usually very important. Generally, a chemical separation is advisable if the sample contains much inert substance.

(b) *Response across the chamber.* Many chambers have a loss in sensitivity at the edge. The chamber should be checked with a point source to indicate the magnitude of this loss with the sample size used.

(c) *Coincidence losses.* Those pulse counters which have long resolution times will have high-resolution losses. This can be estimated by counting a number of low-activity sources individually and then together.

27.3 Air samples collected on filter paper or with an electrostatic precipitator can be counted directly on pulse or proportional counters if correction is made for self-absorption and for the alpha-emitting daughters of radon and thoron.

27.4 A correction for the thoron content of the air sampled may be made by use of the equation

$$A=\frac{N_2-N_1e^{-\lambda\Delta t}}{1-e^{-\lambda\Delta t}},$$

where A is the counting rate of an alpha emitter with a long half-life, N_1 is a measurement made 4 to 6 hr after the sample is taken (to allow the radon daughters to decay), N_2 is a second measurement made 18 to 24 hr after the sample is taken, Δt is the time interval between measurements, and λ is the disintegration constant of Th B.

28. Useful Pertinent Data

28.1 Proton ranges in paraffin are shown in figure 1.

28.2 Range of beta particles in aluminum is represented in figure 2.

28.3 The following table shows sensitive ranges of photographic emulsions. The values given are based, except as noted, on a maximum useful optical density of 3.0 as obtained with the developer listed.

Emulsion	Developer	Useful range (r)
Eastman type A	Kodak	0.05 to 1.0
Dupont 552 (sensitive)	do	.1 to 5.0
Ansco Non Screen	do	.1 to 2.0
Ansco Super Ray	do	.2 to 3.0
Eastman type A	Ansco Reprodol	.3 to 5.0
Dupont 552 (insensitive)	Kodak	.5 to 20.0
Eastman Cine Positive No. 5301	do	5.0 to 100
Dupont 552 (sensitive)	Ansco Reprodol	10 to 100 (d=0.9)
Ansco Super Ray	do	10 to 300
Dupont 605	Kodak	10 to 250
Eastman Cine Positive No. 5302	do	20 to 350
Ansco Non Screen	Ansco Reprodol	25 to 1,000 (d=1.9)
Dupont 552 (insensitive)	do	40 to 250
Eastman Kodalith No. 6567	Kodak	70 to 800
Eastman Cine Positive No. 5301	Ansco Reprodol	100 to 2,500 (d=2.8)
Dupont 605	do	100 to 3,000
Eastman Cine Positive No. 5302	do	200 to 2,500
Eastman 548-0 Double Coat	Kodak	2,000 to 10,000
Eastman 548-0 Single Coat	do	5,000 to 20,000

28.4 Gamma activity of radon is given in figure 3.

28.5 Rate of build-up of radon daughters on collector is shown in figure 4.

28.6 Decay rate of alpha-emitting radon daughters appears in figure 5.

28.7 Figure 6 represents the decay rate of beta-emitting radon daughters.

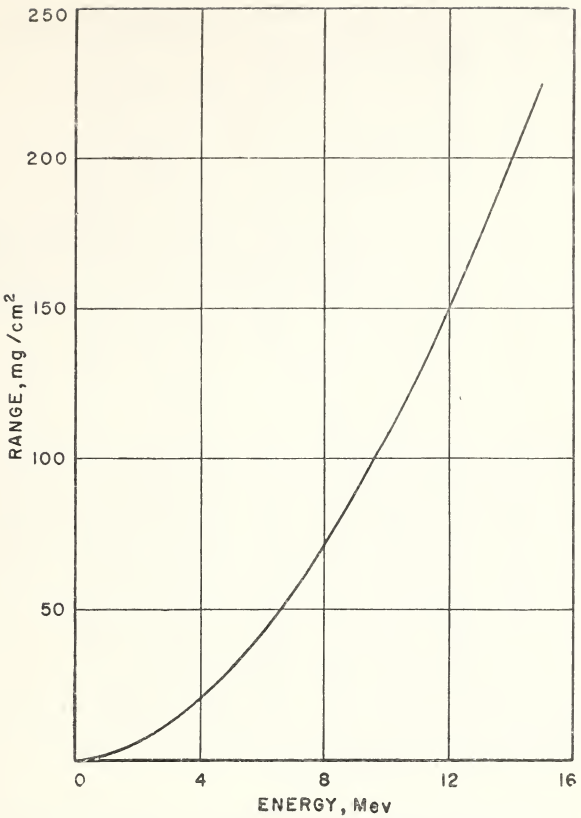

FIGURE 1. *Proton ranges in paraffin.*

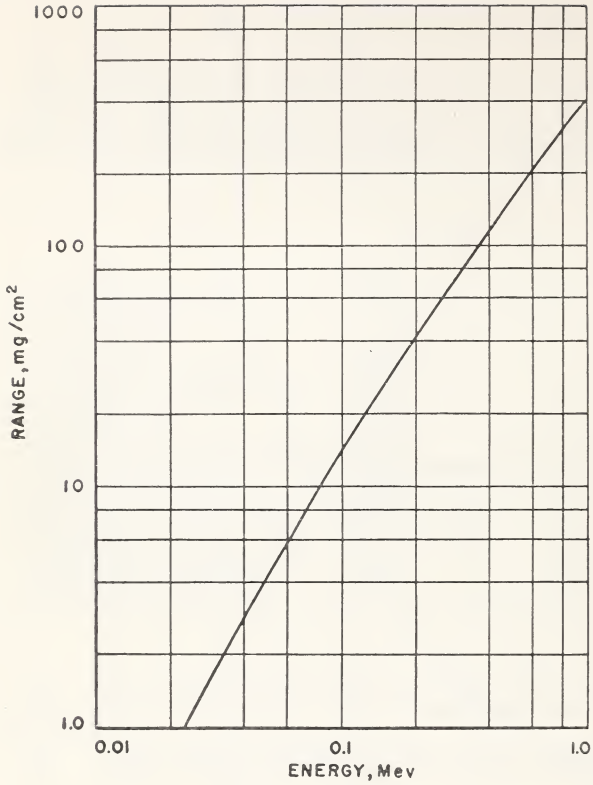

FIG. 2. *Range of beta particles in aluminum.*

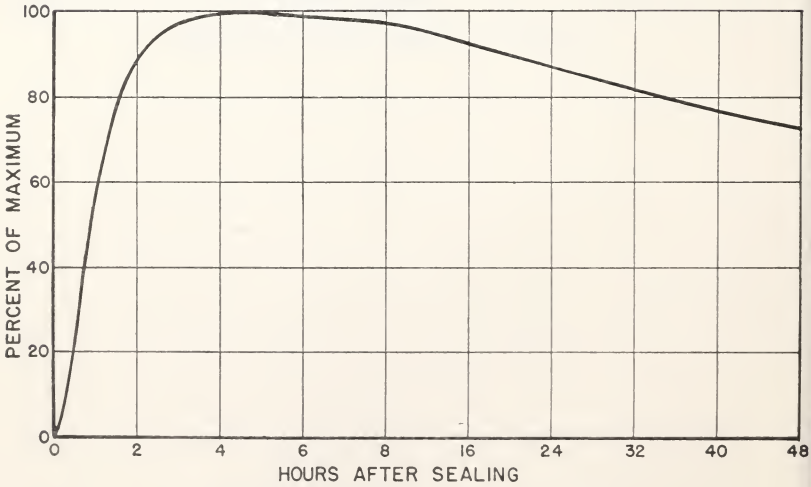

FIGURE 3. *Gamma activity of radon.*

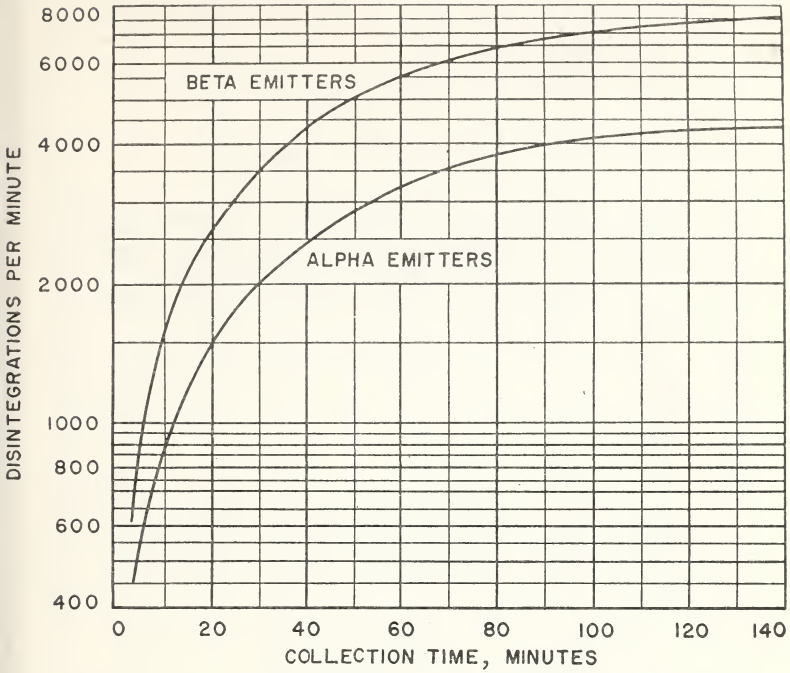

FIGURE 4. *Rate of buildup of radon daughters on collector.*
Collection rate equals one disintegration per second of each daughter per minute.

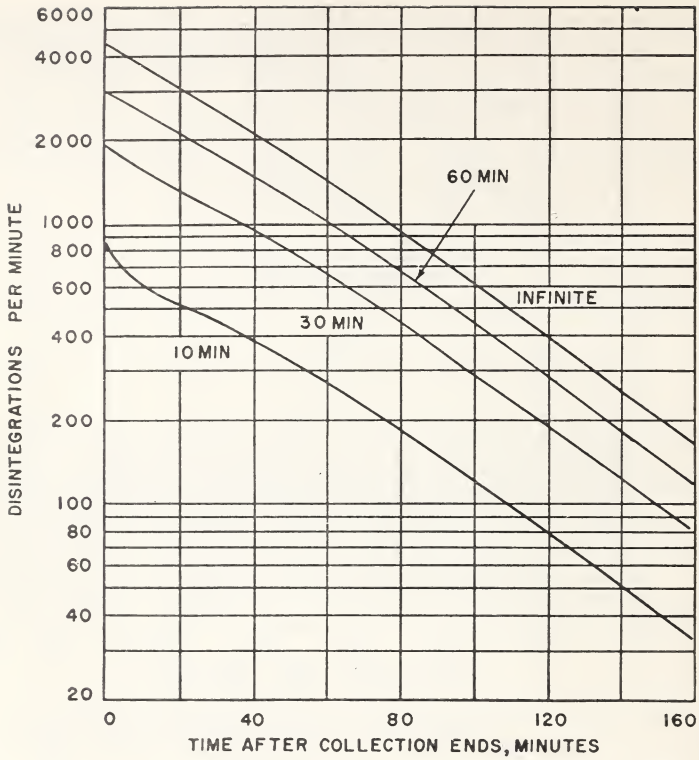

FIGURE 5. *Decay rate of alpha-emitting daughters of radon, when collected from the atmosphere for time specified.*

Collection rate equals one disintegration per second of each daughter per minute.

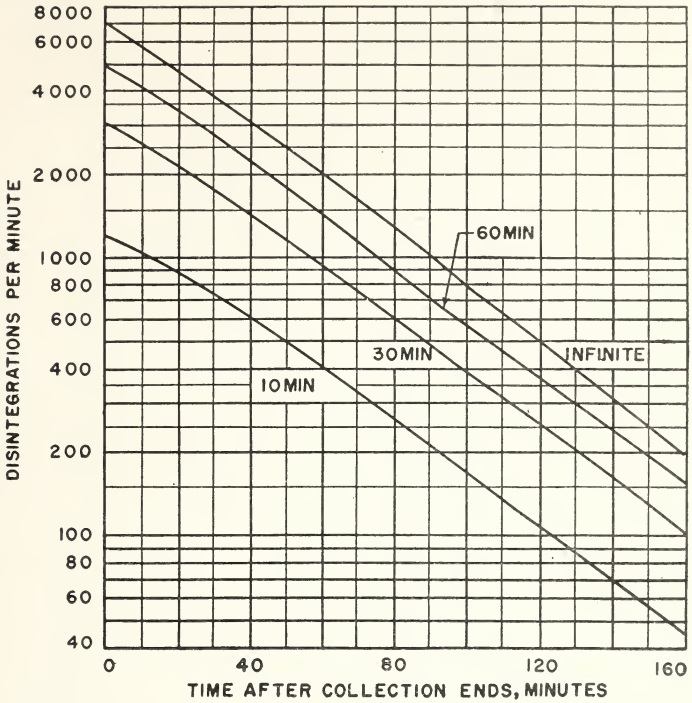

FIGURE 6. *Decay rate of beta-emitting daughters of radon, when collected from the atmosphere for the time specified.*

Collection rate equals one disintegration per second of each daughter per minute.

Submitted for the National Committee on Radiation Protection.

LAURISTON S. TAYLOR, *Chairman.*

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