LA-1835 (3d ed.)

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LOS ALAMOS HANDBOOK OF RADIATION MONITORING

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Los Alamos Handbook of RADIATION MONITORING

LA-1835 (3d ed.)

Compiled and Edited by
Jerome E. Dummer, Jr.

Originally Compiled and Edited by
Robert F. Barker

Los Alamos Scientific Laboratory
of the University of California
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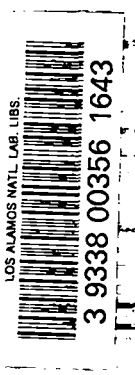

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PREFACE

The first edition of the "General Handbook for Radiation Monitoring" was prepared by Robert F. Barker in 1952 as an attempt to provide the members of the Monitoring Group at the Los Alamos Scientific Laboratory with the basic data which it was felt should be available to them at all times. It rapidly became apparent that many others had felt the same need for a concise, pocket-size compilation of this sort, both for training and reference, and the demand very promptly exceeded the supply.

As might have been expected, the original edition contained some mistakes and in 1954 a second edition was prepared, again under the competent editorship of Robert F. Barker. In the second edition about the only changes were to eliminate the errors that had appeared previously and to remove a few local references that were cryptic to the larger audience the booklet now commanded.

This, the third edition, has been almost entirely rewritten and its publication was delayed to permit inclusion of the most up-to-date data for permissible exposures and permissible body burdens. The format remains unchanged, however, and the handbook is still designed to serve the purposes of the Los Alamos Scientific Laboratory.

Not all of the quantities given have official sanction; there are some instances where official numbers do not exist, but it is necessary to establish some level which can serve as a guide in local work. Organizations out-

side Los Alamos may not agree with all the rules and policies set forth, but again it is emphasized that they were adopted for local use. Mention of any commercial product does not constitute an endorsement; for certain purposes no instruments are completely satisfactory.

The editor of this handbook, Jerome E. Dummer, has been aided by many members of the Health Division. Suggestions for improvement of a future edition will always be appreciated.

THOMAS L. SHIPMAN, M.D.
Health Division Leader

CONTENTS

1. MONITOR'S CHECK LIST

This is a reminder list of some equipment and operations that may be required to accomplish a monitoring job. Be sure you have what you need. Additional check lists are given at the conclusion of the various sections on specific types of monitoring.

A. Equipment

(1) Protective clothing (proper type of respiratory protection).

(2) Film badges (body and/or wrist).

(3) Pocket dosimeters and charger.

(4) Survey meters (type and directions for using).

(5) Tolerance tables, tolerance times, neutron survey data sheets.

(6) Signs (radiation), tags, rope, source tongs.

(7) Air samplers and filters.

(8) Miscellaneous: paper, pencil, cardboard boxes, masking tape, chalk, grease pencil.

(9) Vehicle (gas, trip ticket).

B. Operations

(1) Check for contamination on surfaces, equipment, and personnel.

(2) Limit spread of contamination.

(3) Decontaminate (agents and facilities).

(4) Dispose of contaminated waste.

(5) Take nose swipes.

(6) Collect urine specimens (containers—tag completely filled out).

(7) Summarize in written report.

2. RADIO CODE

10–0 Operations normal at this location or operation.
10–1 Receiving poorly.
10–2 Receiving well.
10–3 Stop transmitting.
10–4 O.K. Roger. Message received and understood.
10–5 Relay.
10–6 Busy.
10–7 Out of service.
10–8 In service (Give name of operator with first 10–8 call, e.g., "Station Hickory 3 to Station 7, 10–8, Doakes").
10–9 Repeat.
10–10 Out of service subject to call (Give telephone number or location).
10–19 Return to your station; come to this location.
10–20 What is your location? or, My location is . . . .
10–21 Call this station or location by telephone.
10–36 Correct time.
10–95 Radio check (Answer with 10–1 or 10–2).
10–97 Arrived at scene.
10–98 Finished with last assignment.
10–99 Emergency within section or area.
5–7 Fire at . . . .

The word *Broadcast* repeated three times means a general or extreme emergency.

3. EMERGENCY MONITORING

A. Emergency Equipment

The emergency vehicle, radio call Station Hickory 3, is equipped with respirators, air samplers, protective clothing, signs, blankets, first-aid kit, etc. Survey instruments can be obtained in the Monitoring Office. With the instrument supplement, the vehicle should provide a self-sufficient operations base in a wide variety of radiation emergencies. Film badges may be picked up from the Photodosimetry Darkroom if needed.

B. Philosophy and Procedures

First! Obtain all readily available information before proceeding on any emergency. Be certain it is an emergency, then proceed, using mature judgment, common sense, knowledge of the hazards, and all available equipment to limit the number of personnel, and their exposure, to a working minimum.

Emergencies will probably be of the following types:

(1) Spill of radioactive material.

(2) Explosion (chemical or nuclear).

(3) Fire.

(4) Dispersal of radioactive materials by fire or explosion.

Of the above, in general, (1) and (2) will probably be local, but (3) and (4) may affect the community. In cases reaching disaster proportions, ALOO will be responsible and the LASL position will be only that of a

technical assistant. (Definitions of abbreviations will be found in Appendix D and a glossary of technical terms in Appendix Q.)

The monitor should be a self-sufficient unit, able and equipped to step into any situation and take over the necessary monitoring duties. He must have a knowledge of the materials being used, their usual location, and an active imagination in deducing just what sort of accidents may occur in the use of these materials.

C. Remember!

(1) Assume all types of hazard are present until proven otherwise.

(2) Gamma radiation should be the first and easiest to detect.

(3) Explosives, chemicals, or other toxic materials may be a problem.

(4) Make qualitative check on Gast pump air sample with PeeWee and/or G–M instrument.

(5) Protect, monitor, decontaminate, and list names of all personnel involved.

(6) Notify an H–1 supervisor as soon as possible.

4. PROTECTIVE METHODS

Radiation hazards are usually divided into two classes, external and internal, the terms referring to the location of the source of radiation with respect to the person being exposed. Methods have been devised for protecting the radiation worker against both types of radiation.

A. Internal Radiation

Internal radiation refers to radiation from radioactive material that enters and irradiates the body from the inside until it is eliminated or decays radioactively. Protective methods for this type of radiation obviously are prevention of entry into the body and elimination of any material that has entered. Except in a very few cases, elimination by means other than biological turnover or radioactive decay is impossible. For this reason, radionuclides with long half-lives that remain in the body for long periods of time (e.g., Pu^{239}, Sr^{90}) are considered especially hazardous. Entry of radioactive materials to the body may be gained by inhalation, ingestion, injection, or absorption through the skin.

A variety of respiratory protective devices is available to attempt to control inhalation of radioactive particles. These devices are illustrated in Section 11 and their uses are described in Section 19. Methods are in use to evaluate airborne hazards by air sampling (Sec. 18). Nose swipes (Sec. 7) taken at the end of a working period give an indication whether material has been inhaled.

Prevention of entry by ingestion is mainly a matter of good housekeeping and observance of the rules prohibiting eating, drinking, or smoking in contaminated areas. Washing and monitoring the hands routinely before eating or leaving the contaminated area is mandatory. Entry through open cuts or abrasions or accidental injections allows deposition directly into the blood stream and is therefore extremely hazardous. When open cuts or sores exist, handling of contaminated material should be avoided. Absorption through the skin is an entry method of some radioactive gases or vapors, e.g., tritium (Sec. 15). Exposures of this type can be prevented only by utilizing closed systems, hoods, or, in emergencies, whole-body plastic air-line suits.

Second only to prevention of internal radiation by assuring cleanliness through constant monitoring and the use of entry-preventing devices is the determination of the amount of radioactive material entering and remaining in the body and the subsequent evaluation of this information in terms of radiation dose. This is accomplished primarily by radiological examination of the body excreta, usually the urine (Sec. 17). Other methods, such as whole-body counting, specific organ counting, and breath sampling, have their specific applications. As a general rule, the above procedures are most accurate if made as soon as possible after the intake occurs. Specific procedures for tritium urine assay are given in Section 15–D.

B. External Radiation

External radiation is radiation that comes directly from a radiation source or from contamination of equipment, clothing, or the person himself. External expo-

sure can be received from β, X or γ, and neutron radiation. Natural α particles do not constitute an external hazard as they cannot penetrate the outer layer of skin. Contamination is controlled by preventing its occurrence or by promptly removing it (Sec. 8). Removal is much easier if surfaces have been first furnished with protective coverings or coatings. Kraft paper or strippable paint can be used on floors or benches; protective coveralls, gloves, and caps should be used by personnel in potentially contaminated areas.

Where complete removal of contamination or the source of radiation is not possible, three general methods of protection—time, distance, and shielding—are used. The methods will be discussed separately, but in practice judicious use of all three is advisable.

1. Time. Radiation exposure can be kept below the maximum permissible limits by restricting the time spent in the radiation area. The "safe" or permissible exposure time (Sec. 9–C) in terms of hours or minutes per week is a convenient method of expressing the extent of a radiation hazard. As any unnecessary radiation exposure is considered too much, every effort should be made to reduce the time spent in a radiation area even below that deemed "permissible" by monitoring measurements.

2. Distance. The intensity of radiation from a source of radiation decreases with the distance from the source. For a point source, this decrease is inversely proportional to the square of the distance, hence the term "inverse square law." For monitoring purposes, point source conditions are met when the dose measurement is made at 2 ft or more from a source

whose largest dimension is no more than 4 in. Expressed as a formula,

$$d=D\times\frac{R^2}{r^2}$$

where D is the dose rate at a distance R from a point source, and d is the dose rate at a different distance r. Dose rates and distances must be expressed in the same units. Two examples are given as demonstration of the inverse square law:

Example 1: 45 mr/hr is measured at 100 cm. What is the dose rate at 10 cm from the same source?

$$d=45\times\frac{100^2}{10^2}=45\times\frac{10000}{100}=4500 \text{ mr/hr}$$

Example 2: 800 mr/hr is measured at 20 cm. At what distance is the dose rate 200 mr/hr?

$$r^2=D\times\frac{R^2}{d};\ r=\sqrt{D\times\frac{R^2}{d}}=\sqrt{800\times\frac{400}{200}}=\sqrt{1600}=40 \text{ cm}$$

In simple language, double the distance, get one-fourth the dose rate; halve the distance, get four times the dose rate.

Note: The inverse square law is accurate only when the distance is large compared to the source and detector size, and also when negligible scattering or absorption occurs in the medium in which the distances are measured. When these conditions do not exist, the inverse square law is, at best, a rough approximation.

3. Shielding. Shielding is the interposition of suitable material between the source of radiation and the position where dosage must be reduced. The shielding

methods of β, γ, and neutrons are very different and will be discussed separately.

a. β Shielding. β particles react with matter mainly by scattering of nuclei, radiative inelastic collisions, and ionization. Despite the complexity of β absorption, it is approximately exponential; i.e., for each increment of added shielding, the same reduction factor is obtained. This permits β shielding to be expressed in terms of half-thicknesses, or the thickness of material which must be interposed to reduce the number of particles passing the shield to one-half the original number striking the shield. Although the half-thickness concept is usable, the thicknesses required to reduce the intensity of even energetic β particles by one-half are so small that it is more convenient to express β shielding by the amount of material required to stop *all* the β particles of a certain energy (Appendix I). Note that since the maximum energy is plotted and the average energy of a β spectrum is about one-third the maximum, the thicknesses given in Appendix I are conservative or "safe."

One β-absorption process, radiative collision, produces electromagnetic radiation called "bremsstrahlung." These are similar to ordinary X rays, exhibiting an energy spectrum from zero to the maximum β energy, with average energy roughly one-third the maximum. The production of bremsstrahlung is proportional to the square of the β energy and to the atomic number of the absorber, making the use of light materials for β shields advisable. This practice is usually practical since a few millimeters of lucite or aluminum is sufficient to stop β particles of around 2 Mev. The creation of bremsstrahlung in light materials such as

these is rather inefficient, on the order of 10% (Appendix C).

b. X and γ Rays. X and γ rays are absorbed by three main processes:

(1) The photoelectric effect, which is an interaction between a γ photon and a bound electron in which the γ ray disappears and an electron is ejected. This process becomes more effective for higher atomic number absorbers and low photon energy.

(2) The Compton effect, in which a photon interaction with a free electron produces a lower energy scattered photon and recoil electron.

(3) Pair production, in which the photon energy is entirely used up in the creation of a positron and an electron in the presence of nuclei. The energy required by a photon to create an electron-positron pair is 1.02 Mev or more, and the process is most effective for high atomic number nuclei.

The complexity of these processes make it convenient to classify shielding methods as narrow beam (good geometry) and broad beam (poor geometry). In the narrow beam case, none of the Compton-scattered photons reach the detector and attenuation is truly exponential. The use of HVL's and TVL's (Appendix G) is permitted with good geometry. In broad beam geometry, the case in most practical applications, some Compton-scattered photons are detected and add to the total intensity. This increase in intensity caused by scattering is called "buildup," and the amount of buildup increases with thickness. Broad beam γ attenuation for several γ emitters in several materials is given in Appendix H.

When large γ sources are handled behind open top shields, γ rays scattered from the air or other material above the source will contribute considerably to the dose. There is no object in reducing the intensity transmitted through the shield to a level much lower than will be produced by scatter. The effect of scatter may be reduced by the addition of a top shield, the thickness necessary being considerably less than the side shield. Open top shields are not practical for greater than about 25 curies of a γ emitter.

c. Neutron Shielding. The attenuation of neutrons is accomplished by elastic and inelastic scattering and radiative capture. The general procedure for neutron attenuation is to slow down the energetic neutrons by successive collisions with nuclei to energies where the probability of radiative capture is higher. All capture processes proceed more easily at lower neutron energies and almost all result in the emission of high energy γ radiation. The attenuation of these rays must be considered in the shield design.

In shielding large neutron fluxes such as are found near reactors, the general procedure is as outlined above; i.e., slow the fast neutrons with hydrogenous material such as water or concrete (elastic scattering) or heavier nuclei (inelastic scattering); capture the slowed neutrons using $H^1(n,\gamma)H^2$ or similar reaction; capture thermalized neutrons with cadmium (n,γ) or similar reaction; shield against γ rays with external shielding or add loading (iron shot) to the hydrogenous material. It must be emphasized that neutron capture γ rays are often very energetic, the 2.2-Mev γ rays from the proton reaction being one of the lower. A variety of reactor shielding materials have been de-

veloped including an alloy of aluminum and boron (Boral) and special loaded concretes. As in the case of γ shielding, open top shields must be examined carefully for air scatter, often called sky-shine.

For shipping or laboratory purposes, paraffin is a suitable neutron attenuating material. It is convenient to use the concept of HVL's for rough design of paraffin shields for small neutron sources. Paraffin HVL's for 4 to 5 Mev (e.g., Po-Be, Ra-Be, or Pu-Be) and for 1-Mev neutrons (fission or mock fission) are 6.93 and 3.2 cm, respectively. By use of the semilog plot of Appendix J, the amount of paraffin needed for a certain reduction in flux or the effectiveness of a certain amount of paraffin can be determined.

Example: If it is desired to reduce the fast neutron flux from a Po-Be source to 10% of its unshielded value (e.g., from 100 to 10 n/cm^2-sec) using paraffin, read from the semilog plot of Appendix J the number of HVL's necessary to reduce the intensity to 10% as 3.3 HVL's. $3.3 \times 6.93 = 22.9$ cm, or about 9 in. of paraffin. If the effectiveness of 6 in. of paraffin for a Po-Be shield is desired, 6 in. = 15.2 cm; 15.2 cm/(6.93 cm/HVL) = 2.2 HVL's which, on the curve, indicates a reduction to 22%.

This method will give unsafe answers for shields less than 2 HVL's thick. The flux attenuated is the fast flux and there will remain considerable thermal neutrons. These can be absorbed in cadmium if necessary.

4. Waste Disposal and Leak Testing. Two other protective measures taken to protect personnel are the disposal of radioactive wastes and the testing of radiation sources for leaks. Wastes of short-lived isotopes can be stored to await decay. Other wastes must be

packaged, labeled with isotope, origin, and date, and buried in a segregated pit. Records are kept as to approximate location in the event recovery is necessary or reuse of the site is planned. In cases of large amounts of slightly contaminated combustible waste, burning with proper checks on airborne activity is advantageous.

Radioactive sources should be leak-tested whenever damage or deterioration of the capsule is suspected, or at least once each 6 months. This routine check also serves as an inventory and assures that the proper authorities are aware of the location of sources. The testing of radium (or Ra-Be) sources is accomplished by testing for radon (actually Rn daughters). The source is placed in a small sealed jar with a 2 or 3 in. diameter filter paper (not in contact with the source) for 12 to 24 hr. A count in excess of 50 c/m $\beta+\gamma$ with a less than 10% efficient, well-shielded, glass-wall G–M counter is considered to be a dirty or leaking source. A high count on a recheck after the source has been scrubbed with trichloroethylene indicates that the source is leaking and must be resealed. Plutonium and Sr^{90} sources and neutron sources containing α emitters (Po-Be, mock fission) should be checked frequently for leaks using the swipe technique (Sec. 7). Any source that swipes positive is cleaned and rechecked.

5. LOS ALAMOS SCIENTIFIC LABORATORY RADIATION SAFETY POLICIES

A. Individual

Individuals at the Los Alamos Scientific Laboratory who have any contact with radioactive materials or radiation are responsible for:

(1) Keeping their own exposures to radiation and also those of others as low as possible and, specifically, below the maximum permissible levels recommended in Section 9. Exceptions are exposures received in medical examinations and treatments and, with prior approval by the Health Division, in cases where urgent situations require exposures in excess of the recommended levels.

(2) Wearing the prescribed monitoring equipment (pocket dosimeters, film badges) in radiation areas. Requesting that neutron films be read when exposure to 0.1 rem is suspected.

(3) Surveying hands, shoes, and body for radioactivity and removing loose contamination to the tolerance levels before leaving the area, in accordance with the recommended decontamination procedures.

(4) Wearing appropriate protective clothing whenever clothing contamination is possible, and not wearing such clothing outside the Laboratory areas. Using gloves, hoods, and respiratory protection (respirators or supplied air masks, as recommended by the Health Division) when necessary. Using proper techniques and facilities in operations involving radioactive materials.

(5) Observing the recommended procedures in regard to eating and smoking in contaminated areas.

(6) Reporting injuries and ingestion or inhalation accidents promptly to the Health Division and carrying out the recommended corrective measures. Cooperating in any and all attempts to evaluate exposures, particularly by promptly returning requested urine specimens.

(7) Carrying out recommendations of the Health Division in roping off hazardous areas, posting warning signs, and otherwise controlling special hazards for which they are responsible. Contacting the Health Division (Group H–1) for recommended procedures in high level radiation areas or when conditions are altered significantly.

(8) Cleaning up contamination for which they are responsible. Arranging for a survey by Group H–1 and carrying out the decontamination recommended for the area when changing locations or ending an operation.

(9) Proper storage and labeling of radioactive materials for which they are responsible.

(10) Proper packaging (sealed containers whenever possible) and labeling (origin and date) of contaminated waste materials.

B. Supervisory

Supervisors are responsible for ensuring that the above individual responsibilities are discharged by those under their control, and are further responsible for:

(1) Instructing those employees for whom they are responsible in the use of safe techniques and in the application of approved radiation safety practices.

(2) Providing such staff as is required for packaging contaminated waste and for decontaminating anything for which they are responsible.

(3) Furnishing information to the Health Division concerning individuals and activities in their areas, particularly additions to or deletions from their personnel rosters.

(4) Contacting the Health Division whenever major changes in operational procedures, new techniques, alterations in physical plant, or new operations which might lead to personnel exposures are anticipated.

C. Monitoring Group, H-1

This group is responsible for:

(1) Furnishing consulting services on all aspects of radiation protection.

(2) General surveillance of all radiation activities, including assistance to individuals and supervisors in discharging their responsibilities.

(3) Distribution and processing of personnel monitoring equipment, including keeping of personnel exposure records, notifying individuals and their supervisors of exposures greater than the permissible levels for their situation, and recommending appropriate restrictions.

(4) Supervision and coordination of the waste disposal program, including keeping of waste storage records.

(5) A continuous program of environmental hazard evaluation and hazard elimination.

(6) Storage, leak testing, issue, and disposal of radioactive sources; supervising the shipping of radioactive material. Further, the inspection of requests for

sources to assure standardization of capsules for general utility.

(7) Scheduling urinalysis measurements when required.

(8) Decontaminating large pieces of equipment (e.g., motor vehicles) and assisting personnel decontamination in cases of contaminated wounds or persistent personal contamination.

6. PERMISSIBLE DOSE AND MEASUREMENT UNITS

Radiation brings about a change in matter only by virtue of the energy that is actually absorbed by this matter. A biological effect may also depend on the type and energy of the radiation, making possible different biological effects from equal energy absorption. It is therefore convenient to measure exposure in purely physical terms and use an additional factor to allow for the *relative biological effectiveness* (RBE) of different types and energies of radiation. (Definitions of all italicized terms are included in the Glossary, Appendix Q.)

It has also become desirable to make a distinction between the X or γ radiation to which a person might be exposed and the energy absorbed from the radiation locally by the person. The former, a field measurement, is designated *exposure dose* and is measured in *roentgens*. The latter, which depends on the field and the material under irradiation, is called the *absorbed dose* and is expressed in *rads*. Absorbed dose can be calculated from exposure dose measurements or from other measurements of ionization, chemical effects, or directly by calorimetry.

Since, in many instances, the absorbed dose can be inferred directly from exposure dose measurements, the roentgen is likely to remain the unit of choice for practical X- or γ-ray dosimetry up to about 3 Mev. A number of other units currently recognized or in wide usage are discussed below.

The *rad* has been accepted as the unit of absorbed dose (i.e., the amount of radiation imparted to matter by any ionizing particle per unit mass of irradiated material) and is 100 ergs/g of any material. The *gram-rad* is the unit of integral absorbed dose (i.e., the summation of the energy absorbed throughout a given region of interest), 1 gram-rad being 100 ergs. *Intensity* and *quality* of radiation are expressed in ergs/cm^2-sec (or watts/cm^2) and ergs/cm^2 (or watts-sec/cm^2), respectively. The *rem* is the unit of RBE dose and its use should be restricted to radiation protection problems, e.g., when it is necessary to add dosages from a variety of radiations, especially for record keeping. The RBE dose in rem equals absorbed dose in rads times RBE. Values of RBE for all ionizing radiations have been recommended (NBS Handbooks 59 and 63).

Several units formerly used are now obsolete. One unit enjoying wide usage until recently was the *rep* (roentgen equivalent physical). Originally defined as that dose of ionizing radiation which produces an energy absorption of 84 ergs/cm^3 in tissue, it was later changed to 93 ergs/cm^3 of tissue to more accurately represent the energy absorbed per cm^3 of aqueous tissue irradiated with a dose of 1 r of X or γ rays. The rep was often used in expressing doses due to β radiation. The difference in magnitude between the rep and rad in tissue is insignificant in the estimation of permissible doses.

Permissible dose is currently defined as that amount of ionizing radiation which, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. The basic value of the *maximum permissible dose*

(MPD) rate has undergone several changes since first being set in 1931 as 0.2 r/day. The currently acceptable values for occupational exposures are summarized in Section 9.

NOTE. Such values are strictly for occupational exposures under controlled conditions and should be divided by 10 for nonoccupational exposures.

7. PERMISSIBLE CONTAMINATION LEVELS

The values listed below apply in the general case. Sound judgment with consideration for the health and safety of personnel as well as the economic and legal aspects of the situation may necessitate revisions in certain cases. It should be remembered that many of these tolerance values are designed for use under controlled laboratory conditions, where levels that can be tolerated by sensitive equipment are often lower than those which constitute an actual hazard to personnel. Since values are often established by the lower limits of sensitivity of the monitoring instruments in use, these levels may not apply to incidents occurring outside of the laboratory. Conformity with the prescribed tolerances is determined by contact measurements with either an open-window G–M instrument or a PeeWee. In the general case, a certain amount of α contamination can be allowed if the contamination can be demonstrated to be fixed, that is, if it cannot readily be tracked, become airborne, or otherwise be inhaled or ingested.

A. Swipes

A "swipe" is a procedure used to determine the presence of contamination and whether or not the contaminant is likely to rub off, thereby presenting a potential inhalation or ingestion and contamination control problem. A swipe is made by rubbing a piece of absorbent tissue, filter paper, or cheese cloth over the area in question and counting it with an appropriate

meter. The swipe may be moistened for β-γ, but not for α since moisture may prevent α's from being monitored. Booties, appropriately checked after being worn through a contaminated area, can give a good indication of the likelihood of spreading the contamination.

Nose swipes, a method of determining the effectiveness of respiratory protection, are made with a 3 x ½ in. strip of paper wrapped tightly with tweezers around the end of a swab stick. Applicators are dipped in distilled water and used by the subject to swab each nostril. Both swipes are placed in an envelope with name, date, and site. After drying, the outer 1 in. of paper is counted in a gas-flow proportional counter.

B. Contamination Levels

β–γ measurements are made at contact with an open-window G–M counter, α measurements at contact with a 60-cm^2 PeeWee probe. Both measurements are readings above background.

	β–γ (mrads/hr)		α (c/m)
	Sr^{90}	Others	
Wounds	Refer all potentially contaminated wounds to the Medical Group and H-1 Supervisor.		
Nose swipes	----------	----------	50 (each swipe in 50% efficiency counter).
Skin*	0.05	1.0	500
Bench tops and floors	0.05	1.0	500
Vehicles (for continuing project use).	0.05	6.0	500
Vehicles (for public sale)	No detectable activity of any kind.		
Clothing (personal)	0.05	1.0	500
Shoes (personal and safety)	0.05 exterior.	6.0 exterior.	500 exterior.
	0.05 interior.	1.0 interior.	500 interior.
Respirators	0.05 N.S.†	1.0 N.S.†	500 N.S.†
Uranium transport containers (intraplant).	----------	----------	250 (swipe).
Equipment (for use in contaminated areas).	0.05	6.0	Varies with situation—usually about 500 c/m.
Equipment (for use outside the project in contaminated areas).	No health hazard; recipient must receive written statement as to extent and kind of contamination and must be able to handle it. Transfer requires H-1 Group Office approval.		
Equipment [for use in "clean" areas, e.g., outside the project (gas cylinders, salvage materials); in counting or photographic labs; in machine shops or stock rooms]‡	No detectable activity of any kind.		
Tritium contamination	Refer all tritium contamination to H-1 Group Office except as noted in Sec. 15.		

*If, after two attempts at skin decontamination, more than 3 mrads/hr remain, notify H-1 Group Office and send subject to Decontamination Room (128) at Medical Center. If less than 3 mrads/hr but greater than permissible levels, release but recheck following day. Measurements should be made after skin has been washed.

†N.S. signifies no detectable activity using swipe technique.

‡Certain salvage materials, especially bulk quantities for reprocessing, carry higher contamination tolerances. Refer to H-1 Group Office.

8. DECONTAMINATION

Removal of radioactive contaminants falls into two general categories, decontamination of "people" and decontamination of "things." In general, first attempts at decontamination can be made under the monitor's supervision. Every effort should be made to control any spread of the contamination during decontamination. This can be accomplished by:

(1) Always working in towards the center of contamination.

(2) Taking care not to track the contamination, which implies complete knowledge of where the contamination lies, and proper use of protective clothing, especially shoe cover (booties).

(3) Covering clean areas in the vicinity with kraft paper.

(4) Being aware that the run-off solutions and all mops, rags, and brushes used in the decontaminating are potentially contaminated.

Gross, widespread, or persistent problems should be handled by specialists, H–1 Decontamination Section for objects and H–2 Industrial Medicine for personnel.

A. Personnel Decontamination

People are decontaminated for two reasons: (1) To prevent possible transfer, especially of α emitters, to internal organs by ingestion or through cuts or abrasions, and (2) to prevent external exposure or possible radiation burns. It is obvious that in both cases

prompt removal will reduce the potential hazard. It is also apparent that methods used to effect decontamination must not spread initially localized material or assist the contaminant in entering the body (excessive scrubbing which abraids the skin).

Skin. Over the years many procedures, some quite lengthy and involved, have been devised for the removal of contamination from radiation workers. The following relatively simple procedures have been widely used at LASL for the removal of a variety of contaminants, mostly α emitters, from workers. Other more drastic measures are available under medical supervision.

(1) Detergent and water wash.

(2) Turco Hand Cleaner (Turco Products, Inc., Los Angeles). A commercial liquid hand cleaner developed specifically for removing radioactive materials from skin. Good results with plutonium, uranium, and β–γ emitters. Contains lanolin to reduce skin irritation.

(3) Tartaric–Citric Acid Mixture. Half-and-half mixture of the acids; used routinely and successfully for plutonium but somewhat irritating with prolonged usage.

(4) Citric Acid Paste. Good for α emitters.

B. General Decontamination

Experience has shown that technique is often more important than the specific decontaminating agent used. For this and other reasons, it is difficult to assign a best method for a certain decontamination problem. Several specific methods used at LASL—successful but not necessarily the best—are listed below. It

is always wise first to try the following five simple methods:

(1) Damp rag.

(2) Water and detergent.

(3) Dilute complexing agent such as Versene (soaking in Versene is considerably better than simple washing). Action is accelerated if the Versene is heated.

(4) Mild acids (citric, low normality HCl or HNO_3).

(5) Combinations of the above.

Other methods used by the Decontamination Section include vacuuming, vacu- and sand-blasting, ultrasonic cleaning, and high pressure steam.

C. Specific Methods

Metals. Oily surfaces must first be removed; then high normality acids and even concentrated acids or aqua regia may be used if surfaces can stand this rough treatment.

Concrete or Brick. Solutions of HCl and Igepal used with commercial scrubbers.

Glassware. Ordinary chromic acid cleaning solution.

Linoleum. If well waxed before contamination, removal of wax with solvents or scouring powder and steel wool will decontaminate.

Wood. No hope short of sanding or planing.

Painted Surfaces. Paint removers.

9. MAXIMUM PERMISSIBLE EXPOSURES

A. Whole-Body Exposure

The maximum permissible accumulated whole-body occupational dose, in rem, at any age greater than 18, is computed MPD=5(N–18), where N is the age in years, provided no annual increment exceeds 12 rem. Not more than one-fourth of the 12-rem maximum permissible yearly dose (3 rem) shall be taken in one-fourth of a year. These values may be doubled when only the skin of the whole body is exposed. Note that although permissible weekly doses are no longer specified, they are used throughout the handbook for convenience, especially the 0.3 rem/wk based on the former MPD of 15 rem/yr.

The acceptable yearly exposure at LASL is 5 rem and the 12-rem maximum is used (1) only when the accumulated exposure after the age of 18 is documented, (2) then only in cases where judicious use of exposure has been made, and (3) when, in unique and unusual instances, after due consideration has been given, restrictions would result in serious impairment to the functions of the Laboratory. Yearly exposures greater than 5 rem can be allowed only when it is documented that this exposure will not violate the 5(N–18) rule. Administration of the above MPD policy and the further LASL restrictions can become complicated for the exceptional case. The necessary information is often difficult to obtain, for instance when an employee has previously worked at another installation and does not have an accurate record of his past exposures, or

when he has worked at LASL for a number of years and it is necessary to do the time-consuming job of compiling his cumulative exposures. The general tendency is to limit exposure whenever possible.

The 5 rem/yr will be handled on a 0.1 rem/wk basis but this does not imply that 0.1 rem/wk shall be the upper limit of weekly exposure. Whenever 0.1 rem/wk is exceeded special measures are taken. These special measures include notification of supervisors that one of their people received a dose which, if continued for a year, would result in more than 5 rem. Overexposure reports are issued only when 3 rem is exceeded in a calendar quarter.

B. Extremity Exposure

The maximum permissible accumulated dose in the hands and forearms, and feet and ankles is 75 rem/yr. Since there is no accumulated age restriction on extremity dose, a weekly dose of 1.5 rem is used. Suitable wrist-to-finger ratios have been developed experimentally to avoid the use of finger badges.

C. Summary

Whole-body and extremity permissible exposures are summarized as follows:

Whole Body

	rem
Maximum permissible yearly dose	12
Maximum permissible accumulated dose	$5(N-18)$
Administrative permissible yearly dose	5
Maximum permissible quarter-year dose	3
Weekly dose to give 5 rem/yr	0. 1

Note: For β or X rays below 40 kev average, the above values may be doubled. Also, if the γ does not exceed the above values, the $\beta+\gamma$ sum may be doubled.

Extremity

	rem
Maximum permissible yearly dose	75
Maximum permissible weekly dose	1. 5

Neutron Whole Body

Neutron energy	RBE	Flux to give 0.3 rem in 40 hr (n/cm²-sec)*	0.3 rem MPD (n/cm²-wk)*
Thermal (3×10^{-2} ev)	3	2000	288×10^6
100 ev	2	1550	223×10^6
5×10^3 ev	2. 5	1700	245×10^6
2×10^4 ev	5	850	120×10^6
0.1 Mev	8	250	36.0×10^6
0.5 Mev	10	90	13.0×10^6
1.0 Mev	10. 5	55	7.92×10^6
2.5 Mev	8	60	8.64×10^6
5.0 Mev	7	55	7.92×10^6
7.5 Mev	7	50	7.20×10^6
10 Mev	6. 5	50	7.20×10^6
10 to 30 Mev	----------	30	4.32×10^6

*The last two columns may be divided by 3 to obtain values based on 0.1 rem/wk.

Neutron Extremity

Neutron extremity dose may be five times the whole-body MPD.

D. Permissible Exposure Times

It is often useful to express permissible dose in terms of the time it takes to receive such a dose. This can be calculated by dividing the permissible dose rate by the measured exposure rate. The choice of permissible dose rate must depend on the type, duration, etc., of the operation.

Example 1: γ measurements show an exposure dose rate of 7.5 mr/hr (0.0075 r/hr) at a certain position. Using as permissible rate 0.3 r/wk, (0.3 r/wk)/(0.0075 r/hr)=40 hr/wk at this position. This is an example of a short term operation. If continued indefinitely, the 0.1 r/wk permissible exposure rate should be used.

Example 2: Suppose a 1-Mev neutron flux of 55 n/cm^2-sec is measured. Since the n/cm^2-wk to give 0.3 rem/wk is 7.92×10^6 n/cm^2-wk, (7.92×10^6 n/cm^2-wk)/(55 n/cm^2-sec$\times$3600 sec/hr)=40 hr/wk allowable at this position to give 0.3 rem/wk.

Example 3: Exposures in mixed fields (say γ rays and neutrons) must be limited to that amount of each so that the total exposure is permissible or less. Suppose 25 mr/hr γ and 100 n/cm^2-sec (1 Mev) are measured simultaneously. 25 mr/hr is 3.33 times permissible weekly γ exposure (25/7.5=3.33), and similarly 100 n/cm^2-sec is 1.82 times permissible (100/55=1.82). The combined effect (1.82+3.33=5.15) is 5.15 times permissible, or the allowable time must be divided by 5.15 (40 hr/5.15=7.77 hr/wk), giving a permissible 7.77-hr exposure in a 40-hr week to give 0.3 rem.

10. TABLE OF ISOTOPES

The following table presents pertinent data for many radioactive isotopes or isotope chains. Element name and atomic number (Z) are listed alphabetically in column (1). Column (2) identifies the isotope, giving element abbreviation with the mass number (atomic weight, A) as superscript. An "m" following the mass number signifies a metastable state (see Appendix Q). When only one daughter is significant in determining MPC, it is identified in the same manner as the parent. When two or more daughters are important they are abbreviated "+drs."

In column (3) radiations to be expected (when monitoring) from the isotope or isotope chain are given. α signifies alpha particle emission; β signifies either electron or positron emission; γ indicates gamma ray emission; "X", used only when no gammas are emitted, signifies electron capture X rays; "s.f." signifies that spontaneous fission neutrons are emitted.

Columns (4) and (5) give the maximum permissible concentrations in air (MPC_a) and water (MPC_w) in disintegrations per minute per cubic meter (d/m-M^3) and disintegrations per minute per liter (d/m-L), respectively. MPC values were taken from a prepublication copy of the "Report of Committees (ICRP and NCRP) on Permissible Dose for Internal Radiation—1958 Revision" and are subject to revision. Values are given for occupational exposures of 40 hr/wk, 50 wk/yr for a continuous 50-yr work period. Other assumptions are (*a*) 10^7 cc breathed per 8-hr

work day (½ the air breathed in 24 hr); (*b*) 1,100 cc of water consumed per 8-hr work day (½ the water consumed in 24 hr). MPC's for parent-daughter combinations or chains are given in terms of d/m of the parent alone. The biological effect of the daughter(s) formed by decay of the parent inside the body is considered, but not the daughter(s) associated with the parent when entering the body. When a parent-daughter mixture is the hazard, a special value of MPC must be computed for the mixture. This has been done for several mixtures encountered at LASL ($Ba^{140}+La^{140}$, natural thorium, $Sr^{90}+Y^{90}$, and several mixtures of uranium isotopes). Rn^{220} and Rn^{222} MPC_a values also assume an equilibrium mixture as the breathing hazard.

Column (6) lists the body burden (q) in μc and critical organ using the following organ abbreviations: B, bone; BT, bone and teeth; BW, body water; F, fat; K, kidney; L, liver; Lu, lung; P, pancreas; Pr, prostate; S, skin; Sp, spleen; T, thyroid; TB, total body; Ts, testes. The ICRP–NCRP data include MPC values for the total body, the lung for insoluble, the GI tract for soluble and insoluble, and several other critical organs for soluble compounds. The critical organ chosen for inclusion in the Table of Isotopes is the one (except GI tract) that gives the smallest soluble MPC_a value. The critical organ is marked with a superscript "b" whenever soluble GI tract number is lower.

In the case of α- or β-emitting isotopes that are critical in the bone, q is determined from a direct comparison with radium. Long experience with radium has shown that 0.1 μc should serve as the basis of choice of body burden for bone seekers. With a body

burden of 0.1 μc of Ra^{226} and its daughter products, the bone receives about 0.56 rem/wk. For isotopes critical in the skin or thyroid, body burdens are picked so that the critical organ will receive no more than 0.6 rem/wk. When a major portion of the body or the gonads is the critical organ, 0.1 rem/wk is the permissible dose to the organ. For all other critical organs, the basic permissible dose is 0.3 rem/wk. MPC's are then the concentration in air or water that result under equilibrium conditions in the maintenance of a body burden except for submersion in a radioactive gas. For gaseous isotopes (except tritium) no MPC_w is given and MPC_a values are computed assuming submersion in an infinite volume of gas. Here the total body is the critical organ and 0.1 rem/wk is the permissible limit unless the radiation does not penetrate the skin, in which case the lung is critical.

Radioactive (T_r) and biological (T_b) half-lives given in Column (7) in appropriate time units are as compiled by W. H Sullivan and the ICRP–NCRP listing, respectively.

Columns (8) and (9) give the mass-activity relationships in grams per curie (g/c) and curies per gram (c/g), respectively, for the parent isotope.

Column (10) gives the category classification and amount of the parent isotope in milligrams (mg) that may be shipped by mail and that is exempt from the packaging and labelling requirements of the Railway Express Agency (see Appendix A). Some interpretation of the REA regulations was necessary to allow all isotopes to fit into the three categories. All α emitters as hazardous as radium or Po^{210} are in Category I. Category II contains all β-γ emitters with hazard equal

to or greater than Sr^{89}, Sr^{90}, or Ba^{140}. All others are placed in Category III. The degree of hazard was calculated using the method of Morgan et al. for inhalation given in "Proceedings of the International Conference on the Peaceful Uses of Atomic Energy," Vol. 13, pp. 139–158, and the prepublication ICRP–

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Actinium (89)	Ac^{227}+drs	α, β, γ	3.3	7.2×10^{4}
	Ac^{228}+drs	α, β, γ	8.0×10^{4}	1.8×10^{6}
Americium (95)	Am^{241}+Np^{237m}	α, γ	13.	3.0×10^{3}
	Am^{243}+drs	α, β, γ	13.	2.9×10^{3}
Antimony (51)	Sb^{122}	β, γ	[a] 7.7×10^{6}	[a] 6.2×10^{8}
	Sb^{124}	β, γ	4.0×10^{5}	3.1×10^{7}
	Sb^{125}+Te^{125m}	β, γ	7.0×10^{5}	5.9×10^{7}
Argon (18)	A^{37}	X	[e] 2.4×10^{9}	(e)
	A^{41}	β, γ	[e] 3.5×10^{6}	(e)
Arsenic (33)	As^{73}+Ge^{73m}	γ	4.4×10^{6}	3.5×10^{8}
	As^{74}	β, γ	1.8×10^{6}	1.5×10^{8}
	As^{76}	β, γ	1.2×10^{7}	9.0×10^{8}
	As^{77}	β, γ	4.4×10^{7}	3.5×10^{9}
Astatine (85)	At^{211}+drs	α, β, γ	[d] 1.6×10^{4}	[d] 1.1×10^{6}
Barium (56)	Ba^{131}+Cs^{131}	γ	[a] 4.2×10^{6}	[a] 2.1×10^{8}
	Ba^{140}+La^{140}	β, γ	2.9×10^{6}	1.5×10^{7}
(Ba^{140}–La^{140})	Equilibrium Mixture	β, γ	5.3×10^{6}	2.9×10^{7}
Berkelium (97)	Bk^{249}+Cf^{249}	α, β, γ	2.2×10^{3}	1.6×10^{5}
Beryllium (4)	Be^{7}	γ	[a] 1.2×10^{7}	[a] 1.3×10^{10}

See footnotes at end of table.

NCRP data. The actual activities in each category are: Category I, 0.1 mc; Category II, 0.135 mc; Category III, 1.35 mc. Since only the parent is considered in setting the exempt amounts, corrections must be made if appreciable amounts of decay products are included in the shipment.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
0.018 B	21.8y	7.3×10^{4}d	1.38×10^{-2}	72.5	I 1.4×10^{-3}
0.022 B	6.13h	7.3×10^{4}d	4.44×10^{-7}	2.25×10^{6}	I 4.4×10^{-6}
0.054 B	462y	7.3×10^{4}d	3.11×10^{-1}	3.22	I 3.1×10^{-3}
0.046 B	8×10^{3}y	7.3×10^{4}d	5.41	1.85×10^{-1}	I 5.4×10^{-1}
[a] 24 [b] TB	2.80d	38d	2.61×10^{-6}	3.83×10^{5}	III 3.5×10^{-6}
11 [b] Lu	60d	100d	5.68×10^{-5}	1.76×10^{4}	III 7.7×10^{-5}
32 Lu	2.4y	100d	8.33×10^{-4}	1.20×10^{3}	III 1.2×10^{-3}
[c] TB	34.1d	[c]	9.61×10^{-6}	1.04×10^{5}	[c]
[c] TB	1.83h	[c]	2.39×10^{-8}	4.18×10^{7}	[c]
320 TB	76d	280d	4.24×10^{-5}	2.36×10^{4}	III 5.7×10^{-5}
36 [b] TB	17.5d	280d	9.90×10^{-6}	1.01×10^{5}	III 1.3×10^{-5}
15 [b] TB	26.6h	280d	6.45×10^{-7}	1.55×10^{6}	III 8.7×10^{-7}
82 [b] TB	38.8h	280d	9.52×10^{-7}	1.05×10^{6}	III 1.3×10^{-6}
[d] 0.016 T	7.20h	36d	4.83×10^{-7}	2.07×10^{6}	I 4.8×10^{-6}
[a] 52 [b] TB	11.6d	65d	1.16×10^{-3} [f]	8.60×10^{4}	III 1.6×10^{-3}
3.7 [b] B	12.8d	65d	1.37×10^{-3}	7.29×10^{4}	II 1.8×10^{-4}
5.4 B					
0.68 B	290d	7.3×10^{4}d	5.52×10^{-4}	1.81×10^{3}	I 5.5×10^{-3}
[a] 560 TB	53.6d	180d	2.87×10^{-6}	3.48×10^{5}	III 3.9×10^{-6}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Bismuth (83)	$Bi^{206}+Pb^{206}$	γ	4.3×10^{5}	9.9×10^{7}
	$Bi^{207}+Pb^{207m}$	γ	3.9×10^{5}	8.7×10^{7}
	$Bi^{210}+Po^{210}$	α, β, γ	1.5×10^{4}	3.6×10^{6}
	Bi^{212}+drs	α, β, γ	2.2×10^{5}	5.1×10^{7}
Bromine (35)	Br^{82}	β, γ	* 2.6×10^{6}	* 1.7×10^{7}
Cadmium (48)	$Cd^{109}+Ag^{109m}$	γ	1.2×10^{5}	1.1×10^{8}
	Cd^{115m}+drs	β, γ	7.7×10^{4}	7.0×10^{7}
	Cd^{115}+drs	β, γ	1.3×10^{6}	1.2×10^{9}
Calcium (20)	Ca^{45}	β	7.3×10^{4}	6.0×10^{5}
	$Ca^{47}+Sc^{47}$	β, γ	5.5×10^{5}	4.5×10^{6}
Californium (98)	Cf^{249}	α, γ	3.6	2.7×10^{5}
	$Cf^{250}+Cm^{246}$	α, s. f.	11.	8.7×10^{5}
	Cf^{253}	α, γ, s. f.	49.	3.6×10^{6}
Carbon (6)	C^{14}	β	8.0×10^{6}	5.4×10^{7}
Cerium (58)	Ce^{141}	β, γ	9.7×10^{5}	2.2×10^{10}
	$Ce^{143}+Pr^{143}$	β, γ	4.4×10^{6}	1.0×10^{11}
	Ce^{144}+drs	β, γ	2.2×10^{4}	5.1×10^{8}
Cesium (55)	Cs^{131}	X	* 2.4×10^{7}	* 1.5×10^{8}
	$Cs^{134m}+Cs^{134}$	β, γ	* 2.4×10^{3}	* 1.6×10^{9}
	Cs^{134}	β, γ	* 8.4×10^{4}	* 5.5×10^{5}
	Cs^{135}	β	1.0×10^{6}	7.0×10^{6}
	Cs^{136}	β, γ	* 8.4×10^{5}	* 5.5×10^{6}
	$Cs^{137}+Ba^{137m}$	β, γ	* 1.4×10^{5}	* 9.7×10^{5}
Chlorine (17)	Cl^{36}	β	* 8.0×10^{5}	* 5.4×10^{6}
	Cl^{39}	β, γ	* 1.0×10^{6}	* 6.6×10^{6}
Chromium (24)	Cr^{51}	γ	2.4×10^{7}	1.1×10^{9}
Cobalt (27)	Co^{57}	γ	* 1.3×10^{7}	* 1.6×10^{8}
	$Co^{58m}+Co^{58}$	β, γ	* 3.1×10^{6}	* 3.7×10^{7}
	Co^{58}	β, γ	* 2.1×10^{6}	* 2.6×10^{7}
	Co^{60}	β, γ	* 7.7×10^{5}	* 9.0×10^{6}

See footnotes at end of table.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
1.3 K	6.4d	6d	1.01×10^{-5}	9.90×10^{4}	II 1.4×10^{-6}
2.1 K	8.0y	6d	4.62×10^{-3}	2.16×10^{2}	II 6.2×10^{-4}
0.040 K	5d	6d	8.03×10^{-6}	1.24×10^{5}	I 8.0×10^{-7}
0.010 K	60.5m	6d	6.80×10^{-5}	1.47×10^{7}	III 9.2×10^{-5}
[a] 11 TB	35.9h	8d	9.38×10^{-7}	1.07×10^{6}	III 1.3×10^{-6}
19 L	1.3y	200d	3.96×10^{-4}	2.53×10^{3}	III 5.3×10^{-4}
3.1 L	43d	200d	3.78×10^{-5}	2.65×10^{4}	II 5.1×10^{-6}
3.2 [b] L	53h	200d	1.94×10^{-6}	5.15×10^{5}	III 2.6×10^{-6}
28 B	164d	1.8×10^{4}d	5.64×10^{-5}	1.77×10^{4}	III 7.6×10^{-5}
6.4 B	4.9d	1.8×10^{4}d	1.76×10^{-6}	5.68×10^{5}	III 2.4×10^{-6}
0.040 B	470y	7.3×10^{4}d	3.29×10^{-1}	3.04	I 3.3×10^{-2}
0.042 B	10y	7.3×10^{4}d	6.85×10^{-3}	1.46×10^{2}	I 6.9×10^{-4}
0.042 B	2.2y	7.3×10^{4}d	1.56×10^{-3}	6.43×10^{2}	I 1.6×10^{-4}
260 F	5.6×10^{3}y	12d	2.19×10^{-1}	4.57	III 3.0×10^{-1}
33 L	32d	293d	3.45×10^{-5}	2.90×10^{4}	III 4.7×10^{-5}
6.7 [b] L	32h	293d	1.46×10^{-6}	6.85×10^{5}	III 2.0×10^{-6}
4.6 B	290d	1500d	3.19×10^{-4}	3.13×10^{3}	III 4.3×10^{-4}
[a] 680 TB	10d	70d	1.00×10^{-5}	9.98×10^{4}	III 1.4×10^{-5}
[a] 100 [b] TB	3.2h	70d	1.34×10^{-7}	7.44×10^{6}	III 1.8×10^{-7}
[a] 18 TB	2.3y	70d	8.62×10^{-4}	1.16×10^{3}	III 1.2×10^{-3}
240 L	3.0×10^{6}y	90d	1.13×10^{3}	8.83×10^{-4}	III 1.5×10^{2}
[a] 30 TB	13d	70d	1.35×10^{-5}	7.40×10^{4}	III 1.8×10^{-6}
[a] 33 TB	30y	70d	1.15×10^{-2}	87.3	III 1.6×10^{-3}
[a] 75 TB	3.2×10^{5}y	29d	32.2	3.11×10^{-2}	III 43.
[a] 8.5 [b] TB	37.5m	29d	7.58×10^{-9}	1.32×10^{8}	III 1.0×10^{-6}
760 Lu	27.8d	616d	1.08×10^{-5}	9.26×10^{4}	III 1.5×10^{-5}
[a] 220 [b] TB	270d	9.5d	1.18×10^{-4}	8.47×10^{3}	III 1.6×10^{-4}
[a] 200 [b] TB	9.0h	9.5d	1.66×10^{-7}	6.02×10^{6}	III 2.2×10^{-7}
[a] 32 [b] TB	72d	9.5d	3.19×10^{-6}	3.13×10^{5}	III 4.3×10^{-6}
[a] 13 [b] TB	5.3y	9.5d	8.88×10^{-4}	1.13×10^{3}	III 1.2×10^{-3}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a ($d/m\text{-}M^3$)	(5) MPC_w ($d/m\text{-}L$)
Copper (29)	Cu^{64}	β, γ	1.4×10^{7}	1.8×10^{5}
Curium (96)	$Cm^{243}+Pu^{239}$	α, γ	2.6×10^{3}	5.9×10^{6}
	Cm^{243}+drs	α, γ	15.	3.3×10^{5}
	$Cm^{244}+Pu^{240}$	α, γ	21.	4.8×10^{5}
	Cm^{245}+drs	α, β, γ	11.	2.3×10^{5}
	Cm^{246}	α	11.	2.4×10^{5}
Dysprosium (66)	Dy^{165}	β, γ	1.1×10^{8}	2.7×10^{12}
	Dy^{166}+drs	β, γ	1.3×10^{6}	2.8×10^{10}
Erbium (68)	$Er^{169}+Tm^{169m}$	β, γ	3.1×10^{6}	7.2×10^{10}
	Er^{171}+drs	β, γ	2.7×10^{7}	6.0×10^{11}
Europium (63)	Eu^{152}	β, γ	1.9×10^{7}	4.4×10^{11}
	Eu^{152}	β, γ	2.6×10^{4}	5.9×10^{5}
	Eu^{154}	β, γ	8.4×10^{3}	1.9×10^{5}
	Eu^{155}	β, γ	2.0×10^{5}	4.6×10^{9}
Fluorine (9)	F^{18}	β	5.8×10^{7}	3.9×10^{6}
Fission Products		β, γ	$*6.7\times10^{3}$	$*6.7\times10^{3}$
Gadolinium (64)	$Gd^{148}+Eu^{148m}$	γ	6.2×10^{3}	1.4×10^{10}
	Gd^{149}	β, γ	2.0×10^{7}	4.5×10^{11}
Gallium (31)	Ga^{72}	β, γ	9.0×10^{6}	2.0×10^{10}
Germanium (32)	Ge^{71}	X	1.2×10^{8}	2.9×10^{10}
Gold (79)	Au^{196}	β, γ	$*5.9\times10^{6}$	$*1.6\times10^{9}$
	Au^{198}	β, γ	5.7×10^{6}	1.5×10^{9}
	$Au^{199}+Hg^{199}$	β, γ	1.7×10^{7}	4.6×10^{9}
Hafnium (72)	$Hf^{181}+Ta^{181m}$	β, γ	8.1×10^{4}	1.9×10^{9}
Holmium (67)	$Ho^{166}+Er^{166m}$	β, γ	4.1×10^{6}	9.3×10^{10}
Hydrogen (1)	H^{3}	β	$*\,1.1\times10^{7}$	$*\,2.1\times10^{8}$

See footnotes at end of table.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
13 [b] Sp	12.82h	2d	2.61×10^{-7}	3.83×10^{6}	III 3.5×10^{-7}
0.048 L	162.5d	3000d	3.01×10^{-4}	3.32×10^{3}	I 3.0×10^{-5}
0.093 B	35y	7.3×10^{4}d	2.37×10^{-2}	42.2	I 2.4×10^{-3}
0.10 B	18.4y	7.3×10^{4}d	1.25×10^{-2}	80.0	I 1.3×10^{-3}
0.044 B	2×10^{4}y	7.3×10^{4}d	13.6	7.35×10^{-2}	III 18.
0.045 B	6.6×10^{3}y	7.3×10^{4}d	4.52	2.21×10^{-1}	I 4.5×10^{-1}
12 [b] B	2.32h	1000d	1.22×10^{-7}	8.20×10^{6}	III 1.6×10^{-7}
4.7 [b] B	82h	1000d	4.34×10^{-6}	2.30×10^{5}	III 5.9×10^{-6}
31 [b] B	9.4d	1000d	1.21×10^{-5}	8.26×10^{4}	III 1.6×10^{-5}
9.1 [b] B	7.5h	1000d	4.08×10^{-7}	2.45×10^{6}	III 5.5×10^{-7}
8.0 [b] L	9.2h	127d	4.45×10^{-7}	2.25×10^{6}	III 6.0×10^{-7}
17 K	13y	1480d	5.50×10^{-3}	1.82×10^{2}	III 7.4×10^{-3}
5.3 K	16y	1480d	6.86×10^{-3}	1.46×10^{2}	III 9.3×10^{-3}
72 K	1.7y	1480d	7.34×10^{-4}	1.36×10^{3}	III 9.9×10^{-4}
15 [b] BT	1.87h	1460d	1.07×10^{-6}	9.34×10^{7}	III 1.4×10^{-6}
	(f)				
110 B	236d	1000d	2.76×10^{-4}	3.62×10^{3}	III 3.7×10^{-4}
16 [b] B	18h	1000d	9.11×10^{-7}	1.10×10^{6}	III 1.2×10^{-6}
5.4 [b] L	14.2h	4.8d	3.26×10^{-7}	3.07×10^{6}	III 4.4×10^{-7}
130 [b] K	12d	12d	6.51×10^{-6}	1.54×10^{5}	III 8.8×10^{-6}
[a] 43 [b] TB	5.6d	120d	8.39×10^{-6}	1.19×10^{5}	III 1.1×10^{-5}
20 [b] K	2.7d	280d	4.09×10^{-6}	2.44×10^{5}	III 5.5×10^{-6}
70 [b] K	3.15d	280d	4.79×10^{-6}	2.09×10^{5}	III 6.5×10^{-6}
4.2 Sp	46d	350d	6.37×10^{-5}	1.57×10^{4}	II 8.6×10^{-6}
5 [b] B	27.2h	1000d	1.44×10^{-6}	6.94×10^{5}	III 1.9×10^{-6}
[a] 1.2×10^{3} BW	12.26y	12d	1.02×10^{-4}	9.80×10^{3}	(h)

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Indium (49)	In^{113m}	γ	4.2×10^{8}	4.8×10^{11}
	$In^{114m}+In^{114}$	β, γ	2.3×10^{5}	2.7×10^{8}
	$In^{115m}+In^{115}$	β, γ	1.6×10^{8}	1.9×10^{11}
	In^{116}	β	5.7×10^{5}	6.6×10^{8}
Iodine (53)	I^{126}	β, γ	[d] 2.7×10^{4}	[d] 1.8×10^{5}
	I^{129}	β, γ	[d] 5.5×10^{3}	[d] 3.6×10^{4}
	$I^{131}+Xe^{131m}$	β, γ	[d] 2.9×10^{4}	[d] 2.0×10^{5}
	I^{132}	β, γ	[d] 8.0×10^{5}	[d] 5.7×10^{6}
	$I^{133}+dr^{s}$	β, γ	[d] 1.1×10^{5}	[d] 7.2×10^{5}
	I^{134}	β, γ	[d] 1.7×10^{6}	[d] 1.2×10^{7}
	$I^{135}+drs$	β, γ	[d] 3.6×10^{5}	[d] 2.5×10^{6}
Iridium (77)	Ir^{190}	γ	3.7×10^{6}	9.9×10^{7}
	Ir^{192}	β, γ	2.9×10^{5}	7.8×10^{6}
	Ir^{194}	β, γ	6.7×10^{6}	1.9×10^{8}
Iron (26)	Fe^{55}	X	1.9×10^{6}	5.4×10^{7}
	Fe^{59}	β, γ	3.4×10^{5}	9.3×10^{6}
Krypton (36)	$Kr^{85m}+drs$	β, γ	[e] 1.0×10^{7}	(e)
	Kr^{85}	β, γ	[e] 1.8×10^{7}	(e)
	Kr^{87}	β, γ	[e] 1.5×10^{6}	(e)
Lanthanum (57)	La^{140}	β, γ	4.6×10^{6}	1.0×10^{11}
Lead (82)	Pb^{203}	γ	9.0×10^{6}	3.1×10^{8}
	$Pb^{210}+drs$	α, β, γ	2.9×10^{2}	9.0×10^{3}
	$Pb^{212}+drs$	α, β, γ	4.0×10^{4}	1.3×10^{6}
Lutetium (71)	Lu^{177}	β, γ	2.9×10^{6}	6.6×10^{10}
Manganese (25)	Mn^{52}	β, γ	9.7×10^{5}	2.6×10^{7}
	Mn^{54}	γ	8.7×10^{5}	2.4×10^{7}
	Mn^{56}	β, γ	1.2×10^{7}	3.3×10^{8}
Mercury (80)	$Hg^{197m}+drs$	γ	1.7×10^{6}	1.3×10^{7}
	Hg^{197}	γ	2.7×10^{6}	2.0×10^{7}
	Hg^{203}	β, γ	1.6×10^{5}	1.2×10^{6}
Molybdenum (42)	$Mo^{99}+drs$	β, γ	1.6×10^{6}	1.2×10^{7}

See footnotes at end of table.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
33 [b] K	1.75h	60d	6.30×10^{-5}	1.59×10^{7}	III 8.5×10^{-8}
6.0 K	49d	60d	4.27×10^{-5}	2.34×10^{4}	III 5.8×10^{-5}
33 [b] K	4.5h	60d	1.65×10^{-7}	6.06×10^{6}	III 2.2×10^{-7}
30 K	6×10^{14}y	60d	1.92×10^{11}	5.21×10^{-12}	III 2.6×10^{11}
[d] 1.0 T	13.3d	138d	1.28×10^{-5}	7.81×10^{4}	II 1.7×10^{-6}
[d] 2.5 T	1.72×10^{7}y	138d	6.18×10^{3}	1.62×10^{-4}	III 8.3×10^{3}
[d] 0.73 T	8.05d	138d	8.06×10^{-6}	1.24×10^{5}	II 1.1×10^{-6}
[d] 0.26 T	2.33h	138d	9.79×10^{-8}	1.02×10^{7}	III 1.3×10^{-7}
[d] 0.31 T	20.8h	138d	8.81×10^{-7}	1.14×10^{6}	II 1.2×10^{-7}
[d] 0.20 T	52.5m	138d	3.73×10^{-8}	2.68×10^{7}	III 5.0×10^{-8}
[d] 0.32 T	6.70h	138d	2.92×10^{-7}	3.42×10^{6}	II 3.9×10^{-8}
36 [b] K	12d	50d	1.74×10^{-5}	5.75×10^{4}	III 2.3×10^{-5}
5.9 K	74.5d	50d	1.09×10^{-4}	9.17×10^{3}	III 2.6×10^{-4}
6.8 [b] K	19.0h	50d	1.17×10^{-6}	8.55×10^{5}	III 1.6×10^{-6}
1.1×10^{3} Sp	2.94y	600d	4.50×10^{-4}	2.22×10^{3}	III 6.1×10^{-4}
19 Sp	45.1d	600d	2.03×10^{-5}	4.93×10^{4}	III 2.7×10^{-6}
[c] TB	4.4h	[c]	1.19×10^{-7}	8.40×10^{6}	[c]
[c] TB	10.6y	[c]	2.58×10^{-3}	3.88×10^{2}	[c]
[c] TB	78m	[c]	3.60×10^{-8}	2.78×10^{7}	[c]
8.7 [b] L	40.2h	400d	1.79×10^{-6}	5.59×10^{5}	III 2.4×10^{-6}
26 [b] K	52h	531d	3.36×10^{-6}	2.98×10^{5}	III 4.5×10^{-6}
0.44 K	19.4y	531d	1.13×10^{-2}	88.5	I 1.1×10^{-3}
0.022 K	10.64h	531d	7.18×10^{-7}	1.39×10^{6}	I 7.2×10^{-8}
21 [b] B	6.7d	1000d	9.07×10^{-6}	1.10×10^{5}	III 1.2×10^{-5}
5.3 [b] P	5.55d	5.7d	2.21×10^{-6}	4.52×10^{5}	III 3.0×10^{-6}
18 L	300d	25d	1.24×10^{-4}	8.06×10^{3}	III 1.7×10^{-4}
1.8 [b] P	2.58h	5.7d	4.50×10^{-8}	2.17×10^{7}	III 6.2×10^{-8}
4.1 K	24h	14.5d	1.51×10^{-6}	6.62×10^{5}	III 2.0×10^{-6}
15 K	65h	14.5d	4.08×10^{-6}	2.45×10^{5}	III 5.5×10^{-6}
3.6 K	45.8d	14.5d	7.11×10^{-5}	1.41×10^{4}	II 9.6×10^{-6}
8.4 K	67.0h	3d	2.11×10^{-6}	4.74×10^{5}	III 2.8×10^{-6}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Neodymium (60)	Nd^{144}	α	1.9×10^{2}	4.2×10^{6}
	Nd^{147}+drs	β, γ	7.7×10^{3}	1.7×10^{10}
	$Nd^{149}+Pm^{149}$	β, γ	3.1×10^{7}	7.0×10^{11}
Neptunium (93)	$Np^{237}+Pa^{233}$	α, β, γ	9.3	2.1×10^{3}
	Np^{239}+drs	α, β, γ	1.0×10^{7}	2.2×10^{11}
Nickel (28)	Ni^{59}	X	1.1×10^{6}	1.3×10^{7}
	Ni^{63}	β	1.5×10^{5}	1.8×10^{6}
	Ni^{65}	β, γ	2.2×10^{7}	2.7×10^{8}
Niobium (41) (Columbium).	Nb^{93m}	γ	4.3×10^{5}	9.9×10^{9}
	Nb^{95}	β, γ	* 1.0×10^{6}	* 2.4×10^{10}
	Nb^{97}	β, γ	2.1×10^{8}	4.8×10^{12}
Osmium (76)	Os^{185}	γ	3.3×10^{6}	8.7×10^{7}
	Os^{191m}+drs	β, γ	2.4×10^{8}	6.6×10^{9}
	$Os^{191}+Ir^{191m}$	β, γ	1.3×10^{7}	3.6×10^{8}
	Os^{193}	β, γ	1.0×10^{7}	2.8×10^{8}
Palladium (46)	$Pd^{103}+Rh^{103m}$	γ	3.1×10^{6}	4.8×10^{7}
	$Pd^{109}+Ag^{109m}$	β, γ	8.7×10^{6}	1.4×10^{8}
Phosphorus (15)	P^{32}	β	* 7.7×10^{5}	* 5.7×10^{6}
Platinum (78)	Pt^{191}	γ	3.0×10^{6}	7.8×10^{7}
	$Pt^{193m}+Pt^{193}$	γ	2.5×10^{7}	6.6×10^{8}
	Pt^{193}	X	2.3×10^{6}	6.3×10^{7}
	$Pt^{197m}+Pt^{197}$	β, γ	6.7×10^{7}	1.9×10^{9}
	Pt^{197}	β, γ	1.1×10^{7}	3.0×10^{8}
Plutonium (94)	Pu^{238}	α, γ	4.4	3.3×10^{3}
	Pu^{239}	α, γ	3.9	3.0×10^{3}
	Pu^{240}	α, γ	3.9	3.0×10^{3}
	Pu^{241}+drs	α, β, γ	2.1×10^{2}	1.5×10^{5}
	Pu^{242}	α	4.1	3.0×10^{3}
Polonium (84)	Po^{210}	α, γ	1.1×10^{3}	4.6×10^{4}
Potassium (19)	K^{42}	β, γ	* 7.0×10^{6}	* 4.8×10^{7}

See footnotes at end of table.

(6)	(7)		(8)	(9)	(10)
q (μc) and critical organ	Half-lives		g/c	c/g	Category and shipping exempt mg
	T_r	T_b			
0.14 B	2×10^{15}y	1500d	8.02×10^{11}	1.25×10^{-12}	III 1.1×10^{12}
9.5 L	11.3d	131d	1.27×10^{-5}	7.87×10^{4}	III 1.7×10^{-5}
2.9 [b] L	2h	131d	9.49×10^{-5}	1.05×10^{7}	III 1.3×10^{-7}
0.061 B	2.20×10^{6}y	7.3×10^{4}d	1.45×10^{3}	6.90×10^{-4}	III 2.0×10^{3}
25 [b] B	2.33d	7.3×10^{4}d	4.26×10^{-6}	2.35×10^{5}	III 5.8×10^{-6}
1.3×10^{3} B	8×10^{4}y	800d	13.2	7.60×10^{-2}	III 18.
160 B	80y	800d	1.40×10^{-2}	71.4	III 1.9×10^{-2}
4.1 [b] B	2.56h	800d	5.30×10^{-8}	1.89×10^{7}	III 7.2×10^{-8}
300 B	10y	1000d	2.59×10^{-3}	3.86×10^{2}	III 3.5×10^{-3}
[a] 38 TB	35d	760d	2.54×10^{-5}	3.94×10^{4}	III 3.4×10^{-5}
12 [b] B	74m	1000d	3.81×10^{-8}	2.62×10^{7}	III 5.1×10^{-8}
8.4 [b] K	95d	5d	1.34×10^{-4}	7.46×10^{3}	III 1.8×10^{-4}
140 [b] K	14h	5d	8.52×10^{-7}	1.17×10^{6}	III 1.2×10^{-6}
30 [b] K	16d	5d	2.34×10^{-5}	4.27×10^{4}	III 3.2×10^{-5}
10 [b] K	31.5h	5d	1.94×10^{-6}	5.15×10^{5}	III 2.6×10^{-6}
18 K	17d	30d	1.34×10^{-5}	7.46×10^{4}	III 1.8×10^{-5}
6.8 [b] K	13.6h	30d	4.72×10^{-7}	2.12×10^{6}	III 6.3×10^{-7}
[a] 28 TB	14.3d	257d	3.50×10^{-6}	2.86×10^{5}	III 4.7×10^{-6}
10 [b] K	3.0d	60d	4.38×10^{-6}	2.28×10^{5}	III 5.9×10^{-6}
100 [b] K	3.5d	60d	5.16×10^{-6}	1.94×10^{5}	III 7.0×10^{-6}
72 K	500y	60d	2.69×10^{-1}	3.72	III 3.6×10^{-1}
5 [b] K	80m	60d	8.37×10^{-8}	1.19×10^{7}	III 1.1×10^{-7}
11 [b] K	18h	60d	1.13×10^{-6}	8.85×10^{5}	III 1.5×10^{-6}
0.044 B	89.6y	7.3×10^{4}d	5.94×10^{-2}	16.8	I 5.9×10^{-3}
0.044 B	2.44×10^{4}y	7.3×10^{4}d	16.2	6.17×10^{-2}	I 1.6
0.044 B	6.6×10^{3}y	7.3×10^{4}d	4.41	2.27×10^{-1}	I 4.4×10^{-1}
0.93 B	13.2y	7.3×10^{4}d	8.86×10^{-3}	1.13×10^{2}	I 8.9×10^{-4}
0.046 B	3.8×10^{5}y	7.3×10^{4}d	2.56×10^{2}	3.91×10^{-3}	III 3.5×10^{2}
0.034 Sp	138.40d	60d	2.22×10^{-4}	4.50×10^{3}	I 2.2×10^{-5}
[a] 12 [b] TB	12.47h	58d	1.67×10^{-7}	5.99×10^{6}	III 2.3×10^{-7}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Praseodymium (59)	Pr^{142}	β, γ	8.0×10^{6}	1.9×10^{11}
	Pr^{143}	β	1.1×10^{6}	2.6×10^{10}
Promethium (61)	$Pm^{147}+Sm^{147}$	β, γ	1.5×10^{5}	3.3×10^{9}
	Pm^{149}	β, γ	6.7×10^{6}	1.6×10^{11}
Protactinium (91)	Pa^{230}+drs	α, β, γ	3.9×10^{3}	8.7×10^{7}
	Pa^{231}+drs	α, β, γ	9.2×10^{-1}	2.1×10^{7}
	Pa^{233}	α, β, γ	1.3×10^{6}	3.1×10^{10}
Radium (88)	Ra^{223}+drs	α, β, γ	[a] 3.3×10^{3}	[a] 4.2×10^{4}
	Ra^{224}+drs	α, β, γ	[a] 1.1×10^{4}	[a] 1.3×10^{5}
	Ra^{226}+drs	α, β, γ	2.1×10^{2}	2.7×10^{3}
	Ra^{228}+drs	α, β, γ	17.	2.1×10^{2}
Radon (86) (Emanation)	$Rn^{220}(Em^{220})$ +drs Equilibrium Mixture	α, β, γ	[i] 2.0×10^{5}	(i)
	$Rn^{222}(Em^{222})$ +drs Equilibrium Mixture	α, β, γ	[i] 2.0×10^{5}	(i)
Rhenium (75)	Re^{183}	γ	[a] 6.7×10^{6}	[a] 4.4×10^{7}
	$Re^{186}+Os^{186m}$	β, γ	[d] 3.6×10^{6}	[d] 3.3×10^{7}
	Re^{187}	β	[j] 2.0×10^{7}	[j] 1.8×10^{8}
	$Re^{188}+Os^{188m}$	β, γ	[d] 4.9×10^{6}	[d] 4.5×10^{7}
Rhodium (45)	Rh^{103m}	γ	3.7×10^{9}	6.0×10^{10}
	Rh^{105}	β, γ	2.0×10^{7}	3.3×10^{8}
Rubidium (37)	Rb^{86}	β, γ	[a] 6.4×10^{5}	[a] 4.4×10^{6}
	Rb^{87}	β	1.1×10^{6}	7.0×10^{6}
Ruthenium (44)	Ru^{97}+drs	γ	1.1×10^{7}	8.7×10^{8}
	$Ru^{103}+Rh^{103m}$	β, γ	2.2×10^{6}	1.7×10^{8}
	Ru^{103}+drs	β, γ	7.3×10^{6}	6.0×10^{8}
	$Ru^{106}+Rh^{106}$	β, γ	3.4×10^{5}	2.7×10^{7}

See footnotes at end of table.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
7.0 [b] B	19.3h	1500d	8.73×10^{-7}	1.15×10^{6}	III 1.2×10^{-6}
17 [b] B	13.7d	1500d	1.50×10^{-5}	6.67×10^{4}	III 2.0×10^{-5}
60 B	2.52y	1500d	1.03×10^{-3}	9.71×10^{2}	III 1.4×10^{-3}
16 [b] B	52h	1500d	2.47×10^{-6}	4.05×10^{5}	III 3.3×10^{-6}
0.074 B	17.7d	7.3×10^{4}d	3.11×10^{-5}	3.22×10^{4}	I. 3.1×10^{-6}
6.8×10^{-3} B	3.43×10^{4}y	7.3×10^{4}d	22.1	4.53×10^{-2}	III 30.
42 K	27.4d	5.1×10^{4}d	4.88×10^{-5}	2.05×10^{4}	III 6.6×10^{-5}
[a] 0.071 TB	11.68d	8.1×10^{3}d	1.99×10^{-5}	5.02×10^{4}	I 2.0×10^{-6}
[a] 0.071 TB	3.64d	8.1×10^{3}d	6.23×10^{-6}	1.60×10^{5}	I 6.2×10^{-7}
0.10 B	1622y	1.6×10^{4}d	1.02	9.80×10^{-1}	I 1.0×10^{-1}
0.057 B	6.7y	1.6×10^{4}d	4.26×10^{-3}	2.35×10^{3}	I 4.3×10^{-4}
(i) Lu	52s	(i)	1.01×10^{-9}	9.90×10^{8}	(i)
(i) Lu	3.825d	(i)	6.39×10^{-6}	1.54×10^{5}	(i)
[a] 80 TB	0.2y	3d	1.02×10^{-4}	9.80×10^{3}	III 1.4×10^{-4}
[d] 19 [b] T	91h	3d	5.39×10^{-6}	1.86×10^{5}	III 7.3×10^{-6}
[j] 310 S	5×10^{10}y	25d	2.60×10^{7}	3.85×10^{-8}	III 3.5×10^{7}
[d] 6.8 [b] T	17h	3d	1.02×10^{-6}	9.80×10^{5}	III 1.4×10^{-6}
210 [b] K	5.4m	28d	2.95×10^{-8}	3.39×10^{7}	III 4.0×10^{-8}
41 [b] K	36.5h	28d	1.22×10^{-6}	8.20×10^{5}	III 1.6×10^{-6}
[a] 28 TB	18.6d	45d	1.22×10^{-5}	8.20×10^{4}	III 1.6×10^{-5}
160 P	5×10^{10}y	60d	1.21×10^{7}	8.26×10^{-8}	III 1.6×10^{7}
25 [b] K	2.8d	2.5d	2.08×10^{-6}	4.81×10^{5}	III 2.8×10^{-6}
16 [b] K	41.0d	2.5d	3.25×10^{-5}	3.08×10^{4}	III 4.4×10^{-5}
1.6 [b] K	4.5h	2.5d	1.50×10^{-7}	6.67×10^{6}	III 2.0×10^{-7}
2.8 [b] K	1.0y	2.5d	2.95×10^{-4}	3.39×10^{3}	II 4.0×10^{-5}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC$_a$ (d/m-M^3)	(5) MPC$_w$ (d/m-L)
Samarium (62)	Sm^{147}	α	1.6×10^{2}	3.9×10^{6}
	Sm^{151}	β, γ	1.5×10^{5}	3.6×10^{9}
	Sm^{153}	β, γ	7.0×10^{6}	1.6×10^{11}
Scandium (21)	Sc^{46}	β, γ	5.3×10^{5}	1.2×10^{10}
	Sc^{47}	β, γ	1.3×10^{7}	2.9×10^{11}
	Sc^{48}	β, γ	4.4×10^{6}	1.1×10^{11}
Selenium (34)	Se^{75}	γ	2.9×10^{6}	2.0×10^{7}
Silicon (14)	Si^{31}	β, γ	4.4×10^{7}	3.3×10^{8}
Silver (47)	Ag^{105}	γ	[a] 6.2×10^{6}	[a] 1.4×10^{9}
	$Ag^{110m}+Ag^{110}$	β, γ	[a] 2.0×10^{6}	[a] 4.8×10^{8}
	$Ag^{111}+Cd^{111m}$	β, γ	7.0×10^{6}	1.6×10^{9}
Sodium (11)	Na^{22}	β, γ	[a] 3.7×10^{3}	[a] 2.5×10^{6}
	Na^{24}	β, γ	[a] 3.8×10^{6}	[a] 2.6×10^{7}
Strontium (38)	Sr^{89}	β	6.3×10^{4}	8.1×10^{5}
	$Sr^{90}+Y^{90}$	β	6.7×10^{2}	3.6×10^{3}
	Sr^{91}+drs	β, γ	3.6×10^{6}	4.5×10^{7}
	$Sr^{92}+Y^{92}$	β, γ	1.0×10^{7}	1.3×10^{8}
(Sr^{90}-Y^{90})	Equilibrium Mixture	β	5.8×10^{2}	7.2×10^{3}
Sulphur (16)	S^{35}	β	[k] 5.9×10^{3}	[k] 4.0×10^{6}
Tantalum (73)	$Ta^{182m}+W^{183m}$	β, γ	8.7×10^{4}	2.0×10^{9}
Technetium (43)	$Tc^{96m}+Tc^{96}$	γ	8.0×10^{8}	7.2×10^{9}
	Tc^{96}	γ	7.3×10^{6}	6.6×10^{7}
	$Tc^{97m}+Tc^{97}$	γ	8.0×10^{6}	7.2×10^{7}
	Tc^{97}	X	2.9×10^{7}	2.7×10^{8}
	$Tc^{99m}+Tc^{99}$	β, γ	[a] 5.5×10^{8}	[a] 4.8×10^{9}
	Tc^{99}	β	6.2×10^{6}	5.7×10^{7}
Tellurium (52)	Te^{125m}	γ	8.0×10^{5}	1.1×10^{7}
	$Te^{127m}+Te^{127}$	β, γ	3.0×10^{5}	4.2×10^{6}
	Te^{127}	β, γ	2.4×10^{7}	3.3×10^{8}

See footnotes at end of table.

(6)	(7) Half-lives		(8)	(9)	(10)
q (μc) and critical organ	T_r	T_b	g/c	c/g	Category and shipping exempt mg
0.12 B	1.3×10^{11}y	1500d	5.32×10^{7}	1.88×10^{-8}	III 7.2×10^{7}
110 B	100y	1500d	4.21×10^{-2}	23.8	III 5.7×10^{-2}
16 [b] L	47.0h	187d	2.29×10^{-6}	4.37×10^{5}	III 3.1×10^{-6}
13 L	85d	36d	2.99×10^{-5}	3.34×10^{4}	III 4.0×10^{-5}
45 [b] L	3.43d	36d	1.23×10^{-6}	8.13×10^{5}	III 1.7×10^{-6}
8.7 [b] L	1.83d	36d	6.72×10^{-7}	1.49×10^{6}	III 9.1×10^{-7}
88 K	127d	11d	7.28×10^{-5}	1.37×10^{4}	III 9.8×10^{-5}
14 [b] Lu	2.65h	60d	2.62×10^{-8}	3.82×10^{7}	III 3.5×10^{-5}
[a] 31 [b] TB	40d	5d	3.21×10^{-5}	3.12×10^{4}	III 4.3×10^{-5}
[a] 12 [b] TB	270d	5d	2.27×10^{-6}	4.41×10^{5}	III 3.1×10^{-6}
23 [b] K	7.5d	10d	6.36×10^{-6}	1.57×10^{5}	III 8.6×10^{-6}
[a] 13 TB	2.6y	11d	1.59×10^{-6}	6.29×10^{5}	III 2.1×10^{-6}
[a] 7.3 [b] TB	15.0h	11d	1.15×10^{-7}	8.70×10^{6}	III 1.6×10^{-7}
4.1 B	51d	1.8×10^{4}d	3.47×10^{-5}	2.88×10^{4}	II 4.7×10^{-6}
2.1 B	28y	1.8×10^{4}d	7.02×10^{-3}	1.42×10^{2}	II 9.5×10^{-4}
2.5 [b] B	9.67h	1.8×10^{4}d	2.80×10^{-7}	3.57×10^{6}	III 3.8×10^{-7}
1.9 [b] B	2.6h	1.8×10^{4}d	7.62×10^{-8}	1.31×10^{7}	III 1.0×10^{-7}
[b] 91 Ts	87.1d	623d	2.23×10^{-5}	4.29×10^{4}	III 3.4×10^{-5}
7.3 L	112d	400d	1.56×10^{-4}	6.41×10^{3}	III 2.1×10^{-4}
60 [b] K	52m	20d	2.65×10^{-8}	3.77×10^{7}	III 3.6×10^{-8}
12 [b] K	4.3d	20d	3.16×10^{-6}	3.16×10^{5}	III 4.3×10^{-6}
18 [b] K	92d	20d	6.82×10^{-5}	1.47×10^{4}	III 9.2×10^{-5}
63 [b] K	10^{4}y	20d	2.70	3.70×10^{-1}	III 3.6
[a] 240 [b] TB	6.04h	1d	1.90×10^{-7}	5.26×10^{6}	III 2.6×10^{-7}
13 [b] K	2.12×10^{3}y	20d	58.5	1.71×10^{-2}	III 79.
15 K	58d	30d	5.54×10^{-5}	1.81×10^{4}	III 7.5×10^{-5}
6.6 K	105d	30d	1.02×10^{-6}	9.80×10^{5}	III 1.4×10^{-6}
15 [b] K	9.35h	30d	3.78×10^{-7}	2.65×10^{6}	III 5.1×10^{-7}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Tellurium (52) Continued	Te^{129m}+drs	β, γ	1.8×10^{5}	2.4×10^{6}
	$Te^{129}+I^{129}$	β, γ	6.4×10^{7}	8.7×10^{8}
	Te^{131m}+drs	β, γ	2.3×10^{6}	3.0×10^{7}
	$Te^{132}+I^{132}$	β, γ	7.7×10^{5}	1.1×10^{7}
Terbium (65)	$Tb^{160}+Dy^{160m}$	β, γ	2.3×10^{5}	5.1×10^{9}
Thallium (81)	Tl^{200}	γ	1.9×10^{7}	1.9×10^{8}
	Tl^{201}	γ	1.1×10^{7}	9.9×10^{7}
	Tl^{202}	γ	2.3×10^{6}	2.2×10^{7}
	Tl^{204}	β, γ	1.4×10^{6}	1.3×10^{7}
Thorium (90)	Th^{227}+drs	α, β, γ	4.7×10^{2}	1.1×10^{7}
	Th^{228}+drs	α, β, γ	13.	2.8×10^{5}
	Th^{230}	α, β, γ	5.1	1.1×10^{5}
	$Th^{231}+Pa^{231}$	α, β, γ	4.1×10^{7}	9.3×10^{11}
	Th^{232}+drs	α, β, γ	9.3×10^{-1}	2.1×10^{4}
	$Th^{234}+Pa^{234}$	β, γ	1.3×10^{5}	3.0×10^{9}
Thorium, Natural	Equilibrium Mixture.	α, β, γ	5.2	7.5×10^{4}
Thulium (69)	$Tm^{170}+Yb^{170m}$	β, γ	8.0×10^{4}	1.8×10^{9}
	Tm^{171}	β	2.5×10^{5}	5.7×10^{9}
Tin (50)	$Sn^{113}+In^{113m}$	γ	8.0×10^{5}	4.2×10^{7}
	Sn^{125}+drs	β, γ	7.3×10^{5}	3.6×10^{7}
Tungsten (74) (Wolfram).	W^{181}	γ	5.0×10^{7}	1.4×10^{9}
	W^{185}	β, γ	2.2×10^{7}	6.0×10^{8}
	W^{187}+drs	β, γ	[a] 4.2×10^{7}	[a] 1.1×10^{9}
Uranium (92)	U^{230}+drs	α, β, γ	4.6×10^{2}	1.1×10^{7}
	[1] U^{232}+drs	α, β, γ	3.5×10^{2}	8.2×10^{6}
	U^{233}	α, γ	4.0×10^{2}	9.0×10^{6}
	U^{234}	α, γ	4.0×10^{2}	9.0×10^{6}
	$U^{235}+Th^{231}$	α, β, γ	4.4×10^{2}	9.7×10^{6}
	U^{236}	α, γ	4.2×10^{2}	9.7×10^{6}
	U^{238}	α, γ	81.	1.9×10^{6}

See footnotes at end of table.

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
2.9 K	33d	30d	3.25×10^{-5}	3.08×10^{4}	II 4.4×10^{-6}
5.3 [b] K	74m	30d	5.07×10^{-8}	1.97×10^{7}	III 6.8×10^{-8}
4.3 [b] K	30h	30d	1.25×10^{-6}	8.00×10^{5}	III 1.7×10^{-6}
3.4 [b] K	3.2d	30d	3.23×10^{-6}	3.10×10^{5}	II 4.4×10^{-7}
16 B	76d	1000d	9.30×10^{-6}	1.08×10^{5}	III 1.3×10^{-5}
37 [b] K	27h	7d	1.72×10^{-6}	5.81×10^{5}	III 2.3×10^{-6}
41 [b] K	72h	7d	4.61×10^{-6}	2.17×10^{5}	III 6.2×10^{-6}
17 [b] K	12d	7d	1.85×10^{-5}	5.41×10^{4}	III 2.5×10^{-5}
14 K	3y	7d	1.70×10^{-3}	5.88×10^{2}	III 2.3×10^{-3}
9.3×10^{-3} B	18.4d	7.3×10^{4}d	3.19×10^{-5}	3.13×10^{4}	I 3.2×10^{-6}
9.4×10^{-3} B	1.91y	7.3×10^{4}d	1.21×10^{-3}	8.26×10^{2}	I 1.2×10^{-4}
0.050 B	8.0×10^{4}y	7.3×10^{4}d	51.3	1.95×10^{-2}	III 69.
47 [b] B	25.6h	7.3×10^{4}d	1.88×10^{-6}	5.32×10^{5}	III 2.5×10^{-6}
9.0×10^{-3} B	1.39×10^{10}y	7.3×10^{4}d	8.98×10^{6}	1.11×10^{-7}	III 1.2×10^{7}
3.5 B	24.1d	7.3×10^{4}d	4.31×10^{-5}	2.32×10^{4}	II 5.8×10^{-6}
9.3 B	127d	1000d	1.65×10^{-4}	6.06×10^{3}	III 2.2×10^{-4}
93 [b] B	1.9y	1000d	9.05×10^{-4}	1.10×10^{3}	III 1.2×10^{-3}
26 B	112d	100d	9.68×10^{-5}	1.03×10^{4}	III 1.3×10^{-4}
6.5 [b] B	9.5d	100d	9.08×10^{-6}	1.10×10^{5}	III 1.2×10^{-5}
68 [b] L	140d	4d	1.94×10^{-4}	5.15×10^{3}	III 2.6×10^{-4}
28 [b] B	74d	9d	1.05×10^{-4}	9.52×10^{3}	III 1.4×10^{-4}
[a] 29 [b] TB	24.0h	1d	1.43×10^{-6}	6.99×10^{5}	III 1.9×10^{-6}
9.1×10^{-3} K	20.8d	30d	3.66×10^{-5}	2.73×10^{4}	I 3.7×10^{-6}
0.047 B	74y	300d	4.78×10^{-2}	20.9	I 4.8×10^{-3}
0.052 B	1.62×10^{5}y	300d	1.05×10^{2}	9.48×10^{-3}	III 2.6×10^{2}
0.052 B	2.48×10^{5}y	300d	1.62×10^{2}	6.17×10^{-3}	III 2.2×10^{2}
0.056 B	7.13×10^{5}y	300d	4.67×10^{5}	2.14×10^{-6}	III 6.3×10^{5}
0.055 B	2.39×10^{7}y	300d	1.57×10^{4}	6.35×10^{-5}	III 2.1×10^{4}
4.7×10^{-3} mK	4.51×10^{9}y	30d	3.00×10^{6}	3.33×10^{-7}	III 4.0×10^{6}

(1) Element (Z)	(2) Isotope	(3) Radiations emitted	(4) MPC_a (d/m-M^3)	(5) MPC_w (d/m-L)
Uranium (92)..... Continued	U^{233} feed (40ppm U^{232})	α, β, γ....	4.0×10^{2}	8.9×10^{5}
	Natural Uranium, Tuballoy	α, β, γ....	84	1.9×10^{6}
	Oralloy (93%)...	α, β, γ....	4.3×10^{2}	9.6×10^{5}
	Oralloy (40%)...	α, β, γ....	4.6×10^{2}	9.9×10^{5}
	[n] D-38.....	α, β, γ....	82	1.9×10^{6}
Vanadium (23).....	V^{48}.....	β, γ.....	5.9×10^{5}	7.0×10^{7}
Xenon (54).....	Xe^{131m}.....	β, γ.....	[c] 3.7×10^{7}	(c)
	Xe^{133}.....	β, γ.....	[c] 3.3×10^{7}	(c)
	$Xe^{135}+Cs^{135m}$....	β, γ.....	[c] 9.4×10^{6}	(c)
Ytterbium (70).....	Yb^{175}.....	β, γ.....	6.0×10^{4}	1.3×10^{11}
Yttrium (39).....	Y^{90}.....	β.....	1.1×10^{6}	2.6×10^{10}
	$Y^{91m}+Y^{91}$.....	β, γ.....	1.3×10^{5}	2.9×10^{12}
	Y^{91}.....	β, γ.....	8.0×10^{4}	1.8×10^{9}
	Y^{92}.....	β, γ.....	1.3×10^{7}	2.9×10^{11}
	Y^{93}+drs.....	β, γ.....	4.9×10^{6}	1.1×10^{11}
Zinc (30).....	Zn^{65}.....	β, γ.....	[a] 2.4×10^{5}	[a] 6.4×10^{6}
	$Zn^{69m}+Zn^{69}$.....	β, γ.....	4.1×10^{5}	1.1×10^{7}
	Zn^{69}	β.....	1.6×10^{7}	4.5×10^{5}
Zirconium (40).....	$Zr^{93}+Nb^{93m}$.....	β, γ.....	2.7×10^{5}	6.3×10^{9}
	Zr^{95}+drs.....	β, γ.....	[a] 2.9×10^{5}	[a] 6.4×10^{6}
	Zr^{97}+drs.....	β, γ.....	6.3×10^{6}	1.5×10^{11}

[a] Major portion of body critical; based on 0.1 rem/wk.

[b] The gastrointestinal tract as critical organ should be examined if chronic or large exposures are involved.

[c] Calculated to give 0.1 rem/wk if body is surrounded by an infinite volume of the gas. MPC_w, η, and T_b are meaningless. Shipping exempt quantities not calculated.

[d] Based on 0.6 rem/wk; factor of 2 allowed because thyroid is the critical organ.

[e] Based on 1954 ICRP recommendations. Calculations show that these numbers are safe for fission products less than 2 years old.

[f] Half-life varies with time. The half-life at any time t after formation is approximately t.

[g] Based on either T_2O or HTO, not T_2; assumes 50% intake by skin absorption

(6) q (μc) and critical organ	(7) Half-lives T_r	(7) Half-lives T_b	(8) g/c	(9) c/g	(10) Category and shipping exempt mg
0.051 B	.....	.....	97.1	1.03×10^{-3}	III 1.3×10^{3}
4.9×10^{-3} [m]K	.....	.....	1.46×10^{6}	6.85×10^{-7}	III 2.0×10^{6}
0.056 B	.....	.....	1.43×10^{4}	6.99×10^{-5}	III 1.9×10^{4}
0.058 B	.....	.....	4.81×10^{4}	2.08×10^{-5}	III 6.5×10^{4}
4.8×10^{-3} K	.....	.....	2.29×10^{6}	4.37×10^{-7}	III 3.1×10^{6}
7.9 [b]K	16.1d	74d	5.91×10^{-6}	1.69×10^{5}	III 8.0×10^{-6}
([c]) TB	12d	([c])	1.12×10^{-5}	8.27×10^{4}	([c])
([c]) TB	5.27d	([c])	5.36×10^{-6}	1.87×10^{5}	([c])
([c]) TB	9.20h	([c])	3.96×10^{-7}	2.53×10^{6}	([c])
26 [b]B	4.1d	1000d	5.49×10^{-6}	1.82×10^{5}	III 7.4×10^{-6}
3.3 [b]B	64.2h	1.8×10^{4}d	1.84×10^{-6}	5.43×10^{5}	III 2.5×10^{-6}
4.8 [b]B	50.3m	1.8×10^{4}d	2.43×10^{-8}	4.11×10^{7}	III 3.3×10^{-8}
5.0 B	58d	1.8×10^{4}d	4.04×10^{-5}	2.48×10^{4}	III 5.5×10^{-5}
2.1 [b]B	3.6h	1.8×10^{4}d	1.05×10^{-7}	9.52×10^{6}	III 1.4×10^{-7}
2.2 [b]B	10h	1.8×10^{4}d	2.96×10^{-7}	3.38×10^{6}	III 4.0×10^{-7}
[n]61 TB	245d	933d	1.22×10^{-4}	8.20×10^{3}	II 1.6×10^{-5}
0.31 Pr	13.8h	14d	3.03×10^{-7}	3.30×10^{6}	II 4.1×10^{-5}
0.76 Pr	52m	14d	1.90×10^{-8}	5.26×10^{7}	III 2.6×10^{-8}
130 B	1.1×10^{6}y	1000d	2.85×10^{2}	3.51×10^{-3}	III 3.8×10^{2}
[n]18 TB	63.3d	450d	4.60×10^{-5}	2.17×10^{4}	III 6.2×10^{-5}
4.9 [b]B	17.0h	1000d	5.25×10^{-7}	1.90×10^{6}	III 7.1×10^{-7}

[b] Exempt amounts of tritium are 5.2×10^{-4} cc STP of the gas, 5.0×10^{-7} cc of pure T_2O.

[i] Adopted value, based on long experience of man. MPC_w, q, and T_b are meaningless. Shipping exempt quantities not calculated.

[j] Based on 0.6 rem/wk; factor of 2 allowed because skin is the critical organ.

[k] Based on 0.1 rem/wk; gonads are the critical organ.

[l] LASL calculated value; not included in ICRP prepublication.

[m] Calculated on basis of toxicity, not radiation damage.

[n] Natural uranium depleted in U^{235} content. The specific activity depends on isotopic analysis; values given in the table are for D-38 with about 0.3% U^{235}.

11. MONITORING INSTRUMENTS

A. Radiation Survey Instruments

In the following listing, the instruments shown in Figures 4, 7, 10, 11, and 12 are used only occasionally at LASL; they are included here for identification purposes.

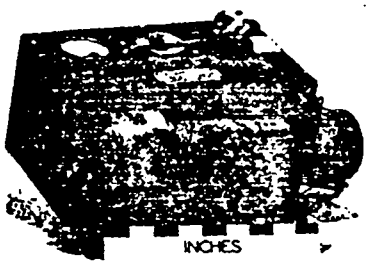


FIGURE 1.—SURVEY METER, TRI (I) Model 101 DC (Tritium Sniffer)—ion chamber, sensitive to any ions (produced by β's, γ's, an open flame, etc.) in air drawn through the 660-cc chamber; 4 scales have been calibrated to tritium water vapor, giving full-scale readings from about 10^2 to 10^5 $\mu c/M^3$; three models, one operating on AC, one on DC, and one on DC with an AC-operated blower; 23 lb.

SURVEY METER, TRI (I) Model 120 (Balanced Sniffer)—dual ion chamber with deionizer; relatively insensitive to γ's and ions formed outside the chamber; similar in appearance and size to Model 101; 5 ranges give full-scale indications for 2×10^2 to 10^6 $\mu c/M^3$.

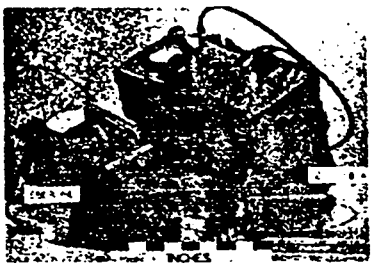


FIGURE 2a.—SURVEY METER, ALP (P) Model 2111 or 48–A (PeeWee)—proportional counter; α-sensitive probe has steel grid over 0.25-mil mylar; effective area about 60 cm^2; probe is delicate, microphonic, and affected by moisture, organic vapors, barometric pressure, high frequency electrical interference; requires frequent calibration checks with uranium source mounted on case; 2 ranges cover 0–20,000 c/m; 0–200,000 and 0–2,000,000 c/m models available; activity indicated on meter and earphones; 19 lb.

FIGURE 2b.—SURVEY METER, ALP (P) Model PAC–1 (Eberline PeeWee)—transistorized version of Model 2111 or 48–A with similar probe; 3 ranges cover 0–100,000 c/m; 6½ lb. (Shown in above illustration at left.)

FIGURE 3.—SURVEY METER, NEU (P) Model 48–N (Converted PeeWee)—proportional counter; instrument is a Model 48–A PeeWee modified for use with a boron-lined probe; 1 in.thick polyethylene moderator and 20-mil cadmium absorber; 4 ranges measure 0–10,000 Ra-Be n/cm²-sec; high range model (red meter) 20–200,000 Ra-Be n/cm²-sec; calibration chart required; correction factors needed for energies other than Ra-Be; 20½ lb.

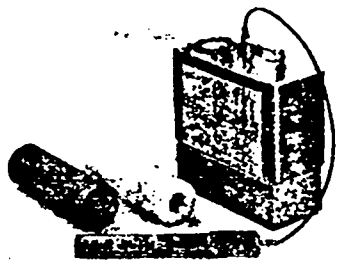


FIGURE 4.—SURVEY METER, NEU (P) Model E–1 (Rudolph)—2-unit fast neutron proportional counter; tissue-equivalent chamber measures 0.2–10 Mev neutrons; 3 ranges measure 0–500 mrep/hr (approximately equivalent to mrad/hr); 0–0.5 mrep integrating range; meter readings must be multiplied by proper RBE to obtain rem; 10½ lb.

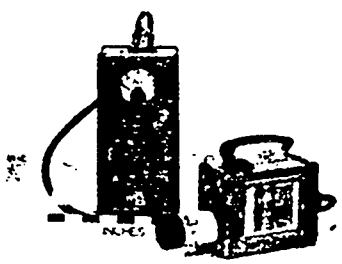
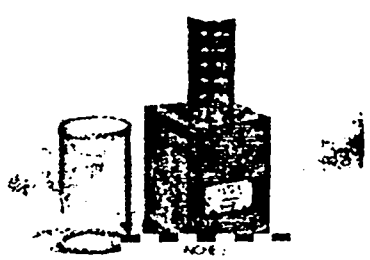


FIGURE 5.—SURVEY METER, BGM (I) Model 100–A—ion chamber; mylar-covered chamber with removable ½-in. lucite β shield; high range model 0.1–100 r/hr; low range model 0.02–20 r/hr; requires calibration chart; β response assumed rad; 8½ lb.



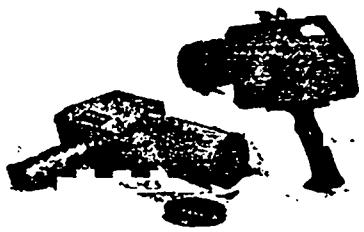


FIGURE 6.—SURVEY METER, BGM (I) Model SIC7A and D-1 (Cutie Pie)—ion chamber; 3 ranges cover 25–10,000 mr/hr; somewhat directional; β response through end window (1 mg/cm^2 mylar) only qualitative without correction factors; calibration chart necessary; all Model D–1 (metal case) converted to SIC7A circuitry; D-1 has cap, SIC7A has slide to cover β window; 3 lb.

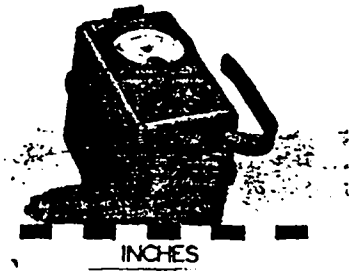


FIGURE 7.—SURVEY METER, BGM (I) Model A6B-500-SR (Jordan Radector)—ion chamber; 2 logarithmic scales cover 0.5 mr/hr to 500 r/hr; β window and built-in Sr^{90} calibration source; small energy dependence above 75 kev; 3½ lb.

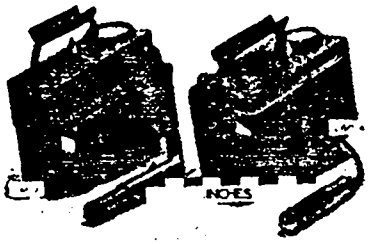


FIGURE 8a.—SURVEY METER, BGM (G) Model SM-3 (Eltronics)—G–M instrument; probe with 30 mg/cm^2 metal tube has sliding β shield; 3 ranges cover 0–20 mr/hr; 9½ lb.

FIGURE 8b.—SURVEY METER, BGM (G) Model 2610–A (Nuclear)—G-M instrument; probe with 30 mg/cm^2 glass G–M tube has rotating β shield; response time somewhat slower than SM–3 or Eberline E–112- B; covers same ranges as SM-3; 10 lb.

FIGURE 9.—SURVEY METER, BGM (G) Model E–112–B (Eberline)—G-M instrument; can utilize various probes; with G–M tube, characteristics similar to SM–3 and 2610–A; measures α (indicates $\mu c/M^2$ directly) with ZnS scintillator probe; neutron-sensitive probe being investigated; has adjustable time constant (labeled "meter response"); 4 lb.

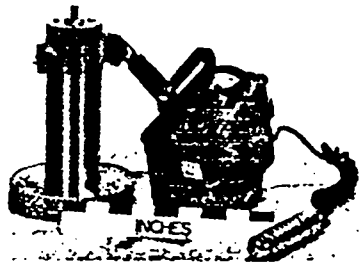


FIGURE 10.—SURVEY METER, GAM (I) Model 300 (Proteximeter)—γ-integrating ion chamber; 0–200 mr; operating instructions on bottom; sensitive down to about 30 kev with metal cap removed; energy dependence at low energies unknown; 5 lb.

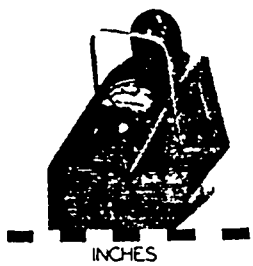


FIGURE 11.—SURVEY METER, GAM (I) Model SU–10 or T–1B—γ ion chamber; 5 ranges cover 0–50,000 mr/hr; long warm-up time; requires frequent zeroing until warmed up. 11 lb.

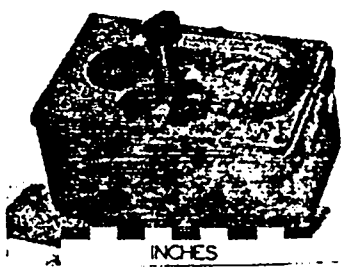


FIGURE 12.—SURVEY METER, ABG (I) Model SRJ–1 (Juno)—ion chamber; sliding α and β shield; slow warm-up time; single calibration not reliable for three types of radiation; 5 lb.

FIGURE 13.—ALPHA FLOOR MONITOR—proportional counter; 2 scales cover 0–20,000 c/m; battery operated; large 3 × 18 in. PeeWee-type probe; counts indicated on meter and loudspeaker; mounted on rolling platform; wheels must be kept well lubricated to prevent static interference in the probe.

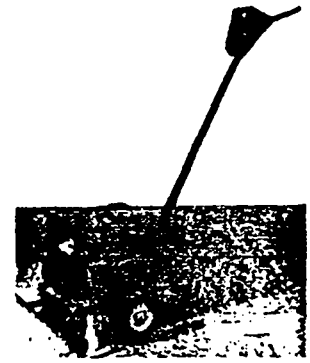
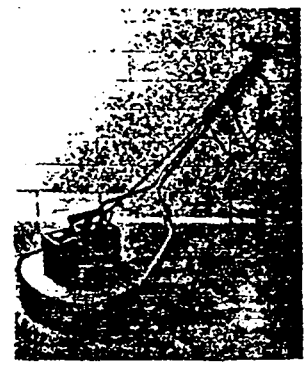


FIGURE 14.—BETA-GAMMA FLOOR MONITOR—G–M instrument; utilizes 4 glass-wall (30 mg/cm^2) G–M tubes and suitable G–M instrument on rolling platform; more sensitive to dispersed activity than a single tube instrument; may become light sensitive.



B. Air Sampling Instruments

Discussion of the instruments shown in Figures 15 to 20 will be found in Section 18, Air Sampling.

FIGURE 15.—FILTER QUEEN AIR SAMPLER—Samples at 4 cfm through 4 × 9 in. (21 in.² effective) HV-70 filter paper; sampling rate automatically regulated by variable throat orifice; flow rate should be checked weekly.

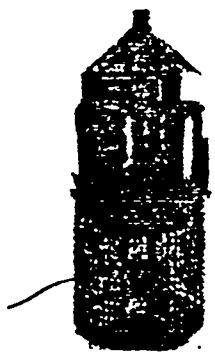


FIGURE 16.—HI-VOLUME AIR SAMPLER (STAPLEX)—Samples at 20 to 50 cfm depending on filter media, 20 cfm with glass fiber, 50 cfm with BM-2133 respirator filters; 4 in. diameter, 9 × 6 in., or 8 × 10 in. filters; can be tripod-mounted for sampling at breathing level.

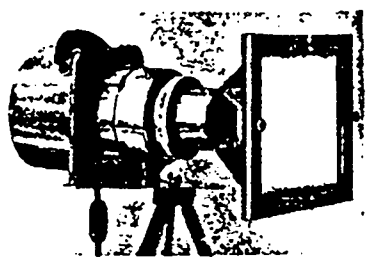


FIGURE 17.—GAST PUMP—AC-operated pump equipped with rotameter adjustable from 5 to 30 liters/min; uses 1⅛ in. diameter sampling head and filters; Whatman No. 41, Whatman No. 4, membrane (molecular), and fine glass fiber may be used.

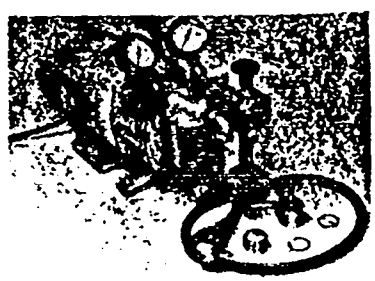


FIGURE 18a.—GIRAFFE SAMPLER—Variation of the Gast Pump; sampling head, usually 2⅛ in. with HV-70 paper, mounted on extendable tube for sampling breathing zone; uses orifice meter rather than rotameter; usual sampling rate is 2 cfm with HV-70.

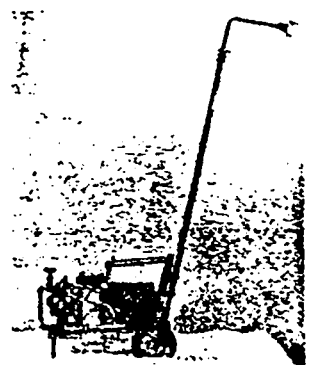
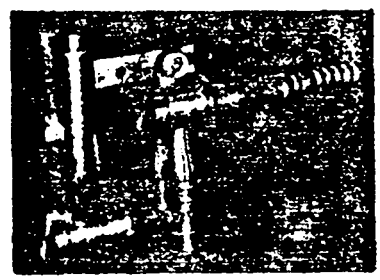


FIGURE 18b.—2⅛-INCH SAMPLING HEAD—Note position of large rings to prevent damage to filter when assembling.

FIGURE 19.—MODIFIED CASCADE IMPACTOR—Commercially available Casella impactor with additional filter stage; designed to sample at 17.5 liters/min; used for particle size analysis.



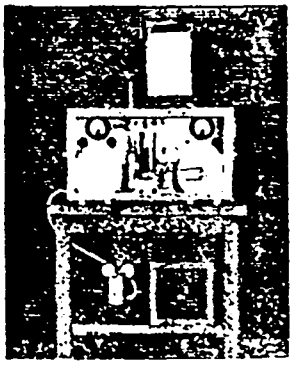


FIGURE 20.—AUTOMATIC SAMPLER RECORDER—Combination sampling, counting, and alarm unit; air is drawn through 1 in. diameter portion of filter paper for 10 min and is counted under α-sensitive scintillation probe while next sample is drawn; samples at 50 liters/min with Whatman No. 4 paper; count-rate results are indicated on a meter and recorded on an Esterline-Angus; alarm sounds at preset level.

C. Respiratory Protective Devices

Detailed discussion of respiratory protective equipment, its uses and limitations, may be found in Section 19.

In the listing below, Figures 21 to 24 show half masks; all of them have interchangeable canisters or cartridges; the user must be certain the proper canister or cartridge is in place. A filter should be used for particulates, an adsorbent for gases and vapors.

FIGURE 21.—WILLSON No. 800 HALF MASK.

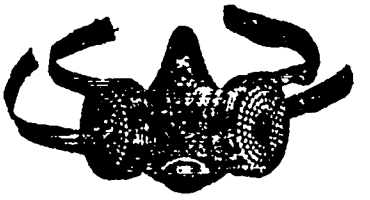


FIGURE 22.—MSA COMFO HALF MASK.

FIGURE 23.—AMERICAN OPTICAL R-5000 HALF MASK.

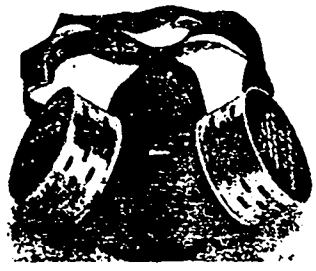


FIGURE 24.—MSA DUSTFOE HALF MASK.

FIGURE 25.—WILLSON FULL FACE MASK—Chin style DFM filter; effective only for solid particles and fumes.

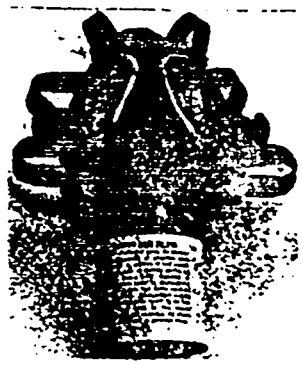


FIGURE 26.—MSA FULL FACE MASK—Chin-type canister holder; may be used with filter, gas adsorbent cartridge, or both.

FIGURE 27.—U.S. ARMY M-9 ASSAULT MASK—Can be fitted with AEC high efficiency filter or Army all-purpose canister.

FIGURE 28.—ACME FULL FACE MASK—Chin style canister holder; can be used with several canisters including the AEC high efficiency filter and the Army all-purpose canister; mask can be fitted to support prescription eyeglass lenses.

FIGURE 29.—SCOTT-O-RAMIC FULL FACE MASK—Chin-style DFM filter; effective only for solid particles and fumes.

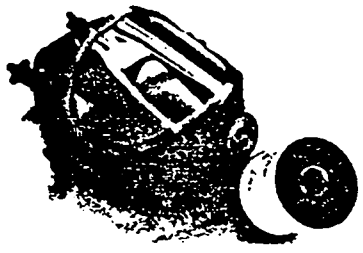


FIGURE 30.—SCOTT AIR PAK—Self-contained breathing unit; demand-type regulator; air tank supported valve down on the back, regulator suspended on left side of the chest; two masks available, the regular and the Scott-o-ramic.

FIGURE 31.—MSA SUPPLIED OXYGEN BREATHING APPARATUS—Self-contained demand type; oxygen tank supported valve down on the back, demand valve suspended on left side of chest.

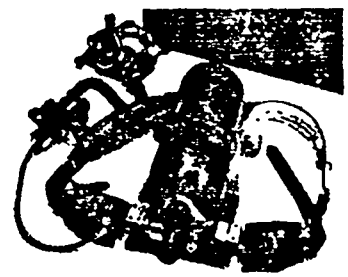


FIGURE 32.—MSA CHEMOX OXYGEN GENERATING APPARATUS—Self-contained unit capable of generating breathing oxygen; generator and lungs are suspended on the chest; equipped with warning timer; directions for use on carrying case and canisters.

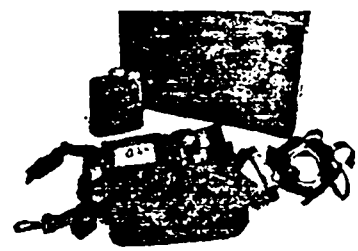


FIGURE 33.—SUPPLIED AIR HALF MASK—Comfo half mask supplied with respirable air from a 220 ft^3 H-type cylinder (or an air compressor); used with constant flow or demand regulator valve; air line limits mobility.

FIGURE 34.—SUPPLIED AIR FULL FACE MASK—A MSA full face mask supplied with respirable air from a 220 ft³ H-type cylinder (or an air compressor); used with constant flow or demand regulator valve; air line limits mobility.

FIGURE 35.—SUPPLIED AIR HOOD—Plastic hood with transparent window; air supplied from H-type cylinder or compressor.

FIGURE 36.—PLASTIC SUPPLIED AIR SUIT—Completely enclosed suit closed with double zipper; used in atmosphere where whole body protection is desired (T, HCN).

D. Personal Monitoring Devices (See Sec. 16)

FIGURE 37.—SELF READING DOSIMETERS AND CHARGING UNIT—γ-ray correction factor on dosimeter; available in several ranges.

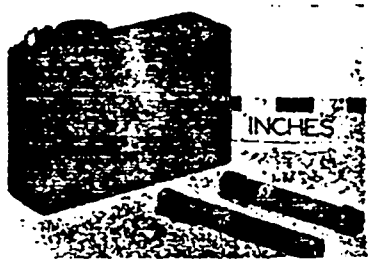
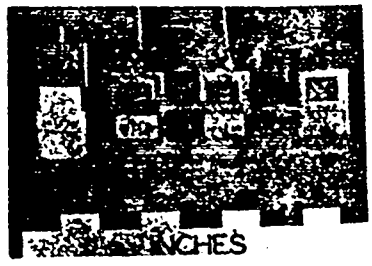


FIGURE 38.—FILM BADGES—Shown open, ready for use, with contamination-preventing petticoat, and as a wrist badge.



12. ALPHA MONITORING

A. Characteristics

α monitoring entails the detection of a heavy, doubly charged, highly ionizing particle with a short range. The most energetic natural α particle, 10.5 Mev, has a range of only about 4 in. in air or a few mils in light material. An α particle of greater than 7.5 Mev is necessary to penetrate the outer dead layer of skin. Since only a few short-lived isotopes emit α's of this energy, the biological hazard from α particles is strictly an internal hazard. α monitoring is therefore aimed toward the detection of contamination which might hinder delicate radiation measurements or ultimately find its way into the body and there, because of the intense ionizing power of the α's, do considerable damage.

B. Detection

The characteristic of the α particle that eliminates the external hazard and the necessity for shielding complicates its detection. Survey instruments must be constructed with very thin windows (a few mg/cm^2), and the detector must be held very close to the site of contamination to allow the short-range particle to enter the chamber. Thin films of water or oil can partially or completely prevent α's from being monitored. Porous surfaces (wood, concrete) may harbor many times the activity measurable with monitoring instruments.

C. PeeWee Survey Meter

The α-monitoring instrument currently in use at LASL is the PeeWee proportional counter (Fig. 2a). It consists of a thin window probe attached by a 3-ft cable to the hand-carried instrument. The 9 $\times$ 2 in. probe has an effective area of 60 cm^2 and the window is covered with 0.25-mil (1 mg/cm^2) mylar, allowing α's with energies greater than about 1.6 Mev to penetrate to the sensitive volume. The instrument has a pulse height selector (PHS) which allows only pulses above a certain fixed size to be counted. As α pulses are normally much larger than β or γ pulses, the PeeWee detects α contamination in the presence of the other types of radiation. The presence of large numbers of β's or γ's may be noticed as a "hiss" in the earphones and can alter the α sensitivity slightly. Neutron-produced recoils that enter the sensitive volume are counted, the earphone "pop" being indistinguishable from an α event. A preliminary attempt to calibrate this effect is being made. The visual indication is given by a microammeter which has two ranges—$\times$100 and $\times$1000. The meter has a rather slow response (long time constant) and rapid fluctuations are best noticed on the earphones. A piece of natural uranium is attached to the meter case to be used frequently as a one-point check on the calibration made when the meter is serviced. The PHS may be adjusted slightly to obtain agreement with this source. Fifteen seconds or so are required for the meter to reach the value of the calibration source. Other features are a reset button and a high voltage switch.

A transistorized version of the PeeWee (Fig. 2b) is the Eberline PAC–1. Its use and operation are es-

sentially the same as the larger PeeWee. The instrument has 3 range positions which measure up to 100,000 c/m.

D. Sources of Error

Spurious counts on the PeeWee can be caused in a number of ways, especially by physical vibrations of the probe. Although the PeeWee will often operate fairly well with small holes in the window, erratic operation is apt to occur after window damage. The probe is sensitive to barometric pressure, lower probe voltage being necessary at higher altitudes. The instrument is also sensitive to moisture and is inconsistent or nearly inoperative in areas of high humidity. Organic vapors present on materials after decontamination procedure with trichloroethylene, alcohol, etc., can reduce the sensitivity of the PeeWee considerably. The meter has been known to respond rather markedly to automobile ignition noise and some fluorescent lights.

E. Use of PeeWee

The PeeWee probe must be held as close as possible to the monitored surface. Readings at ¼ in. from a plutonium-contaminated surface indicate only about 80% of a contact PeeWee reading; at ½ in., only about 50% of the contact reading. This range effect is even more pronounced for lower energy α's. The necessity of keeping the probe close to the surface being monitored enhances the possibility of mechanical jarring and also the chance of probe contamination. For these reasons, and the fact that the PeeWee has a rather slow meter response (earphones are instantaneous),

careful, methodical surveying punctuated with frequent use of the reset button is advisable in order to obtain, at best, a rough estimate of contamination magnitude. Exact location of contamination can be accomplished using a piece of paper with a small hole in the center as a mask.

F. Determination of Quantity

The use of the PeeWee for determination of quantity of material (curies or mg) is not possible except under stringent conditions. If the α activity to be determined is uniformly and thinly deposited on a smooth, flat surface larger than the probe area and if the probe is positioned properly, it is sometimes possible to determine an approximate PeeWee reading that corresponds to a certain number of disintegrations per minute (d/m) over a given area, e.g., the reading that corresponds to 500 d/m-100 cm^2. First, an area correction factor must be used. Since the effective area of the PeeWee probe is about 60 cm^2, for our example this correction factor is 60/100. In addition, a correction factor of 0.5 is used to allow for the fact that only about one-half of the α disintegrations are directed upward in the detectable direction. Therefore, 150 c/m read on the PeeWee dial corresponds to 500 d/m-100 cm^2. Use of only these two correction factors assumes that the detector detects all the α's emitted from the source in the upward direction. This is not the case. Under the geometry conditions described above, only about 30% of the upward emitted plutonium α's (15% of the disintegrations) cause a pulse, heard as a click in the earphones. Other α energies or geometries would give different efficiencies. The

meter is, however, adjusted to compensate for this inefficiency and reads directly in c/m (d/m if multiplied by 2). It is apparent that counting earphone "clicks" does not measure c/m. For our example, 45 clicks/min in the earphones correspond to 500 d/m-100 cm^2.

G. Alpha Scintillation Detection

The scintillator and photomultiplier combination as an α detector is becoming more and more useful. Detectors with sensitivity similar to the PeeWee can have excellent inherent discrimination against other radiations, are devoid of altitude and humidity effects, and are reasonably insensitive to microphonic noise. The α scintillation probe in use at LASL consists of a 2 in. diameter photomultiplier coupled through a ¾ in. thick by 5⅛ in. diameter lucite light-pipe, one side of which has been prepared with a thin layer of silver-activated ZnS powder. This is covered with two sheets of aluminum leaf (about 0.13 mg/cm^2 each) and one layer of aluminized mylar (1 mg/cm^2). The mylar is set ¼ in. back from the protective metal grid. The sensitivity near the edges of the probe in use at LASL is about 67% that at the center. The photomultipliers produce a pulse that can be handled by most ordinary count-rate meters designed for G–M probes and can utilize the same high voltage supply, thus making possible a light, dual-purpose instrument. The probe described above, when attached to an Eberline E–112–B G–M instrument (Fig. 9), reads roughly in $\mu c/M^2$. Probes developed to date do not have the convenient size and shape of the PeeWee probe, but this disadvantage could no doubt be overcome. Scintillator windows must be kept lighttight, small holes being

easily repaired with Glyptol or some other opaque substance.

H. Alpha Monitoring Check List

(1) Check instrument with check source.

(2) Be sure surface to be monitored is dry.

(3) Reset PeeWee often—especially after probe has been jarred.

(4) Check probe for contamination.

13. BETA-GAMMA MONITORING

β–γ monitoring involves the detection, measurement, and ultimate evaluation of findings in terms of personnel hazard of photons (γ and X ray) and/or β particles (high energy electrons). β–γ monitoring is somewhat easier than α monitoring, as the radiation has a considerable range in air, allowing surveys at some distance from the radiation source or site of contamination. The fact that even "contact" measurements with survey instruments are really only "near" measurements must be recognized, especially when comparison is made with true contact measurements. How near the measurement may be made is, of course, a function of the size of the probe.

β's, γ's, and X rays are normally monitored with either an ion chamber, Geiger-Müller (G–M), or scintillation detector attached to a suitable portable counting rate meter, sometimes equipped with an audible indicator. Each type of instrument has its own special advantages and limitations. Knowledge of these characteristics is essential for intelligent monitoring.

A. G–M Instruments

G–M devices (Figs. 8a, 8b, 9, 14) are widely used for low level (less than 20 mr/hr) β–γ monitoring. They have advantages of small weight, ruggedness, rapid response, and sensitivity to both β and γ radiation. There are, however, several distinct limitations in the use of G–M instruments. One is energy dependence, i.e., the response of the instrument is not the same as

that of air or tissue for all radiation energies. The energy dependence relative to air or tissue response for several instruments is shown in Appendix O.

Other sources of error encountered when monitoring with a G–M instrument are sensitivity to light, temperature sensitivity, and erroneous response to very high fluxes. The use of aluminum-wall G–M tubes eliminates the problem of light sensitivity often encountered with glass-wall tubes. Temperature extremes can affect the operation of G–M tubes or battery characteristics, causing instrument failure or erratic operation in only moderately cold temperatures. It is wise to check a G–M instrument for this characteristic before attempting cold weather monitoring out of doors. Saturation, often seen as an apparent lowering of dose rate as one moves a G–M tube to a region of higher radiation intensity, is caused by operating the meter in fluxes higher than the tube and circuit were designed to handle. Although this effect should require fluxes several times full scale (several r/hr), much lower fluxes will cause saturation in a tube that is near the end of its life.

With the β shield off, G–M tubes will detect β particles with energies of about 0.2 Mev. Readings of β contamination with a G–M tube are not in units of dose (rads), and reporting β readings in roentgens is incorrect by definition of the roentgen. In certain cases, correction factors can be developed which convert G–M instrument readings to β rads.

B. Ion Chamber Instruments

Ion chamber instruments (Figs. 5, 6, 7, 10, 11, 12) are ordinarily used for higher levels of radiation than

G–M devices, although some, for example the Radector, are also useful at low levels. Ion chamber devices are devoid of many of the inherent troubles of G–M devices and usually show considerably better energy characteristics (Appendix O). It is seen from Appendix O that the Cutie Pie has a correction factor of 1 or less from 1.25 Mev to about 20 kev, that is, it is "safe" over this energy range. Below 20 kev it is "unsafe." The Jordan Radector ion chamber instrument requires no correction for γ's between 0.10 and 1.2 Mev.

Ion chamber instruments in use at LASL are calibrated for γ response and, although somewhat β sensitive, require corrections to give β rads. Troubles to be expected with ion chamber devices include battery failure at low temperatures, drift of zero setting, and long warm-up time.

C. Scintillation Counter

Characteristics which make the use of scintillation detectors attractive for β–γ monitoring are high sensitivity, ability to cover a wide range of intensities, and an energy response near that of an air-wall ion chamber. Also, inherent troubles due to temperature and barometric pressure are not found in scintillation detectors. Currently-used instruments using scintillating materials of high Z, such as NaI, are likely to demonstrate a considerable energy dependence, being over-sensitive to γ's around 150 kev. A scintillation detector phosphor which detects γ rays will also respond to β particles that penetrate the window. As with the G–M instrument, pulses are measured, and β measurements are not in terms of rads. Again, correction factors may be developed.

D. Beta-Gamma Monitoring Check List

(1) Be aware of nature of source or contaminant, including presence of β and energy of radiation.

(2) Utilize proper correction factors for γ energy or β response.

(3) Know limitations and possible difficulties to be found with instrument in use.

14. NEUTRON MONITORING

A. Neutron Characteristics

The neutron is an uncharged particle with a mass roughly that of a proton. As the neutron has a very short life outside of the nucleus (about 13 min) no contamination problems in the usual sense of the word exist. Activation or scattering processes often lead to emission of γ's or charged particles during or after neutron bombardment of a material. The neutron is not directly ionizing and its detection (and its biological damage) is accomplished through several intermediate processes that result ultimately in ionization. The magnitudes of these processes are strongly dependent on the energy of the neutron being detected, greatly complicating the interpretation of measurements. The RBE and tolerance flux for various energy neutrons (Sec. 9) have been changed several times in the past few years as more and better biological and physical data have been obtained.

For convenience, neutrons are often classified in four energy ranges: Slow, 0–0.1 kev; Intermediate, 0.1 kev–0.02 Mev; Fast, 0.02–10 Mev; High Energy, above 10 Mev. The slow region includes thermal neutrons.

B. Production of Neutrons

Neutrons may be produced by nuclear reactions in reactors (fission), accelerators, or a radioactive isotope in combination with a suitable target material. Fission neutrons average 1 to 2 Mev. Around a reactor, neutron energies will vary from several Mev down to

thermal energies, with an average about 0.5 Mev. Accelerator-induced nuclear reactions produce neutrons of nearly any energy, depending on the particle accelerated and its energy, the reaction energy, and the angle at which the neutron is ejected. Cyclotron-accelerated particles have a considerable spread in energy and therefore produce neutrons with an energy spread. Van de Graaff or Cockcroft-Walton machines produce monoenergetic particle beams, and therefore monoenergetic neutrons are generally produced at a particular angle with respect to the incident beam. Neutron sources, homogeneous in direction and energy, can be produced with accelerators operating at proper energies (usually a few kev) and utilizing appropriate nuclear reactions. For discrete neutron sources, the alpha-neutron (α,n) reaction is utilized using an intimate mixture of an α emitter and a light element (e.g., Be, B). Photoneutron sources, utilizing the gamma-neutron (γ,n) reaction with beryllium or deuterium, are also available. Information on neutron sources is given in Appendix K. The flux (n/cm^2-sec) at any distance R (cm) from a source of known total neutron emission rate Q (n/sec) is

$$\text{n/cm}^2\text{-sec} = \frac{Q}{4\pi R^2} = \frac{0.08Q}{R^2}$$

C. Neutron Detection

The neutron monitoring instrument generally in use at LASL is a modification of the PeeWee α meter (Fig. 3). The "Converted PeeWee" counts the α particle produced by the reaction $B^{10}(n,\alpha)Li^7$ when a neutron impinges on a B^{10} atom in the boron-lined counter tube substituted for the conventional PeeWee

probe. To compensate in part for a low efficiency in the boron response at about 1-kev neutron energies, a 1 in. thick polyethylene moderator is placed around the tube to reduce a fraction of the fast neutron flux to energy levels which will react efficiently with the B^{10}. This converted or moderated fraction is dependent on the initial energy of the neutrons and the geometry of the moderator. When calibrated with Ra-Be neutrons, the following correction factors are used.

Neutron energy	*Energy dependence correction factor (Moderator and Cd)*
Thermal	1.25 (bare tube)
1 kev	0.3
1 Mev	0.5
5 Mev	1.0
14 Mev	3.0
22 Mev	4.0
28 Mev	5.0 (estimated)

As can be seen from the wide variation in the correction factors, the most important bit of information to a person monitoring neutrons with a converted PeeWee is the average energy of the neutrons being measured. The importance of this information is further magnified by the fact that neutron tolerances also vary greatly with energy (Sec. 9). Unfortunately, the average energy of monitored neutrons is seldom readily available.

A measure of the thermal neutron flux is obtained from the difference between a bare-tube and a cadmium-shielded reading, the cadmium stopping essentially all neutrons below about 0.5 ev. A ratio of these two readings, bare-tube divided by cadmium-shielded, yields a number called the cadmium ratio (R_{Cd}). The use of

this ratio affords an approximate evaluation of the number of neutrons in the intermediate region. For each R_{Cd} an intermediate tolerance factor (ITF) has been determined (see Fig. 39) from a calculation

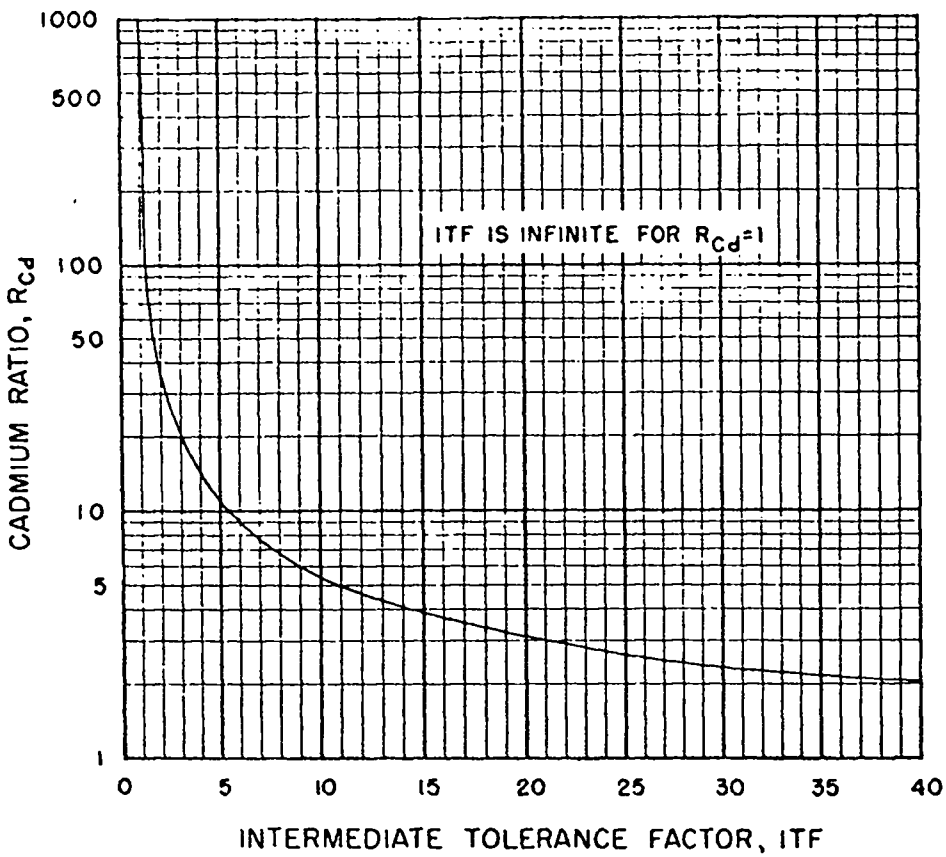


FIGURE 39.—Intermediate Tolerance Factors (ITF) for various cadmium ratios (R_{Cd}) for use with the Converted PeeWee neutron meter, calculated from the relation $ITF = 1 + 40/(R_{Cd} - 1)$.

based on certain restricted conditions (D. J. Hughes, *Pile Neutron Research*, 1953) and the accepted neutron tolerances. The proper ITF, when multiplied by the fraction of tolerance due to thermals, yields the fraction of tolerance due to the *sum* of thermal and intermediate

neutrons. The several assumptions made in arriving at the ITF's are nebulous enough that the method should be considered usable only until a more precise method is devised. Fast and high energy neutron fluxes are measured with the tube enclosed in both the moderator and cadmium.

Neutron monitoring with the converted PeeWee consists of making three measurements at each point of interest: bare-tube, cadmium-shielded, and cadmium plus moderator. A γ measurement is also taken whenever neutrons are monitored, as γ rays are nearly always associated with the production or attenuation of neutrons. A rather detailed set of data and evaluation sheets are available in the H–1 office for use with the converted PeeWee to aid in the determination of the per cent MPD at each point monitored.

The Rudolph neutron-detecting instrument (Fig. 4) reads directly in mrep/hr (approximately equivalent to mrads/hr), since the chamber has a response essentially equivalent to tissue for neutrons in the energy range between 0.2 and 10 Mev. The fraction of MPD is the observed mrep/hr divided by the ratio 7.5/RBE, using the RBE for the average neutron energy being measured. An RBE of 10 is satisfactory for the Rudolph range.

Neutron-sensitive scintillators are being developed, presenting the inviting possibility of one instrument with an assortment of α, β–γ, and neutron-sensitive scintillator probes.

Additional information about neutrons is found in Appendix C and in Section 4. Neutron shielding information is given in Appendix J. A description of many neutron sources is given in Appendix K.

D. Neutron Monitoring Check List

(1) Ascertain average neutron energy at each point where measurements are taken.

(2) Complete data sheets, especially data sheet No. 1.

(3) Always make γ measurements.

15. TRITIUM MONITORING

A. Characteristics

Tritium, or H^3, is the only known radioactive isotope of hydrogen. It emits a β of 18 kev maximum energy (about 6 kev average) and has a radioactive half-life of 12.26 yr. Undiluted tritium gas (T_2) has an activity of 2.6 curies/cc STP or 9.8×10^3 curies/g. Pure tritiated water (T_2O) has an activity of about 2700 curies/g.

B. Detection

Because of the extremely low energy or penetrating power of the β particles from tritium, ordinary β-sensitive devices are not suitable for tritium monitoring, since the particle cannot penetrate to the sensitive volume of the chamber. Instruments allowing the tritium gas or T_2O vapor to flow inside the counter chamber are utilized. A portable instrument of such design is the Tritium Sniffer (see Fig. 1) which sounds an alarm when a preset number of ions per unit time (of any origin) are measured. Although a calibration has been performed on the Sniffer (Report LA–1683) and permissible times have been assigned to each scale, the meter must be used primarily as a qualitative detector because the chamber also responds to ions in the air formed by means other than tritium (e.g., heat, smoke, or γ rays). Sensitivity also depends on the sampling rate, the average ion concentration in the sampled area, and the location of the meter with respect to the source.

A new tritium monitoring instrument, Model 120

Balanced Sniffer, is equipped with a dual chamber and deionizer. The deionizer removes all ions formed by any agency outside the chamber and makes the instrument insensitive to flow rate. The dual chamber renders the Model 120 relatively insensitive to γ rays, thus making the instrument truly a tritium detector (or at least a radioactive-vapor or airborne-particle detector). After an initial calibration to tritium, the Model 120 can be recalibrated routinely with γ rays.

A more reliable continuous monitoring device utilizing a vibrating reed electrometer and a recorder to measure the current from an ion chamber is used in enclosed areas where tritium is a constant hazard. The time lag between tritium sensing and alarm must be recognized in this instrument.

C. Maximum Permissible Concentration

The MPC value for tritium (as HTO or T_2O) for a 40-hr week is 5.1 $\mu c/M^3$ (1.1×10^7 d/m-M^3). These concentrations are based on a weekly permissible exposure of 0.1 rem/wk because tritium has as a critical organ the body water, and the major portion of the body is limited to 5 rem/yr (about 0.1 rem/wk). LASL operations are such that it is more convenient to handle tritium exposures on a 0.3 rem/wk basis, and the MPC values above may be tripled. A limit of 5 rem/yr is still maintained for tritium. The MPC in air is determined assuming equal skin and lung absorption, which means the value of MPC may be only doubled when utilizing supplied air devices. According to Pinson and Langham (*J. Appl. Physiol. 10*, 1, 1957, p. 108) the amount of tritium maintained in the body that will deliver 0.3 rem/wk to the body is 3.7 mc. The

effective half-life in the body is about 12 days and can be shortened considerably by increasing the daily intake of fluids. With 3.7 mc in the body, urine assay will show 85 μc/L. Calculations (Report LA–1469) show that only one breath of T_2O saturated air will result in a lethal dose, if no attempt to increase water turnover is made.

D. Urine Assay

The only means of measuring a person's actual tritium exposure is by urine analysis. It is therefore imperative that persons working with tritium or tritium-contaminated materials submit routine urine samples, the frequency of sampling being determined by the amount of tritium handled and the working conditions. In case of accident or where instruments indicate a possible high exposure, a urine specimen should be collected immediately and a second specimen of at least 10 cc as soon as possible after the first voiding, since the first sample may be diluted by urine in the bladder at the time of exposure. Group H–5 will at any time run an emergency analysis within 2 hr. An emergency urine assay kit, located in the Decontamination Laboratory, CM Building, is available for use by the monitor when an immediate rough estimate is needed. The procedure is rather insensitive but simple and can be performed in less than half an hour. In certain cases the Medical Group may prescribe an accelerated intake of fluids. Unless otherwise prescribed by the physician, intake should be limited to 1 pt/hr for 10 hr or no more than 5 qt/day. Tritium urine analyses are evaluated in terms of whole-body rem exposure by Group H–1 (Report LA–2163). A

12-day elimination half-life is assumed for all exposures less than 124 μc/L concentration. When this level is exceeded, the actual elimination half-life is determined, and appropriate corrections are made in the dose calculations. An acute dose resulting in 124 μc/L in the body fluids (including urine) will expose the person receiving it to 0.6 rem in the first 2 weeks following the exposure, and until completely eliminated (assuming a 12-day elimination half-life) 1.08 rem to the whole body. Such tritium exposures are totaled along with any additional radiation exposures (such as X ray, γ, neutron, etc.) that the person receives.

E. Precautions

Precautions to be taken when working with tritium or tritium-contaminated materials include the wearing of rubber gloves, the use of negative-pressure dry boxes, hoods with linear flow at least 100 ft/min, and/or the wearing of supplied air equipment. Rubber gloves should be worn and changed frequently, since tritium water vapor passes through the rubber in hours or less. The use of thin rubber gloves in addition to the installed dry box gloves is desirable. All equipment which has come in contact with tritium, either gas or T_2O vapor, will retain some tritium and should be considered contaminated. Stopcock grease, vacuum pump oil, and plastics are readily contaminated, whereas materials such as glass or stainless steel retain smaller quantities. Under ordinary use, the Sniffer is seldom contaminated. Under conditions where the monitored tritium has passed through a vacuum pump, oil contaminated with tritium may be deposited on the inside Sniffer chamber walls. At ordinary room temperatures,

the diffusion of tritium through glass or stainless steel or from T-Zr accelerator targets is negligible. However, at elevated temperatures and pressures there is appreciable diffusion of tritium through stainless steel. Tritium losses from targets may result from heating or by an exchange mechanism when in contact with ordinary hydrogen. Such targets must always be handled with rubber gloves, as quantities up to several curies per cm^2 of target surface may be adsorbed on the target.

F. Tritium-Contaminated Vacuum Pumps

Tritium contamination is so often associated with vacuum pumps that special precautions are observed. The present policy concerning tritium-contaminated pumps is: (1) Pumps or other equipment which have been exposed to tritium are not allowed to leave the project without H–1 Group Office approval; (2) pumps reading one-half No. 4 scale at "contact" with the Sniffer may be repaired by the users without a hood but with rubber gloves and urine sampling; (3) pumps more severely contaminated must be decontaminated or repaired in a hood under H–1 supervision. Oil and mercury associated with the pumps should be carefully checked; remember that most of the activity will not be detected owing to the very short β-particle range.

G. Tritium Monitoring Check List

(1) Ventilation: Do hoods have proper flow?

(2) Air: Is supplied air advisable?

(3) Instruments: Are they working? What do readings indicate on the Sniffer? On the vibrating reed electrometer? Are γ rays interfering?

(4) Gloves: Is there a chance of skin absorption?

(5) Urine samples: Are sample containers available? Instructions for sampling.

(6) Contamination: Allowable contamination. How to package waste.

(7) Location of emergency urine assay equipment and how to operate it.

See also Beta Particles, Appendix C–2; Decontamination, Section 8.

H. Interpretation of Sniffer Measurements

The permissible time per week given in the tabulation below is based on 15.3 $\mu c/M^3$ (concentration to give 0.3 rem/40-hr wk) and the assumption that the entire tritium contaminant is in the form of water vapor (HTO or T_2O), and not as gaseous tritium (HT or T_2). If the tritium encountered is in the form of a gas and not the oxide, urine analyses for tritium will not be as high as Sniffer readings would have predicted, owing to the lower biological response to the gas than the oxide. Since the proportion of tritium that is in the form of the oxide cannot be determined in the field, the "safe" assumption that only the oxide is measured must be made. Measurements are to be made of general area or room activity to give a picture of breathing concentration rather than local contamination.

Scale No.	$\mu c/M^3$ full scale	Permissible time/wk	Permissible time/wk with supplied air
5	2×10^2	~3 hr	~6 hr.
4	1×10^3	~40 min	~1 hr 10 min.
3	1×10^4	~4 min	~7 min.
2	1×10^5	Do not remain	Do not remain.
1	*1×10^5	Do not remain	Do not remain.

*Model 120 only.

16. PERSONNEL DOSIMETRY

Dosimetric devices used at LASL for measuring integrated doses of ionizing radiation are of two general types: (1) pocket dosimeters and (2) film badges.

A. Pocket Dosimeters

Self-reading pocket ion chambers and charging devices (Fig. 37) are available in several ranges from the Photodosimetry Section. These dosimeters are essentially capacitors constructed to discharge in a predictable manner when exposed to ionizing radiation. The charge, placed on the chamber upon proper insertion in the dosimeter charger unit, can also leak off, indicating an erroneous exposure. Dosimeters are tested for leakage and those which leak 5% of full scale after a 24-hr agitation are sent in for repair. Each dosimeter carries a correction factor which, when multiplied by the indicated reading, corrects for average temperature and pressure and the chamber's response to radium or Co^{60} γ rays. When the dosimeter is subsequently exposed to radium, the corrected reading should be within 20% of the actual exposure received. Because of physical limitations of the dosimeters, any off-scale reading must be reported only as "greater than full-scale." The actual exposure may in fact be several times full-scale or only a few per cent high. Dosimeters are energy dependent (Appendix O), indicating more exposure than actually received for effective γ energies between about 20 and 400 kev. Below about 20 kev the correction factor rises rapidly because of wall

attenuation, indicating considerably less than the dose actually received. Dosimeters are relatively insensitive to β particles, the magnitude of the insensitivity being only roughly known. For certain specific β emitters, correction factors to give an approximate agreement with film dosimeters are given below.

Nuclide	*Approximate dosimeter correction factor*
Au^{198}	6
$Ba^{140} + La^{140}$	3.3
Fission products	10
$Sr^{90} + Y^{90}$	10

Dosimeters are used only to give the wearer an *estimate* of his exposure while receiving the dose, in order that he may limit himself to the permissible levels. Disagreement, often as large as tenfold, between dosimeter and film badge measurements is to be expected, the dosimeter usually reading low. A detailed policy and instruction sheet for dosimeter users is available from Group H–1.

B. Film Badges

The official records of radiation exposure at LASL are the film dosimetry measurements, except in special cases to be noted later. Developed photographic film is used to provide a permanent record of exposure to hard and soft γ and β, hard and soft X-ray, thermal neutron, and fast neutron radiations.

The LASL film badge is illustrated in Fig. 38. The body of the film badge is 20-mil brass with an open window (unfiltered area) and a 20-mil cadmium window. In each badge are two film packets containing a total of three films. The DuPont-543 packet contains only

DuPont-502 film. The other packet is the Eastman Experimental Personal Neutron Monitoring Film, Type B. It contains an NTA film for fast neutron dosimetry. The emulsion of this film is between its own cellulose backing and a piece of Eastman Fine Grain Positive film. The films are sandwiched between two 27 mg/cm^2 aluminum foils. This laminate is then wrapped in a lightproof packet.

The film badge, using the film packets mentioned, is capable of measuring the following ranges of exposure:

Hard γ ($>$200 kev)	0.04 to $\sim$1500 r
Soft γ ($<$200 kev)	$<$0.01 to $\sim$85 r
β (assumed $\sim$2 Mev)	0.04 to $\sim$30 rads
Thermal neutrons	0.01 to $\sim$2.0 rem
Fast neutrons (0.5 to 20 Mev)	0.04 to $\sim$12 rem

Due to technical difficulties, all combinations of the above ranges are *not* possible. For instance, thermal neutrons and soft γ measurements are incompatible, as are fast neutron measurements when very large γ exposures are present. The normal accuracy of measurement is claimed to be $\pm$20% for hard and soft γ, β, and thermal neutrons. For fast neutrons, the recorded exposures are within a factor of 2 of the actual exposure. The basic area for γ evaluation is the area under the cadmium window, and for β radiation the unfiltered (open window) area. All exposures are compared to a radium or cobalt calibration of the cadmium-filtered area. It has been found that β radiation (about 2 Mev maximum energy) effect on the unfiltered area, as measured in rads, is approximately equivalent to the radium γ radiation effect under the cadmium filter. The density differences of the film under the cadmium and brass filters can be

used to determine the energy of the γ radiation, if the exposure is large enough. If the exposure is not large and known low energy γ's are the source of radiation, and it has been determined that β radiation is not present, the area under the unfiltered portion may be used for determining the soft γ exposure by applying appropriate correction factors. The determination of thermal neutron exposure requires that any γ exposure be from hard γ's. The density difference under the brass and cadmium filters is then a measure of the thermal neutron exposure. Special calibrations are used when X rays from plutonium metal are the source of radiation, and the unfiltered area is used for the evaluation.

Fast neutron exposure is determined by a microscopic count of tracks in the nuclear track emulsion. Within the limits of the claimed accuracy, the film packet now in use for neutron dosimetry does not necessitate knowledge of the neutron energy.

Film badges are normally issued for a period of 1 month, except in areas of potentially high exposure, where they are issued weekly. The DuPont-502 film is processed and evaluated each time the badge is returned. The Eastman packet is routinely processed only after 6 months, unless (1) the range of the DuPont-502 film is exceeded, (2) the DuPont-502 film is lost or damaged in processing, or (3) a fast neutron evaluation is required. Persons potentially exposed to fast neutrons have their Eastman packets processed, but not necessarily evaluated, monthly. All persons working with radioactive sources—in the vicinity of reactors or critical assemblies, in the vicinity of various particle accelerators or X-ray generators, or with any other

source of radiation—are routinely issued film badges. Visitors not needing film badges in their own work should be issued film badges by the operating persons or by H-1 Photodosimetry Section. Depending on the nature of the work, body badges, wrist badges, or both body and wrist badges are issued.

It is suggested that the body film badge be worn clearly visible on the front of the body somewhere between the waist and neck. This procedure is intended to prevent unintentional shielding of portions of the film by pocket-carried pencils, pens, rulers, etc., to allow a more consistent interpretation of film badges, and also to enable a visual check by the monitor that the film badge is being worn. In certain areas where the probability of physical contamination is high, body badges are supplied with an unsealed, removable plastic petticoat. This plastic cover is provided to prevent actual contamination of the film badge, and does not appreciably affect the response of the film.

Wrist badges should be worn on the inside of the wrist on the hand which the wearer estimates will receive the greater exposure. When wrist badges are worn in this manner, experience has shown that the best representation of hand exposure is measured. Wrist film badges are always encased in sealed polyvinyl chloride envelopes. These envelopes, supplied with snap-fastened watch bands, provide a simple means of attachment to the person. Sealing in plastic is necessary to prevent loss of film badge data should the wearer inadvertently wet the film badge when washing his hands. The plastic envelopes, while absorbing a small amount of β radiation, do not affect the indicated exposure appreciably.

It has been determined that in work with normal and enriched uranium (but not U^{233}), an approximate ratio of 2 exists between the exposure as measured at the wrist and that received by the fingers. In work with plutonium, americium, and curium solutions, the same wrist-to-finger ratio of 2 has been found. A factor of 4 has been determined for work with plutonium metal. These correction factors are routinely applied to the actual measured exposures on the wrist badges, thus eliminating the need for finger badges.

Experience has shown that two points are not fully understood by persons to whom film badges are issued. One is that film badges are not to be abused. "Abused" includes deliberate exposure of the badge to radiation while it is not being worn by the person to whom it was issued, the use of the film badge as an experimental detector, the rearranging of the films in the badge, and the repairing of the badge (especially resoldering the clip) while film is in the badge. The other point is that a film badge routinely issued to a person at a particular area should be worn by that person in all areas that he visits so that he maintains a single cumulative record for any one period. The issue of a visitor badge to any person who already has a routinely issued badge unnecessarily complicates the records.

In cases of exposure to radiation when film badges were not worn, estimates of exposure are taken from other sources such as pocket dosimeters, time-rate studies, or measures of body activation. These estimates are recorded as exposures received with a remark describing the situation.

C. Records

Beginning in 1957, the records of all film badge and tritium exposures at LASL have been carried on IBM cards. Past records are being transcribed to IBM to make cumulative exposure totaling possible. Quarterly and annual summary cards are prepared to give the total exposures received by each person. On these cards are recorded, for the body, β-rads, γ-r, γ-rem, thermal neutron-rem, fast neutron-rem, and total rem, and for the extremities, γ-r, γ-rem, $\beta+\gamma$-rads, $\beta+\gamma$-rem, thermal neutron-rem, fast neutron-rem, and total rem. Other information included on a person's card is the last name and initials, Z (identification) number, and birth year; a monitor should attempt to obtain all of this information whenever he initiates a film badge issue.

17. URINALYSIS

Urine samples are analyzed to obtain information regarding the amount of foreign material present in the body. The relation between the urine result and the actual amount of radioactive material in the body or the actual damage done the body tissues is extremely difficult to interpret and especially dependent on the time between exposure and urine sampling. For this and other reasons, permissible levels can be given only in a few specific cases.

Urine samples should be submitted as 2/2 voidings (composite of 2 evening and 2 morning voidings) except in the case of tritium, polonium, and natural uranium where spot samples of a few hundred ml are sufficient.

The following table lists radioactive materials that can be routinely determined in urine at LASL. Other radioactive materials can be determined using special techniques.

Material	Method of determination (Report LA-1858, 2nd Ed.)	Specificity	Comments
Americium.....	α proportional counting.	Does not separate Th, Pu, Cm, Ac, Np.	For lack of better data, see plutonium. 0.5 d/m-24 hr sample lower limit of detection.
Gross beta (f.p., Sr-Y^{90}, Ba-La^{140}).	β counting.	Not specific without performing decay and absorption studies.	If over 200 d/m-L, exposure should be suspected and investigation started.

Material	Method of determination (Report LA-1858, 2nd Ed.)	Specificity	Comments
Plutonium.....	α nuclear track counting.	Specific.	0.2 d/m-24 hr sample should be investigated if no known acute exposure has occurred since last specimen (this value indicates no more than 1/5 body burden regardless of method or time of exposure). 14 d/m-24 hr sample in specimen taken $\sim$ 30 days after exposure indicates $\sim$a permissible body burden (0.044 μc).
Polonium (Po^{210}).	α proportional counting.	Specific for Po.	If over 10 d/m-L, the possibility of exposure should be investigated.
Protactinium (Pa^{231}).	α proportional counting.	Relatively specific for Pa.	
Radium.....	α proportional counting.	Po eliminated; specific for Ra^{226} under certain conditions.	
Thorium (Th^{230}).	α proportional counting.	Does not separate Nat. Th, Pu, Cm, Ac, Np, Am.	
Tritium.....	β counting; internal G-M technique	Specific.	124 μc/L acute exposure considered permissible level (delivers 0.6 rem in first 2 wk after exposure; 1.08 rem integrated dose); 28 μc/L maintained chronic level permissible (delivers 0.1 rem/wk).
Uranium (U^{235}, U^{233}).	α proportional counting.	Specific.	50 d/m-24 hr sample considered positive indication of enriched uranium in the body; 200 d/m-24 hr sample indicates need for examining working environment.
Uranium (Natural, D-38).	Fluorimetry.	Specific for uranium.	50 μg/L considered positive indication of material in body; 100 μg/L indicates need for examining working environment.

Tritium urine results are evaluated in terms of dose and are added to the employee personal exposure record (Report LA–2163). A method has been developed by which plutonium urine results can be evaluated in terms of per cent of body burden. This plutonium information is kept with the exposure records but no attempt is made to express the results in terms of dose.

Urine analyses are also made for nonradioactive but otherwise toxic agents (e.g., mercury and lead). When exposures to these agents are suspected, it is necessary to call Group H–5 for an evaluation of the situation and suggestions for corrective action.

18. AIR SAMPLING

By H. F. SCHULTE and E. C. HYATT

Radioactive material inside the body may cause intense irradiation of the tissues in which it is deposited. Inhalation is the principal means by which such material enters. The amount deposited in the body depends largely on the concentration in the air which is inhaled, the particle size of the contaminant, and the length of time the individual is exposed to this atmosphere. It is essential that the concentration of radioactive substances in the air be kept to a minimum. Maximum permissible concentrations for various isotopes have been established (Sec. 10), and to determine whether such standards are being met, routine air samples are collected and analyzed.

A. Atmospheric Contaminants

The type of atmospheric contaminant depends on the operation from which it evolves. Contaminants may occur as dusts, fumes, smokes, gases, vapors, or mists.

Dusts, fumes, smokes, and mists are particulate matter, the particles being liquid droplets in the case of mists. The distinction between dusts and fumes is based on their method of formation and particle size, fumes being material of very small particle size. The term "fume" is frequently used very loosely to include all types of air contaminants, although this is technically incorrect.

B. Particle Size

When radioactive or other material is suspended in the atmosphere as a result of laboratory or industrial operations, it usually exists there in a range of particle sizes. When a person breathes air containing this material, all sizes are not equally retained in the body. The percentage of a given size particle which is retained in the body depends not only on the particle size but also on the particle density and the rate and depth of respiration. It is frequently stated that only particles ranging in diameter from 0.5 to 5 μ reach and are retained in the depths of the lungs. This is a very rough approximation based largely on experience with silica dusts. For very heavy dusts, such as uranium and plutonium oxides, the optimum sizes for deposition in the lung are smaller than those given above.

When dust is inhaled, part of it is deposited in the nose and upper respiratory tract, while another part is deposited in the alveoli or the deeper parts of the lung at the end of the air passages. Because of the mechanics of respiration, the nose and upper respiratory system are most effective in trapping dust of large particle size. Studies of dust retention and deposition are very difficult to make and there is still need of accurate information. Several excellent studies are now in progress.

C. Methods of Air Sampling

Particulate matter is most conveniently sampled by means of filter papers of various types, although other methods (impaction, impingement, electrostatic precipitation) may be used in special cases. Other types of air contaminants (gases and vapors) are less fre-

quently encountered and require special equipment for sampling.

Air samples may be divided into two principal groups, based on the length of time involved in the collection. They may be taken instantaneously (spot or grab samples), or over a measured period of time (continuous or integrated samples).

(1) Spot samples, when analyzed, will indicate the concentration of airborne contamination at a precise time and thus may prove very valuable in identifying a specific source of contamination. A series of samples of this type, when taken during a known period, will show whether the operation produces cyclic variations in the concentration. These samples are taken by means of evacuated flasks or bottles (e.g., liter flasks for radon gas samples) or, for emergency evaluations, by use of a hand-operated pump (Samplair pump) drawing air through a filter paper. One of the chief disadvantages of spot samples is that a large number of such samples is required to evaluate the worker's daily exposure. Another limitation is that no indication of contamination will be found unless high concentrations are present or a very sensitive counter is used for analysis of the sample.

(2) Continuous samples more nearly represent the type of exposure to which the worker is subjected, although they give less information than spot samples about how the contamination is produced. Various sampling rates may be used as long as the rate and the collecting efficiency of the sampling apparatus at that rate are known. When very low air concentrations must be measured, or where the counting or analytical method is very insensitive, higher than normal sampling

rates may be used, or samples may be collected over a long period. Continuous sampling is the method predominantly used at Los Alamos and the most widely used sampler is the Filter Queen (Sec. 11, Fig. 15).

D. General Air Sample vs Breathing Zone Sample

A common practice at LASL is to collect a general air sample in the workroom over an 8-hr work period with a Filter Queen at the breathing level of the workmen. This then represents the average concentration in the section of the room sampled. A breathing zone sample is collected within 1 ft of the worker's nose for 5 to 60 min. It is usually taken by means of the Giraffe sampler (Fig. 18) with which a small filter paper holder is positioned in the operator's breathing zone and the holder is connected to a pump and flowmeter at ground level. This latter type of sample more nearly represents the concentration of contaminants actually breathed during the sampling period. Either of the above types of samples or a combination of both types may be used to evaluate the worker's exposure to airborne contaminants.

For example, a general air sample may adequately evaluate the exposure in a workroom where all the radioactive materials are processed in dry boxes and any airborne contaminants will be dispersed uniformly into the room air, but only a breathing zone sample can be used in evaluating the exposure during the machining of tuballoy on an open lathe. An air sampler located "out of the way" in a corner of the workroom, however, will collect a sample which is *not* representative of the air breathed by anyone in the room. To estimate the airborne contamination in an open uranium foundry,

both types of samples are necessary—the general air sample for the longest exposure during the melting and pouring processes, and a breathing zone sample for the worker who stands over the casting during its removal from the mold and "shakeout." Ideally, it would be desirable to have both general air and breathing zone samples on all operations at all times. However, this is not practical and a compromise must be made in most cases.

In some working areas at LASL the air sampling equipment has been built in. In these areas a large permanently mounted air pump is the source of vacuum for all the samplers in the area. Pipes run from the pump to a number of appropriately located points where filter paper holders can be plugged in. A simple valve at each takeoff point regulates the rate of air flow through the filter head. Short hose lines can be run from these outlets to permit the collection of breathing zone samples.

E. Types and Calibration of Air Samplers

All sampling units must be carefully calibrated for flow rate in order to evaluate the activity per unit volume of air (d/m-M^3). Commercial instruments which have been calibrated at sea level must be recalibrated at LASL because of the lower air density at this altitude. Various devices are used for routine calibration of air samplers and Group H–5 will do any special type of calibration work.

(1) The Filter Queen (Fig. 15) is a commercial vacuum cleaner adapted to draw air through a 4 x 9 in. piece of filter paper at a rate of 4 cfm (0.113 M^3/min). It is equipped with a variable orifice regulator which

maintains a constant air flow with variations in voltage from 90 to 125 volts and in pressure differential from 5 to 14 in. of water. The flow rate of this sampler should be checked weekly with a Seico or orifice meter as well as serviced regularly (by CMB–7) on the preventive maintenance program.

(2) The Hi-Volume Sampler (Fig. 16), as indicated by the name, draws a large volume of air (20 to 50 cfm depending on the filter media used) and can be used for sampling very low concentrations of particulate matter. Such concentrations are encountered in atmospheric pollution studies and in populated areas, for instance during nuclear tests which disperse radioactive dusts over great distances. This commercially available unit uses an Electrolux motor and fan and will operate with intermittent use with a 4 in. diameter paper, not to exceed 12 hr at a time, up to a total of 1,500 hr before requiring service. Servicing consists principally of replacing brushes in the motor. After 3,000 hr of use at 50 cfm, the armature commutator may require turning down. Where a higher resistance filter such as the all-glass fiber paper is used, the unit operates at a much higher temperature and requires more frequent service. However, the service life may be lengthened by using commercially available sampling heads that hold a 9 x 6 in. or 10 x 8 in. filter paper. An adaptor is provided for mounting the unit on a camera tripod for sampling at the breathing level. The flow rate varies from 20 cfm with a 4 in. diameter glass fiber paper to 50 cfm with the BM–2133 respirator filter. This latter filter is principally used for sampling for β-γ emitters since the paper has a high absorption factor for α particles. The sampler unit, calibrated for air flow with a pitot tube

or orifice meter, is equipped with a flowmeter covering the range from 10 to 70 cfm. The air flow varies with voltage and if the latter varies appreciably during the sampling period, a record of voltage variations must be kept and necessary corrections made.

(3) The 1⅛ in. Diameter Sampler (Fig. 17) consists of a small brass sampling head connected to a vacuum pump (usually a Gast pump). The Gast pump is equipped with a rotameter on which the flow rate is set from 5 to 30 L/min by adjusting a valve so the middle of the float is at the desired value. A variation of this unit is the Giraffe sampler (Fig. 18a). In this unit the filter holder is mounted at the end of an extendable tube. The tube is connected through an orifice flowmeter to a Gast pump which is mounted on wheels. The whole unit is very portable and flexible in use. This unit usually uses 2⅛ in. HV–70 filter paper. Whatman No. 41 is the most popular type of filter paper in the 1⅛ in. size. Other types of filter paper include Whatman No. 4, a molecular or membrane filter, and a fine glass fiber filter paper. The molecular filter is used extensively at LASL because it is more efficient than any other type of filter tested and it can be examined directly with a microscope. The glass fiber filter paper has a collecting efficiency equivalent to that of the HV–70 and is particularly useful in stack sampling where high temperatures and high humidity are problems during collection.

(4) The Modified Cascade Impactor (Fig. 19), when attached to a vacuum pump, samples at a rate of 17.5 L/min and separates the collected dust into five fractions for particle size analysis. It has been calibrated for several radioactive dusts and, when the density of

the dust is known, an individual calibration for each collecting stage can be readily calculated. The mass median diameter of the dust is determined by counting the activity on the four glass slides and the follow-up filter paper and plotting on log probability paper the accumulated percentage found on each stage.

(5) The Automatic Sampler Recorder (Fig. 20) is a combined sampling and counting unit in which air is drawn through a 1 in. diameter portion of filter paper for 10 min. At the end of 10 min, the paper through which the air has been drawn moves a short distance to a point under a scintillation probe where its counting rate is measured. Meanwhile, another 10-min sample is being collected. The results of the count-rate measurement are indicated on a meter and recorded on an Esterline-Angus Recorder. The unit samples at a rate of 50 L/min (1.77 cfm) and is capable of detecting the presence of a concentration of 440 d/m-M^3 of an α emitter. This is many times the permissible 8-hr tolerance of most α emitters, but it serves to indicate the presence of peak concentrations which show a failure of some control measure. An alarm may be connected to the sampler, thus giving warning to correct the difficulty, put on respirators, and evacuate the area.

(6) The MSA Samplair Pump is a small hand-operated device used to collect samples on a 1½ in. diameter filter paper (Whatman No. 41, 1⅛ in. diameter paper will work) at a sampling rate of 0.6 L/stroke. It is used primarily for emergency evaluations of airborne contamination. Enough pump strokes must be taken so that the material collected on the paper contains sufficient activity to be counted. This device is almost exclusively a piece of emergency equipment used in the

field to give a very rough indication of the presence of a very high concentration of airborne radioactive material. If 30 pump strokes are taken, a total volume of 18 L is sampled. If this activity shows up as a minimum detectable reading on an α survey meter, the air concentration will be at least 500 d/m-M^3.

(7) Evacuated Flasks of 1-L capacity are generally used for radon gas and can be used for collecting spot samples of either the breathing zone or general room air. A radon gas counter located in the Source Storage Building operated by Group H–1 is used for counting radon gas samples.

F. Counting and Calculation

Counters for α or β measurements have been adapted to count practically all samples, including the entire 4 × 9 in. Filter Queen sample, and are located in the count room in CM Building (SM–29), the Health Research Laboratory, and the Administration Building.

Any air filter sample will show an appreciable background due primarily to the daughters of naturally occurring radon and thoron. The radon daughters, whose longest half-life is only 30 min, may be considered as completely decayed 4 hr after completion of the sampling. The thoron daughters, whose longest half-life is 10.6 hr, will not decay sufficiently before about 72 hr. Decay can be estimated, however, by taking two counts—one 4 hr and another 24 hr after sampling is completed. Then the actual count of long-lived α emitters, C, is given by

$$C = \frac{C_2 - 0.271 C_1}{0.729}$$

where C_2 is the count on the paper after 24 hr and C_1 is the count on the paper after 4 hr.

Samples counted at CM Building are allowed to decay 20 to 24 hr before counting, assuming that residual thoron daughters will compensate for counts lost due to surface effects of the filter paper on α particles.

Maximum permissible concentrations for air found in the Table of Isotopes (Sec. 10) are given in d/m-M^3. To transform the c/m given by the counter to d/m, the *efficiency* (see Glossary) of the counter must be known. For α, the counters at CM Building are adjusted (by meter deflection) to give an efficiency of 50% for plutonium standards. For β counters, the efficiency will vary from 5 to 45%. The number of c/m is divided by the efficiency to give d/m. The cfm is converted to M^3/m.

Example 1: A Filter Queen sampler is operated from 2:00 PM to 5:00 PM at the normal rate of 4 cfm. The entire filter paper when counted on a counter with an efficiency of 40% has an activity of 50 c/m. Find the concentration of airborne contamination in d/m-M^3 of air.

(a) Total d/m for the filter paper

$$\frac{\text{c/m filter paper}}{\text{counter efficiency}}=\frac{50\text{ c/m}}{40\%}=\frac{50}{0.40}=125\text{ d/m}$$

(b) Volume of air sampled

Time of sampling=3 hr=180 m

$$\text{Rate of sampling}=4\text{ cfm}\times\frac{1\ M^3}{35.3\ ft^3}=0.113\ M^3/m$$

Total volume=0.113 M^3/m×180 m=20.3 M^3

(c) Therefore,

$$\text{d/m-M}^3=\frac{125\ \text{d/m}}{20.3\ \text{M}^3}=6.2\ \text{d/m-M}^3$$

NOTE: The final value is given to only two significant figures because of several inherent errors in the determination.

In the event it is impossible to count the entire filter paper, a portion of the paper may be counted. The Filter Queen sampler uses a filter paper approximately 9×4 in. in size, but the effective collecting area is limited by the supporting grid to twenty-one 1-in. squares. The effective squares become darkened after a short sampling time and it is simple and convenient to remove a whole number of squares. Assuming uniform distribution over the paper, it is only necessary to obtain an area correction factor which is the ratio of the total effective filtering area to the filtering area of the portion to be counted.

Example 2: Assume that two 1-in. squares were cut from a Filter Queen paper that was too "hot" to count in its entirety. To obtain the total counts per minute on the paper, multiply the count on the two 1-in. squares by 21/2 or 10.5.

G. Characteristics of Filter Papers

No single figure can be given to characterize the efficiency of a filter paper. Efficiency varies with filtering velocity and particle size, shape, and density. Considerable data are available that give efficiencies at specific values of these parameters.

Designation	*Characteristics*
HV–70	High efficiency, long record of use. Cannot be dissolved.
MSA glass fiber paper	High efficiency, good wet strength, chemically resistant. Cannot be dissolved.
MSA, BM–2133	Low resistance, unsuitable for α counting, moderate efficiency.
Whatman No. 4 and Whatman No. 41.	Cheap, available, moderate efficiency at high flow rates, low resistance. Can be dissolved readily.
Millipore	Can be dissolved in organic solvents. Can be examined in microscope. High efficiency, low α-absorption loss.

19. RESPIRATORY PROTECTIVE EQUIPMENT

In spite of the fact that the atomic energy industry is over 10 years of age, there has been no official effort to evaluate or approve respiratory protective equipment for protection against radioactive material. It is important, therefore, that the Health Division representative specifying the use of such equipment for protection against radioactive material recognize the limitations and shortcomings of existing equipment. Group H–5 is available upon request to conduct respirator and mask-fitting tests in the gas chamber located in HRL Building. It is recommended that all new men working with radioactive isotopes and toxic chemicals be tested for proper face fit. For the purposes of this discussion, respiratory protective equipment may be divided into two classes: filter and supplied air.

Class I—Filter Type Respirators

A. Half Masks

A half mask is the respirator in common use that covers only the nose and mouth (Figs. 21–24). The possibility of leakage around the face piece is the main limitation of the half mask. Since half masks come in only one standard size, it is evident that certain individuals with extreme facial contours will not be fitted perfectly by the standard half mask. Special attention should be given to such individuals to fit them properly. For any half mask in normal routine use, a 20% penetration has to be assumed. It follows,

therefore, that for continuous exposure half masks can be used safely only in atmospheres in which the concentration of the contaminant does not exceed 5 times the MPC_a. Since, however, it is unlikely and also highly undesirable for individuals to wear respirators for more than 50% of any working day, the upper limit of airborne contamination for which the half mask could be considered to offer suitable protection is 10 times the MPC_a.

B. Monitoring Check List for Half Masks

Before starting a job on which personnel will have to wear half masks the monitor should:

(1) Note that half masks should not be used for plutonium dust or fumes.

(2) Assure himself that the possibility of the level of airborne contamination exceeding 10 times the MPC_a is extremely remote. If there is any doubt regarding this level, full face masks or supplied air equipment should be used.

(3) By inspection, determine that the half masks are in proper condition:

(a) Straps and attachments in good condition.

(b) Filter or adsorber cartridge in good condition and properly installed.

(c) Exhalation and inhalation valves properly installed and capable of functioning as intended.

(4) Make sure that each individual has adjusted the mask tightly and that the best possible face fit has been obtained.

(5) Ascertain that the appropriate cartridge for the toxic atmosphere to be encountered is used.

C. Full Face Masks

The main limitations of the full face mask (Figs. 25–29) are the possibility of leakage around the face and malfunctioning of the cartridge. It is possible to obtain less than 1% penetration for a properly fitted full face mask. However, because of the difficulty of fitting all faces with but the one size, it is generally assumed that full face masks are 98 to 99% efficient. For this reason, it is desirable to use full face masks in atmospheres in which the concentration of the contaminant is less than 50 times MPC_a.

D. Monitoring Check List for Full Face Masks

Before starting a job in which personnel will have to wear full face masks the monitor should:

(1) Assure himself that there is little possibility of the concentration of airborne contaminant exceeding 50 times the MPC_a. If there is any doubt regarding the possible level, supplied air equipment should be used.

(2) Inspect the full face mask:

(a) Straps and fasteners in good working condition.

(b) Filter or adsorber cartridge in good condition and properly attached to the mask.

(c) Eye pieces secure in the mask, clean, and fog-proof compound on inside of lens.

(d) Inhalation and exhalation valves working properly.

(3) Check the adjustment of each mask. Make sure the mask is on tight and that the webbing formed by the straps is centered on the back of the person's head. Tightness of fit should be checked by sealing the inlet

to the cartridge. WITH PRESENT-DAY MASKS, IT IS CONSIDERED IMPOSSIBLE TO SECURE A LEAKPROOF FACE FIT IF EYEGLASSES ARE WORN.

CAUTION

Class I Filter Type Respirators of the kind generally used for protection against radioactive material will prevent penetration of only *particulate* matter. They do not provide protection against toxic or radioactive gases or atmospheres deficient in oxygen.

CLASS II—SUPPLIED AIR MASKS

A. Self-Contained Breathing Equipment

(1) Air Demand Type, Scott Air Pak (Fig. 30).
Model 6000—A2M, Air Bottle A2M.
Contains 40 ft^3 at 1600 psi pressure.
Approx. dimensions: 7 in. in diameter and 20 in. long.
Allowable time: 30 min.
Bottle carried in vertical position on back.

(2) Oxygen Demand Type, MSA (Fig. 31).
Contains 40 ft^3 of oxygen at 1600 psi pressure.
Approx. dimensions: 7 in. in diameter and 20 in. long.
Allowable time: approx. 30 min.

(3) Oxygen Self-Generating, Chemox MSA (Fig. 32).
A self-contained mask with an oxygen-generating canister.
Allowable (working) time: approx. 45 min.

WARNING

DO NOT USE CANISTERS IF SEAL HAS BEEN BROKEN IN ANY WAY. Make sure canisters are capable of generating oxygen BEFORE entering contaminated area. Do not allow apparatus lungs to collapse while in contaminated atmosphere. If this should happen, leave contaminated area immediately. Short, quick, panting breaths should reinflate the lungs and allow escape from the contaminated area. DO NOT BREAK THE MASK SEAL IN SUCH AN EMERGENCY! Dispose of used canisters immediately in accordance with instructions.

B. Air-Line Equipment (Figs. 33–36)

The following table lists the types of supplied air equipment and gives the correct operating pressures and volumes required. All of this equipment can be used with either H-size cylinders of pure breathing air or air compressors specifically designed for supplying respirable air.

C. Monitoring Check List for Supplied Air Equipment

Before starting a job in which personnel will wear supplied air equipment the monitor should:

(1) Make sure that the individual wearing the equipment has been properly instructed in the use of the equipment.

(2) Make sure that individuals with known physical impairments, that would be aggravated by using the equipment, are prohibited from wearing the supplied air masks.

OPERATION OF AIRLINE EQUIPMENT

Type	Air flow regulation	Air pressure at source (psi)	Ft^3 air/min	Hose type	Max. length of hose (ft)	Operating time/man with H-size cylinder
Full face or half mask	Demand flow	100–125	As demanded	Medium pressure	100	5 hr.
Full face or half mask	Constant flow manual valve.	10–15	4	Medium pressure	100	55 min.
Plastic hood	Constant flow manual valve.	10–15	6	Low pressure (cloth covered).	100	50 min.
Plastic suit	Constant flow	18–28	5 to 7	Medium pressure	100	40 min.

(3) Make certain the equipment, especially the face piece, is properly fitted on the individual. AN ADEQUATE SEAL CANNOT BE OBTAINED WITH A FULL FACE MASK USING A DEMAND FLOW TYPE REGULATOR WHEN THE INDIVIDUAL IS WEARING GLASSES.

(4) Check the air source for supplied air equipment. Do not depend upon any color coding on gas bottles. The bottle MUST HAVE A LABEL indicating that it contains breathing air and check every bottle before entering the contaminated area. Air compressors *not specifically designed* for supplying respirable air should not be used. The supply of compressed air in a building should not be used unless it has specifically been approved for this purpose.

(5) Make sure an individual will be in attendance at all times at the source of supplied air. Only in extreme emergencies should the Type-H cylinder be wheeled into the contaminated area with the individual. This procedure leaves the valves and regulators unattended and, therefore, is to be avoided if at all possible.

(6) Establish simple positive signals between individuals using the supplied air respirators and individuals in attendance at the air source so that a message indicating impending or actual trouble can be conveyed from one end of the air line to the other.

NOTE: After wearing self-contained or supplied air equipment, make certain that this equipment is in proper working condition, that the face pieces are cleaned with detergent or alcohol, and that all apparatus is correctly put away.

APPENDIXES

A

Appendix A

SHIPPING RADIOACTIVE MATERIALS

Various regulations are condensed and interpreted here for field use. They are classified as to mode of transportation. The italics are to aid in distinguishing rules from interpretations or notes and do not imply exact quotations from published regulations.

A–1. Interstate Commerce Commission (ICC) Regulations

In general, the following regulations apply to rail, motor, water, and air transportation, i.e., common carrier.

(1) *No significant surface contamination on any surface of the container is permissible.*

For purposes of these regulations, "significant" shall be defined as equal to or greater than 500 d/m α measured over 100 cm² (150 c/m with PeeWee), or 0.1 mrad/hr β (arbitrary, convenient number).

(2) *Gamma radiation may not exceed 200 mr/hr or equivalent at any readily accessible exterior surface of the container, or 11.5 mr/24 hr (0.5 mr/hr) at 15 ft from the container at any time during transportation.*

"Equivalent" is interpreted to mean physical equivalent as defined in paragraph A–1(5) below. It is assumed that the factor of 5 used in paragraph A–1(5), which reduces the allowable neutron flux to that physically equivalent to 2 mr/hr γ rather than 10 mr/hr γ, should also be used here. For Rule A–1(2) the neutron flux allowable should be physically equivalent to 40 mr/hr γ (200/5) at the surface of the package. This equivalence is given by either 4600(1 Mev) n/cm²-sec or 2400 (5 Mev) n/cm²-sec. Likewise the neutron flux allowable at 15 ft must be physically equivalent to 0.5/5 mr/hr, which is either 12 (1 Mev) or 6(5 Mev) n/cm²-sec.

(3) Radioactive materials are classified Class D Poisons and are regulated in three groups by the ICC:

Group I. Radioactive materials that emit gamma rays only or

both gamma and electrically charged corpuscular rays (e.g., alpha or beta particles).

Group II. Radioactive materials that emit neutrons and either or both radiations mentioned above.

Group III. Radioactive materials that emit electrically charged corpuscular rays only, or any other radiation that is so shielded that the gamma radiation at the surface of the package does not exceed 10 mr/24 hr (0.42 mr/hr) at any time during transportation.

For material with half-life (T_r) less than 40 hr, package may have an initial contact dose-rate (D) given by

$$D(\text{mr/hr}) = \frac{6.93}{T_r(1 - e^{-16.6/T_r})} \qquad T_r \text{ in hours}$$

assuming a 24-hr transit time.

(4) *For Group I materials, the gamma radiation should not exceed 10 mrhM (milliroentgens per hour at one meter distance) from any point on the source at any time during transportation. The shielding must not open or break during transportation and must be sufficient to prevent the escape of any primary corpuscular radiation from the container.*

"Corpuscular radiation" usually refers to α or β radiation. To insure that all corpuscular rays that penetrate the shipping container are secondary, i.e., generated by the passage of the γ rays through the shield and/or container, adequate shielding must be incorporated in, or adjacent to, the source holder. Any γ shielding will usually prevent primary α or β penetration to the package surface.

External containers 18 in. across or larger that read 10 mrhM will meet the requirements of paragraph A–1(2), i.e., 200 mr/hr at the surface if the source is a point source at the center of the box. For boxes smaller than 18 in. across, the surface measurement will be the limiting factor.

(5) *Group II materials should be packed so that, at any time during transportation, radiation measured at right angles to any point on the long axis of the shipping container will not exceed any of the following: (a) 10 mrhM gamma; (b) electrically charged corpuscular radiation which is the physical equivalent of 10 mrhM gamma; (c) neutron radiation which is the physical equivalent of 2 mrhM gamma; (d) if more than one type of radiation named is present, the amount of each must be adjusted so that the total does*

not exceed the above equivalents. Physical equivalent of a roentgen is that amount of radiation that would be absorbed in tissue to the extent of 100 ergs per gram.

The physical equivalent of 10 mrhM γ for charged corpuscular radiation is 10 mrads/hr at a meter; 120(5 Mev) or 230(1 Mev) n/cm²-sec are equivalent to 2 mrhM γ. For neutron sources of around 5 Mev with appreciable γ emission (Ra-Be, Pu-Be, Po-Be), the following equations may be used to comply with item (d) above:

$$\gamma = 10 - \frac{n}{12}$$

$$n = 120 - 12\gamma$$

where γ is the number of radiation units (mrhM) and n is the neutron flux in n/cm²-sec at 1 meter.

(6) *Group III materials must be packed to prevent the escape of primary corpuscular radiation to the exterior of the container and the secondary radiation must not exceed 10 mr/24 hr.*

Measured with an open window G–M meter, half-life considerations as in paragraph A–1(3) above, 10 mr/24 hr is equal to 0.42 mr/hr.

(7) *Approval from the Bureau of Explosives must be obtained for shipments that exceed (a) 2,000 mc radium, polonium, or other members of the radium family of elements; (b) 2,700 mc of any other radioactive substance; (c) 300 curies of solid Cs^{137}, Co^{60}, Au^{198}, Ir^{192}.*

(8) *Radioactive materials that present special biological hazards due to their tendency to remain in the body for long periods of time (i.e., radium, plutonium, Sr^{90}) must be enclosed in a Specification 2R container in addition to the packaging hereinafter described.*

"Specification 2R" container is a stainless steel, malleable iron or brass tube of O.D. 6 in. or less, length 16 in. or less. Minimum wall thickness is $\frac{3}{32}$ in. for O.D. up to 2 in.; $\frac{1}{8}$ in. for O.D. up to 6 in. Screw-type ends are to be used or one end may be brazed or welded. A teflon gasket is desirable.

(9) *Liquid radioactive materials in Groups I, II, or III must be packed in tight glass, earthenware, or other suitable inside containers surrounded by sufficient absorbent material to absorb the entire liquid contents, and of such a nature that its efficiency will not be impaired by chemical reaction with the contents. Absorbent material is not required when a 2R container is used.*

(10) *Finished package must have no dimension smaller than*

4 in. Outside container must be strong and tight and made of wood, fiberboard, or other approved material and must be able to withstand the shocks encountered in ordinary transportation without permitting leakage of radioactive material.

ICC Tariff 10, Part 78, gives detailed descriptions of approved containers; the 15A nailed wooden box, paragraph 78.168, is generally used at LASL for shipping up to 2,700 mc; the Specification 55, paragraph 78.250, metal-encased, lead or uranium shielded container is authorized for shipments up to 300 curies. Containers not ICC approved require Bureau of Explosives approval.

(11) *Each package must be labeled with standard radiation labels.*

For Groups I and II the ICC red label is used. The following information is needed to complete the label: (a) principal radioactive contents; (b) activity of contents in mc; (c) radiation "units" from the package; (d) shipper's name. The radiation "unit" is 1 mr/hr measured at a meter (mrhM).

For Group III the ICC blue label is used. This label requires only the name of the contents and the shipper's name. If the contents are flammable, appropriate labels must be affixed. Thorium and uranium powders, not in oxide form, are flammable. If special inner containers are used (such as a Specification 2R) the package should be so labeled.

(12) *No more than 40 units of radiation may be shipped in any one car, truck, or plane. Also no Class D poisons are to be loaded in the same vehicle with explosives.*

This rule is interpreted to mean a total of 40 units measured separately.

(13) *Large machines (e.g., bulldozers) which cannot be completely decontaminated by practical means or readily packaged may be shipped providing there is no hazard to personnel or materials. Decontamination must have been effected to the extent that no significant amount of activity rubs off. It is the responsibility of the consigner and/or consignee to supervise all loading and unloading operations and to monitor all personnel involved.*

Paragraph (13) above is an unofficial rule in use at LASL.

A-2. Air Shipments

Restrictions and regulations for air shipments apply in addition to those mentioned above. Also, it should be noted that certain

airlines will not accept radioactive or flammable materials in any amounts for shipment.

(1) *No more than 40 units of Group I or II materials may be carried on any aircraft.*

(2) *The package must provide shielding for full protection to undeveloped film at 30 ft and full protection of all airline passengers or personnel.*

Full film protection at 30 ft is given when the 40-unit limit is met. Protection of personnel is a function of the relative location of passenger and cargo and is the responsibility of the persons loading the aircraft.

(3) *In addition to ICC labeling as prescribed in paragraph A–1 (11) above, a special label stating,* DO NOT PLACE IN SAME COMPARTMENT WITH UNDEVELOPED FILM OR MAIL, *must be prominently displayed. Also if the package is acceptable for shipment on a passenger-carrying aircraft, see paragraph (2) above, a statement to that effect must be plainly visible on the exterior of the package.*

A–3. Courier Service

Courier service is free of all ICC regulations; however, the spirit of the regulations is followed for reasons of public welfare in case of accident. Escort personnel assume responsibility for preventing injury to personnel and films.

Information on how this protection can be accomplished must be furnished the escort and should include estimated permissible exposure time (hr/2 wk) for personnel at several distances from the shipment. A dittoed label, available in the H–1 Monitoring Office, when properly completed and affixed to the shipping container will furnish the escort the necessary information. Tolerance times for the label are computed by dividing a 2 week's permissible body exposure by the dosage measured at the point of interest to obtain hours per 2 weeks.

A–4. Parcel Post Regulations and Exempt Amounts for Common Carrier

When the following requirements are met, articles are exempt from ICC packaging and labeling requirements and as such may be sent by parcel post or common carrier:

(1) *Package must be such that no leakage can occur under normal shipping conditions.*

(2) *Contents must not be greater than 0.1 mc radium or polonium; 0.135 mc of* Sr^{89}, Sr^{90}, *or* Ba^{140}; *or 1.35 mc of any other radioactive substance.*

Milligram amounts of various radioactive materials falling in these three categories are included in the listing in Sec. 10 (column 10).

(3) *No significant alpha, beta, or neutron radiation may be emitted from the exterior of the package and gamma radiation must be less than 10 mr/24 hr (0.42 mr/hr) at the package surface.*

"Significant alpha or beta" is as defined in paragraph A–1(1); significant neutrons, by analogy with significant beta, 6 (5 Mev) or 12 (1 Mev) n/cm²-sec.

(4) *Package must have no significant surface contamination.*

"Significant" defined as in paragraph A–1(1).

(5) *All liquids must be packed in tight glass, earthenware, or other suitable inside containers surrounded by absorbent material sufficient to absorb the entire contents and of such nature that its efficiency will not be impaired by chemical reaction with the contents.*

(6) Parcel Post Only: *Package must be marked on the outside:* RADIOACTIVE MATERIAL—GAMMA RADIATION AT SURFACE OF PARCEL LESS THAN 10 MILLIROENTGENS FOR 24 HOURS—NO SIGNIFICANT ALPHA, BETA, OR NEUTRON RADIATION.

"Significant" is as previously defined, paragraph A–1(1) and A–4(3).

(7) Rail, Motor, or Air Freight Only: *Boxcar, truck, or planeload lots of low-activity materials (e.g., ores, residues) may be shipped exempt from ICC regulations provided:*

(a) *They are packed in strong, tight containers braced to prevent shift of lading with no loose material in the vehicle.*

(b) *Gamma radiation or equivalent does not exceed: 10 mr/hr—12 ft from any car or truck surface, 10 mr/hr—5 ft from any end surface of car or truck, and 10 mr/hr—1 meter from any outside surface of aircraft.*

(c) *Car or truck must be labeled with a placard by shipper. Placard to have a diamond shape, 10¾ in. on each side, to read—* DO NOT REMAIN IN OR NEAR THIS CAR UNNECES

SARILY—NOTIFY SHIPPER OR BUREAU OF EXPLOSIVES IF NECESSARY TO TRANSFER LADING EN-ROUTE—DANGEROUS CLASS D POISON—THIS CAR MUST NOT BE NEXT TO A CAR CONTAINING EXPLOSIVES. AVOID CONTACT WITH LEAKING CONTENTS. WHEN LADING IS REMOVED THIS PLACARD MUST BE REMOVED.

(8) Cleaning Cars and Vehicles: *Any boxcar, motor vehicle, or aircraft which has been contaminated to the extent that a survey of the interior surface shows that the beta-gamma radiation is greater than 10 mr physical equivalent in 24 hr or that the average alpha contamination is greater than 500 d/m-100 cm² (150 c/m PeeWee) shall be thoroughly cleaned such that a resurvey shows the contamination to be below these levels. A certificate to that effect must be furnished to the local agent of the carrier or to the driver of the motor vehicle.*

Certificates are available in H–1 Monitoring Section Office.

A–5. Used Containers

Empty containers and accessories which have been used for shipments of radioactive materials must meet exempt specification (Sec. A–4) and have no label other than an empty label for shipment.

A–6. Shipment Check List

A comprehensive check list for shipment monitoring is available from the H–1 Monitoring Section Office. As well as being a check list, it serves as a record of the pertinent details of the shipment.

A–7. Shipping Regulations Summary

The accompanying table serves as a ready reference guide for shipping regulations; by use of the reference numbers it also serves as an index to pertinent paragraphs in this appendix where the regulations are discussed in detail.

SHIPPING REGULATIONS SUMMARY

(Bracketed references refer to paragraph numbers, Appendix A)

Carrier	Surface	Distance	Labels	Quantity limits	Container
ICC General Information, further restricted by group classification [A-1]	150 c/m α 0.1 mrad/hr β [A-1(1)] 200 mr/hr γ [A-1(2)] 4,600 (1 Mev) or 2,400 (5 Mev) n/cm²-sec [A-1(2)]	0.5 mr/hr γ at 15 ft [A-1(2)] 12 (1 Mev) or 6 (5 Mev) n/cm²-sec at 15 ft [A-1(2)]	Depends on group classification (see below).	2,000-mc radium, polonium, or other member of radium family 2,700-mc any other 300-c Cs^{137}, Co^{60}, Au^{198}, Ir^{192} in Spec. 55 Container [A-1(7)] No more than 40 units in one car, truck, or plane [A-1(12)] No Class D Poisons in same car with explosives [A-1(12)]	Sr^{90} or other bone seeker (Pu, Ra) must be shipped in Spec. 2R Container [A-1(8)] Liquids (any group) in tight inside containers surrounded by adequate absorbent material [A-1(9)] No outside dimension less than 4 in. [A-1(10)] Outside container 15A wooden box or equivalent or Bureau of Explosives Permit [A-1(10)]
ICC, Group I α, β, γ [A-1(3)]	No corpuscular radiation	10 mrhM each box (measurement made from the source) [A-1(4)]	Red ICC label [A-1(11)]		
ICC, Group II Neutrons plus either/or α, β, γ [A-1(3)]		10 mrhM γ 10 mrads/hr β 120 (5 Mev) or 230 (1 Mev) n/cm²-sec all measured at 1 meter from	Red ICC label [A-1(11)]		

		long axis of the container [A-1(5)]			
ICC, Group III Electrically charged corpuscular rays only or other so that surface γ less than 0.42 mr/hr [A-1(3)]	No primary corpuscular radiation Less than 0.42 mr/hr secondary or γ radiation [A-1(3)]		Blue ICC label [A-1(12)]		
AIR, Must meet all above requirements and → [A-2]			Additional label "Do not place in same compartment with undeveloped film or mail" [A-2(3)]	No more than 40 units Group I and II materials in one aircraft [A-2(1)]	
COURIER, Should meet all ICC requirements if possible and → [A-3]			Additional informational label for courier [A-3]		

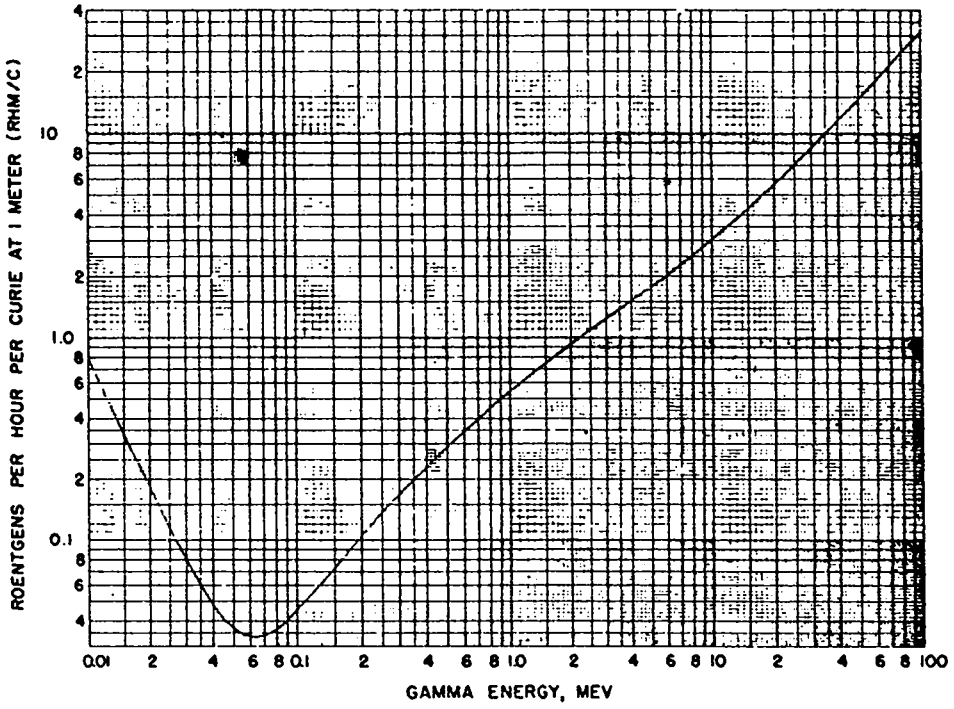
SHIPPING REGULATIONS SUMMARY—Continued

Carrier	Surface	Distance	Labels	Quantity limits	Container
PARCEL POST [A-4]	No significant α, β, or neutron: 0.1 mrad/hr β 6 (5 Mev) or 12 (1 Mev) n/cm²-sec 0.42 mr/hr γ [A-4(3)] No significant contamination: 150 c/m α 0.1 mrad/hr β [A-4(4)]		Labeled: "Radioactive Material, Gamma radiation at surface of parcel less than 10 mr/24 hr. No significant Alpha, Beta or Neutron Radiation" [A-4(6)]	0.1-mc Ra or Po 0.135-mc Sr^{89}, Sr^{90}, Ba^{140} 1.35-mc any other [A-4(2)]	No leakage under normal conditions [A-4(1)]
RAIL, MOTOR FREIGHT OR AIR FREIGHT, Lots of low level activity materials, ores, residues [A-4(7)]		10 mr/hr at 12 ft from any surface, 5 ft from any end, 1 meter from any outside aircraft surface [A-4(7)]	Label: "Do not remain in car unnecessarily . . ." [A-4(7)]		Strong, tight containers, braced in the vehicle; no loose material in vehicle [A-4(7)]

Appendix B

GAMMA-RAY DOSE RATE AT ONE METER PER CURIE POINT SOURCE (rhM/c)

B



The dose rate in r/hr at 1 meter (rhM) from a curie point source is given by

$$\text{rhM/c} = 1.5 \times 10^4 \, \mu E$$

where μ is the true absorption coefficient (cm^{-1}) in air, and E is the γ energy (Mev) per disintegration. This equation, using the true absorption coefficients of White, NBS–1003 (1952), is plotted based on the assumption that 1 monoenergetic γ ray is emitted per disintegration. For nuclides emitting several γ's the resultant value of rhM/c may be found by adding the contributions of each energy γ multiplied by its relative abundance. This has been

done for several γ emitters [Appendix C–3(1)]. A sample calculation is given below.

Example: Calculate the r/hr at 1 meter from a curie point source of Fe^{59}. Fe^{59} is known to have the following three γ's with noted abundances: 1.1 (57%) Mev, 1.29 (43%) Mev, and 0.191 (2.8%) Mev. The rhM/c for each of these energies is read from the curve to be 0.576, 0.656, and 0.098, and the total rhM/c = $(0.576 \times 0.57) + (0.656 \times 0.43) + (0.098 \times 0.028) = 0.613$ rhM/c.

Appendix C

RULES OF THUMB

C

C-1. Alpha Particles

(1) It requires an α particle of at least 7.5 Mev to penetrate the protective layer of skin, 0.07 mm thick.

(2) With 2π geometry, the surface of a thick source of tuballoy will give about 2400 α c/m-cm^2; plutonium about 70,000 α c/m-μg, 16.2 g of plutonium has an activity of 1 c.

C-2. Beta Particles—Bremsstrahlung

(1) The Keleket pocket dosimeter records about $\frac{1}{10}$ the dose received from β exposures of about 1-Mev energies.

(2) When working with Au^{198}, experience has shown that under some conditions the β exposure will be 5 times the γ value. Therefore, the dosimeter will record only $\frac{1}{6}$ of the total exposure and should be limited to readings of 100 mr/wk for the body and 250 mr/wk for the hands.

(3) It requires a β particle of at least 70 kev to penetrate the protective layer of skin, 0.07 mm thick.

(4) The range (R) of β rays in g/cm^2 (thickness in cm multiplied by the density in g/cm^3) is approximately equal to the maximum energy (E) in Mev divided by 2.

$$R=\frac{E}{2}$$

(5) Range of β particles in air is about 12 ft per Mev; for example, a 3-Mev β has a range of 36 ft in air.

(6) Contact dose rates and MPE for hand contacts are listed below. Except for thorium, contact dose rate is a LASL measured value.

Radioactive material	mrads/hr	hr/wk
Th	*40	37.5 bare hands.
Tuballoy, D-38	200	7.5 bare hands. 15.0 1-mm leather gloves.
Oralloy (40%)	180	8.4 bare hands.
(93%)	140	10.9 bare hands.
Pu (nickel-coated)	360	4.3 bare hands.
(uncoated)	440	3.4 dry box gloves.
U^{233} (1-mo U^{232} buildup)	7,000	12.6 (min/wk).
(1-yr U^{232} buildup)	58,000	1.5 (min/wk).

*4 to 5 yr after separation.

(7) Tuballoy may show a much higher β–γ activity during the initial 50 to 100 days after casting because of an increase in the concentration of $UX_1(Th^{234})$ and $UX_2(Pa^{234})$ on the top of the melt.

(8) A correction factor of 2 should be applied to measurements of uranium β radiation made with γ-calibrated G–M instruments, shield open (Ra-Det, July–Oct. 1953).

(9) β-ray surface dose rates (AECD–2753, 1949) with 7 mg/cm² filter:

Source	*mrads/hr**
U slug	233
UO_2 (brown oxide)	207
UF_4 (green salt)	179
$UO_2(NO_3)_2 \cdot 6H_2O$ (yellow uranyl nitrate hexahydrate)	111
UO_3 (orange oxide)	204
U_3O_8 (black oxide)	203
UO_2F_2 (cliptite or uranyl fluoride)	176
$Na_2U_2O_7$ (soda salt or sodium diuranate)	167

*Values formerly given in mrep/hr.

(10) When the β particles from a 1-c source of $Sr^{90}+Y^{90}$ are absorbed, the bremsstrahlung hazard is approximately equal to that presented by the γ's from 12 mg of radium. The average energy of the bremsstrahlung is about 300 kev (Haybittle, *Phys. in Med. Biol. 1*, 3:270, 1956).

(11) The bremsstrahlung from a 1-c P^{32} aqueous solution in a glass bottle is about 3 mrhM.

(12) The dose rate at 1 ft from a β point source is about $200C$ rads/hr neglecting self- and air-absorption where C is the number of curies. The variation with energy is small over a wide range (AERE HP/L23).

(13) When β's of 1 to 2 Mev pass through light materials such as water, aluminum, or glass, less than 1% of their energy is dissipated as bremsstrahlung (AERE HP/L23).

C–3. Gamma Rays

(1) The γ rhM (roentgens per hour at 1 meter) of 1 c of some radioisotopes is listed below (also see Appendix B):

Element	Isotope	rhM/c	Element	Isotope	rhM/c
Arsenic	As^{76}	0.31	Iodine	I^{131}	0.218
Bromine	Br^{82}	1.50	Iron	Fe^{59}	0.613
Cesium	Cs^{137}	0.32	Lanthanum	La^{140}	1.2
Cobalt	Co^{58}	0.556	Manganese	Mn^{52}	1.93
Cobalt	Co^{60}	1.28	Manganese	Mn^{54}	0.46
Copper	Cu^{64}	0.11	Sodium	Na^{22}	1.29
Gold	Au^{198}	0.235	Sodium	Na^{24}	1.84
Iodine	I^{126}	0.018	Zinc	Zn^{65}	0.27
Iodine	I^{130}	1.2			

Element	Isotope	Filter	rhM/c
Radium	Ra^{226} (In equilibrium with its decay products.)	Thuringian glass	0.93
		0.5 mm Pt-Ir	0.84
		1.0 mm Pt-Ir	0.78
		0.5 mm Pt-Ir and 5 mm brass. Each mm of lucite reduces the γ output by 0.35%.	0.7

(2) For Co^{60}, the number of mc is $0.00156\,R^2$, where R is the distance in cm at which 20 mr/hr is measured.

(3) The air-scattered radiation (sky-shine) from a 100-c Co^{60} source 1 ft behind a 4-ft-high shield is about 100 mrads/hr at 6 in. from the outside of the shield (AERE HP/L23).

(4) Within $\pm 20\%$ for point source γ emitters with energies between 0.07 and 4 Mev, the dose rate (r/hr) at 1 ft is $6CE$, where C is the number of curies and E the energy in Mev.

(5) A Cutie Pie correction factor of 10 should be used in computing handling times for U^{233} that has been cast for some time and that contains about 20 ppm U^{232} contaminant. Measurements with the Cutie Pie should be at contact for use of this factor.

C–4. Neutrons

(1) An approximate HVL for 1-Mev neutrons is 1.26 in. (3.2 cm) of paraffin; 2.72 in. (6.93 cm) for 5-Mev neutrons.

(2) One g of Ra-Be emits about 12×10^6 n/sec and has an output about equal to 5 c of Po-Be or 3 g of Ra-B. One c of Po-Be has approximately 3 times the neutron output of 1 c of Po-B.

C–5. Miscellaneous

(1) Barometric correction factor (for use with all unsealed ionization chambers except Victoreen Thimble Chambers) is

$$f = 2.78 \left(\frac{t+273}{p} \right)$$

and for the Victoreen Thimble Chambers, the temperature correction is to 22°C and the factor is

$$f = 2.576 \left(\frac{t+273}{p} \right)$$

where

t = temp in °C
p = pressure in mm Hg

(2) The activity of any radioisotope is reduced to less than 1% after 7 half-lives:

$$2^{-7} = 0.8\%$$

(3) The activity-mass relation may be found as follows:

$$\text{curies/gram} = \frac{1.308 \times 10^8}{A T_r}$$

$$\text{grams/curie} = 7.645 \times 10^{-9}\ A T_r$$

where

A = atomic weight
T_r = radioactive half-life in days

(4) A 1-c source of polonium has a γ output equivalent to 7 μg of radium or about 65 mr/hr at 1 cm when unshielded. It is normally requested that the impurities (oxygen in particular) in separated polonium be reduced so that the neutron activity is not greater than 100 n/sec-c; however, the activity may be as great as 200 n/sec-c. If polonium is exposed to air, the activity may become as great as 2800 n/sec-c. Also, 1 c of polonium when in an intimate mixture with beryllium has a γ output equivalent to 0.12 mg of radium or about 1.1 r/hr at 1 cm when unshielded.

(5) There is 0.64 mm^3 of radon gas in transient equilibrium with 1 c of radium.

(6) When sampling air contaminated by radioactive noble gases with filter paper, the efficiency of the collection may be very inconsistent due to variations in adsorption of the decay products on dust and on the filter, zones of gas concentrations, equilibrium state, etc. For example, certain conditions around a homogeneous reactor result in a collecting efficiency of 5% for airborne activity (multiply the count on HV–70 paper by 20).

(7) The dose rate from fission products at any time t can be represented by

$$\text{r/unit time} = I_1 t^{-1.2}$$

Where I_1 is the dose rate at unit time, and t is in the same time units (Glasstone, *The Effects of Nuclear Weapons*).

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Appendix D

ABBREVIATIONS

Å	Angstrom unit
A	atomic weight
ALOO	Albuquerque Operations Office
amu	atomic mass unit
B.G.	background
BTU	British Thermal Unit
c	curie
° C	degrees Centigrade
cal	calorie
cfm	cubic feet per minute
c/g	curies per gram
cm	centimeter
cm^2	square centimeter
cm^3, cc	cubic centimeter
c/m	counts per minute
d	day
d/m	disintegrations per minute
drs	daughters
d/s	disintegrations per second
e	natural logarithm base
esu	electrostatic unit
ev	electron volt
° F	degrees Fahrenheit
f.p.	fission product
ft	foot
ft^2	square foot
ft^3	cubic foot

g	gram
gal	gallon
G-M	Geiger-Müller
h, hr	hour
HVL	half-value layer
i.p.	ion pair
in.	inch
in.^{2}	square inch
in.^{3}	cubic inch
ITF	intermediate tolerance factor
kev	thousand electron volt
kg	kilogram
km	kilometer
kv	kilovolt
kwh	kilowatt-hour
L	liter
LASL	Los Alamos Scientific Laboratory
lb	pound
LET	linear energy transfer
M	meter
M^2	square meter
M^3	cubic meter
m, min	minute
mc	millicurie
Mev	million electron volt
mg	milligram
mi	mile
mi^2	square mile
mi^3	cubic mile
mil	one-thousandth inch
ml	milliliter
mm	millimeter
MPC	maximum permissible concentration
MPD	maximum permissible dose
MPE	maximum permissible exposure
mrhM	milliroentgens per hour at 1 meter

n	neutron
O.D.	outside diameter
oz	ounce
PHS	pulse height selector
ppm	parts per million
psi	pounds per square inch
qt	quart
r	roentgen
RBE	relative biological effectiveness
rhM	roentgens per hour at 1 meter
s, sec	second
STP	standard temperature and pressure (0° C, 760 mm Hg)
T	effective half-life
T_b	biological half-life
T_r	radioactive half-life
TVL	tenth-value layer
W	electron volt per ion pair
wk	week
y, yr	year
Z	atomic number

Greek Letter Symbols

α	alpha particle
β	beta particle
γ	gamma ray
ρ	(rho) density
μ	(mu) micron, absorption coefficient, "micro" prefix
λ	(lambda) decay constant
τ	(tau) mean life

Appendix E

CONVERSION FACTORS*

Multiply →	*by* →	*To obtain*
To obtain ←	*by* ←	*Divide*

LENGTH

Å	10^{-8}	cm
	10^{-10}	M
mm	10^{-1}	cm
cm	0.3937	in.
	10^{-2}	M
M	39.37	in.
	3.2808	ft
	1.0936	yd
	10^{-3}	km
	6.2137×10^{-4}	mi
km	3280.8	ft
	0.62137	mi
mi	5280	ft
	1760	yd
micron (μ)	10^{-3}	mm
	10^{-4}	cm
	10^{-6}	M
	3.937×10^{-5}	in.
mil	10^{-3}	in.
	2.54×10^{-3}	cm

AREA

cm^2	0.155	$in.^2$
	1.076×10^{-3}	ft^2
	10^{-4}	M^2

*Accuracies are given to several more decimal places than ordinarily necessary. For everyday use, three significant figures are adequate. Examples of three "significant" figures are: 0.000412, 4.12, 41200.

Multiply →	*by* →	*To obtain*
To obtain ←	*by* ←	*Divide*

AREA—Continued

M^2	1550	$in.^2$
	10.76	ft^2
	1.196	yd^2
	3.861×10^{-7}	mi^2
mi^2	2.7878×10^7	ft^2
	3.0976×10^6	yd^2
	640	acre
acre	4.356×10^4	ft^2
barn	10^{-24}	cm^2
circular mil	7.854×10^{-7}	$in.^2$

VOLUME

cm^3 (cc)	0.99997	ml
	6.1023×10^{-2}	$in.^3$
	10^{-6}	M^3
	9.9997×10^{-4}	liter
	3.531×10^{-5}	ft^3
liter	33.8147	fluid oz
	1.05671	liquid qt
	0.26418	gal
	3.5316×10^{-2}	ft^3
M^3	6.1023×10^4	$in.^3$
	35.31	ft^3
	9.9997×10^2	liter
gal	231	$in.^3$
	0.13368	ft^3
ft^3	1728	$in.^3$

TIME

day	1440	min
	8.640×10^4	sec
calendar year (365 days).	3.1536×10^7	sec
	5.256×10^5	min
	8.760×10^3	hr

Multiply →	*by* →	*To obtain*
To obtain ←	*by* ←	*Divide*

TIME—Continued

work week	1.44×10^{5}	sec
	40	hr
work month	4.2	work week
	168	hr
shake	10^{-8}	sec

MASS

mg	10^{-3}	g
	3.527×10^{-5}	oz av.
	1.543×10^{-2}	grain
g	3.527×10^{-2}	oz av.
	10^{-3}	kg
kg	2.2046	lb
lb	16	oz av.
	453.592	g

DENSITY

g/cm^3	3.613×10^{-2}	$lb/in.^3$
	62.43	lb/ft^3

PRESSURE

g/cm^2	1.4223×10^{-2}	$lb/in.^2$
bar	10^{6}	$dynes/cm^2$
$dyne/cm^2$	1.4504×10^{-5}	$lb/in.^2$
	1.0197×10^{-3}	g/cm^2
$lb/in.^2$ (psi)	27.673	in. of water (4° C)
	2.3066	ft of water (39.1° F)
	2.0360	in. Hg (32° F)
atmosphere (sea level).	1.0133	bar
	1.0332×10^{3}	g/cm^2
	14.696	$lb/in.^2$
	760	mm Hg (32° F)
	29.921	in. Hg (0° C)

Multiply →	*by* →	*To obtain*
To obtain ←	*by* ←	*Divide*

WORK AND ENERGY

erg	6.24×10^{5}	Mev
	1	dyne-cm
	10^{-7}	joule
	10^{-7}	watt-sec
ev	10^{-6}	Mev
	10^{-3}	kev
	1.60207×10^{-12}	erg
atomic mass unit (amu).	931.162	Mev
	1.6596×10^{-24}	g

RADIOLOGICAL UNITS

rad	100	erg/g
(W=34 ev/i.p.)	8.07×10^{4}	Mev/cc air STP
	2.37×10^{9}	i.p./cc air STP
	10^{-5}	watt-sec/g
	6.24×10^{7}	Mev/g
r	98	erg/g soft tissue
(W=34 ev/i.p.)	87.7	erg/g air
	2.08×10^{9}	i.p./cc air STP
	1.61×10^{12}	i.p./g dry air
	7.08×10^{4}	Mev/cc air STP
	5.47×10^{7}	Mev/g dry air
	1	esu/cc air STP
rep	93	erg/g tissue
(W=32.5 ev/i.p.)		
curie (c)	3.7×10^{10}	dis/sec (d/s)
	10^{12}	$\mu\mu$c
	10^{6}	μc
	10^{3}	mc
μc/cc (μc/ml)	2.22×10^{12}	d/m-M^3
	2.22×10^{9}	d/m-L
d/m-M^3	4.5×10^{-1}	$\mu\mu$c/M^3

Multiply	→	*by*	→	*To obtain*
To obtain	←	*by*	←	*Divide*

MISCELLANEOUS CONVERSION

ampere	2.998×10^9	esu/sec
	6.25×10^{18}	electrons/sec
gram-calorie	4.185×10^7	erg
radian	57.296	degree
temperature	°C = (°F − 32)/1.8	
	°F = 1.8° C + 32	
kev to Å	kev = 12.4/Å	

Appendix F

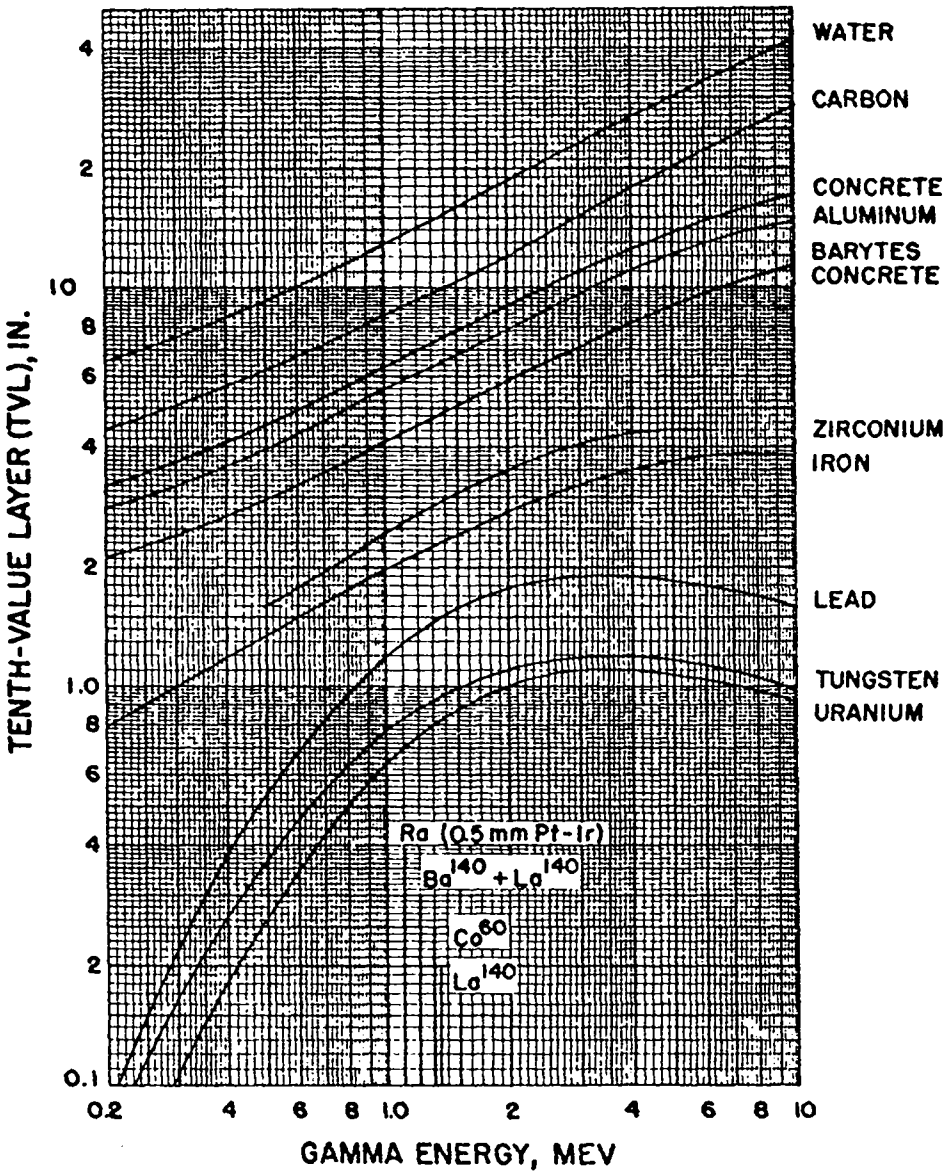
FUNDAMENTAL CONSTANTS*

Avogadro's number (N)	6.025×10^{23} atoms/mole
electron charge	4.803×10^{-10} esu
electron rest energy	0.5110 Mev
electron rest mass	9.108×10^{-28} g
	0.5488×10^{-3} amu
electron radius (classical)	2.818×10^{-13} cm
gravitational acceleration	32.174 ft/sec^2
	980.665 cm/sec^2
hydrogen atom mass	1.008142 amu
natural logarithm base (e)	2.7182818285
neutron mass	1.008982 amu
pi (π)	3.1415926536
Planck's constant	6.625×10^{-27} erg-sec
proton mass	1.007593 amu
ratio of proton mass to electron mass	1836.1
velocity of light in vacuum	2.99793×10^{10} cm/sec
velocity of sound in air (STP)	331.45 meters/sec
	0.206 mi/sec
volume of 1 mole ideal gas (STP)	22.4208×10^{3} cc

*From DuMond and Cohen, *Revs. Modern Phys. 25*, 691 (1953).

Appendix G

NARROW BEAM GAMMA-RAY ATTENUATION (APEX 176)



F

G

The graph gives the amount of material (TVL) to reduce γ's of known energy to $\frac{1}{10}$ their unshielded intensity. Effective energies for narrow beam shielding purposes are indicated for several common γ emitters. Linear absorption coefficients (cm^{-1}) can be obtained from the curves using the following relation:

$$\mu(cm^{-1}) = \frac{0.904}{TVL(in.)}$$

To obtain other narrow beam attenuation factors, multiply the TVL by the $\log_{10}$ of the desired attenuation factor.

Example: To find the amount of lead to give an attenuation factor of 2 for 1-Mev γ's, multiply the TVL, which is 1.2 in., by $\log_{10}$ of 2, which is 0.301. $0.301 \times 1.2 = 0.36$ in.

Appendix H

BROAD BEAM GAMMA-RAY ATTENUATION (WITH BUILDUP)*

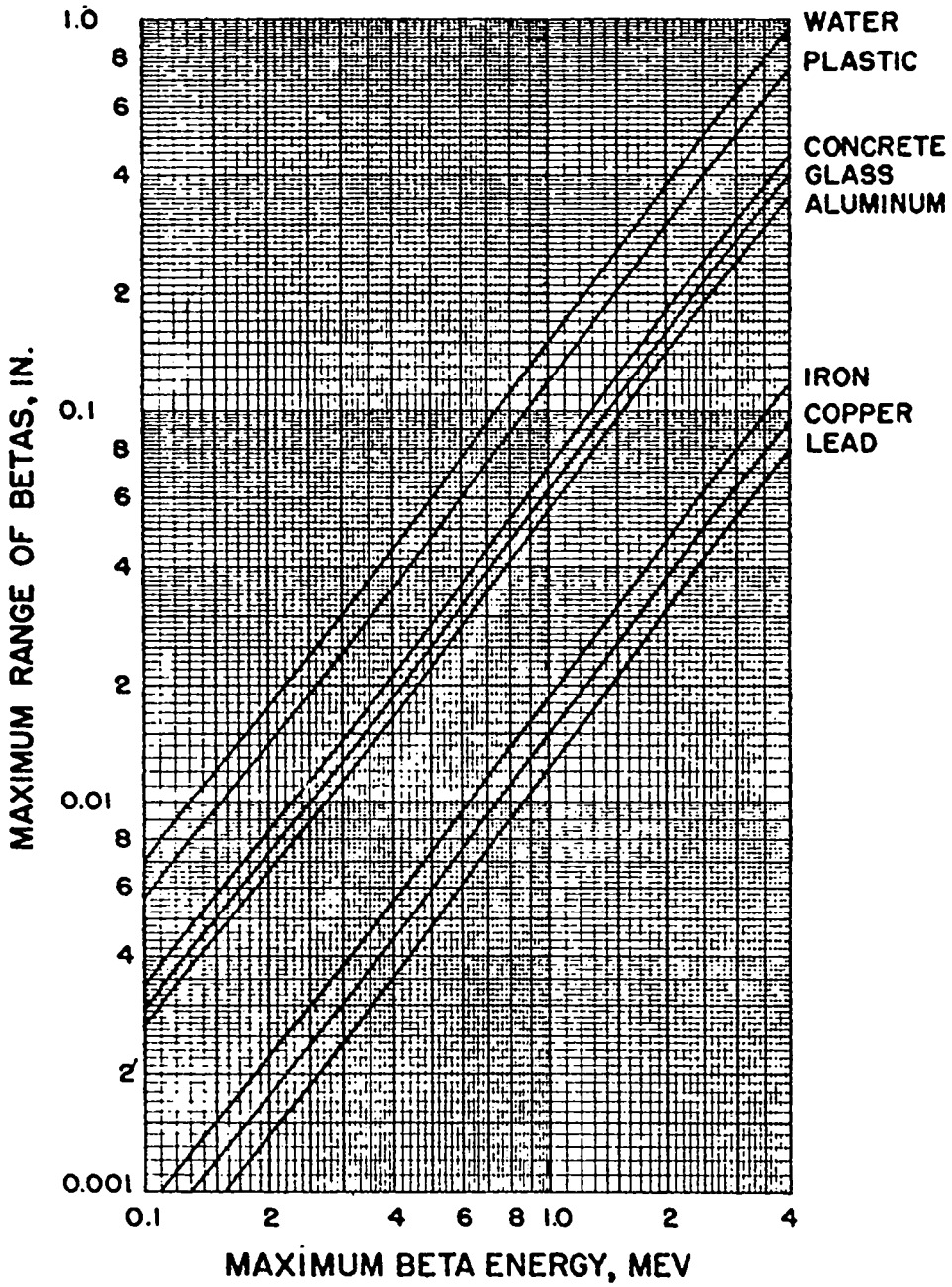
Isotope	Shield material	Inches of shield material					
La^{140}	Water	26	46	62	83	106	-------
	Aluminum†	10.5	19	28	35	43	50
	Iron	3.6	6.6	9.6	12.2	15.2	-------
	Lead	1.8	3.7	5.5	7.4	9.4	-------
	Uranium	1.1	2.1	3.2	4.2	5.3	6.3
Co^{60}	Water	26	44	62	77	98	-------
	Aluminum†	10.6	18	26	32	39	46
	Iron	3.6	6.2	8.8	11.1	13.7	-------
	Lead	1.8	3.4	4.8	6.5	8.3	-------
	Uranium	1.0	1.9	2.7	3.5	4.4	5.2
$Ba^{140}+La^{140}$	Water	25	45	65	82	105	-------
	Aluminum†	9.7	19	27	35	43	50
	Iron	3.4	6.4	9.2	12.0	14.9	-------
	Lead	1.6	3.6	5.3	7.2	9.2	-------
	Uranium	.96	2.1	3.1	4.1	5.2	6.2
Ra^{226} (in equilibrium with drs, encased in 0.5 mm Pt-Ir).	Water	25	44	64	81	104	-------
	Aluminum†	9.8	18	27	35	44	51
	Iron	3.4	6.4	9.2	11.8	14.8	-------
	Lead	1.6	3.4	5.2	7.1	9.0	-------
	Uranium	.87	2.0	3.0	4.1	5.2	6.3
Attenuation factor		10	10^2	10^3	10^4	10^5	10^6

*Calculated from data of Fano (as plotted in AERE HP/L23) and recent values for spectra energies, relative intensities, and attenuation coefficients. Figures are probably conservative as buildup values were calculated for inside an infinite shield.

†Reasonable approximation for ordinary concrete.

Appendix I

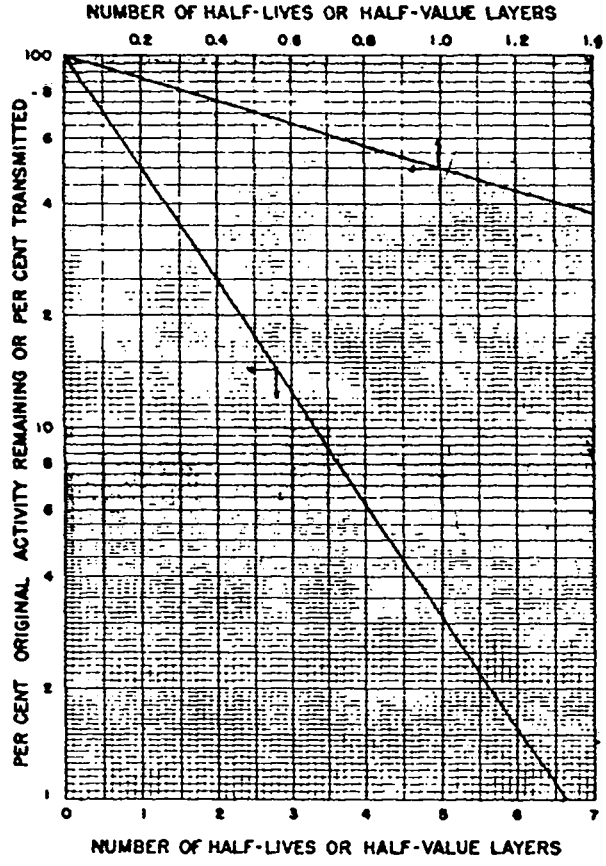
BETA-RAY SHIELDING



The graph shows the maximum range of beta particles in various common materials (AECU–1673).

Appendix J

SEMILOG PLOT FOR RADIOACTIVE DECAY AND NEUTRON ATTENUATION



To find the per cent original activity remaining, divide the elapsed time by the half-life in similar units. Read from the curve the per cent original activity remaining.

Example: What per cent Po^{210} (half-life 138 days) remains after 40 days? 40/138 = 0.29; 0.29 on the curve yields 82% remaining.

Using 6.93 and 3.2 cm as approximate half-value layers (HVL) for 4 to 5 Mev and 1-Mev neutrons, respectively, the per cent radiation transmitted may be similarly calculated. An example is given in Section 4, subhead Neutron Shielding.

Appendix K

SOURCES OF NEUTRONS

Source	Reaction	Average neutron energy (Mev)	Yield* (n/sec-c)	Characteristic problems
Accelerators	$H^3(p,n)He^3$	0.7, 3.2†		γ, tritium
	$H^2(d,n)He^3$	2.45‡		γ
	$H^3(d,n)He^4$	14.1‡		γ, tritium
	$Li^7(d,n)Be^8$	13 3‡		γ
Critical Assemblies and Reactors.	fission	Fission spectrum~1.		γ, f.p., α
Mock Fission (Po+Be+B+F+Li).	α,n	~fission spectrum.	$\sim 4\times10^5$	α
Na^{24}+Be	γ,n	0.83	1.3×10^5	γ
$Na^{24}+D_2O$	γ,n	0.22	2.7×10^5	γ
Mn^{56}+Be	γ,n	0.1(90%), 0.3(10%)	2.9×10^4	γ
$Mn^{56}+D_2O$	γ,n	0.22	3.1×10^5	γ
Ga^{72}+Be	γ,n	0.78	5×10^4	γ
$Ga^{72}+D_2O$	γ,n	0.13	6×10^4	γ
Y^{88}+Be	γ,n	0.16	1×10^5	γ
Y^{88}+D	γ,n	0.31	3×10^5	γ
In^{116}+Be	γ,n	0.30	8.2×10^5	γ
Sb^{124}+Be	γ,n	0.024	1.9×10^5	γ
La^{140}+Be	γ,n	0.62	3×10^5	γ
$La^{140}+D_2O$	γ,n	0.15	8×10^5	γ
MsTh+Be (Ra^{228}+Be).	γ,n	0.83	3.5×10^4	γ
MsTh+D_2O ($Ra^{228}+D_2O$).	γ,n	0.20	9.5×10^4	γ
Ra+Be	γ,n	spectrum	3.0×10^4	α, γ, Rn
Ra+Be	α,n	~5	1.7×10^7	α, γ, Rn
Ra+B	α,n	3	6.8×10^6	α, γ, Rn
$Ra+D_2O$	γ,n	0.12	1.0×10^5	α, γ, Rn
Rn^{222}+Be	α,n	5	1.5×10^7	α, γ, Rn
Po^{210}+Be	α,n	4	3×10^6	α
Po^{210}+B	α,n	2.5	$\sim 9\times10^5$	α
Po^{210}+F	α,n	1.4	$\sim 4\times10^5$	α

See footnotes at end of table.

SOURCES OF NEUTRONS—Continued

Source	Reaction	Average neutron energy (Mev)	Yield* (n/sec-c)	Characteristic problems
Po^{210}+Li	α,n	0.42	$\sim 9\times 10^{4}$	α
Ac^{227}+Be	α,n			α
Pu^{239}+Be	α,n	4	10^{6}	α
Cf^{252}	spon. fission	fission spectrum~1	10^{6}	α

*For photoneutron sources (γ,n reactions), "Standard Yield" is given, i.e., 1 g of target material at 1 cm from 1 c of γ emitter. Higher yields are possible. For (α,n) reactions, yields are for an infinite ratio of target material to α emitter. In this case achievable yields are lower.

†Forward direction energies with 1.5- and 4-Mev protons, respectively.

‡Energies are for low (a few hundred kev) projectile energies. Higher energy projectiles will produce higher energy neutrons.

Appendix L

DENSITIES OF COMMON MATERIALS*
(g/cm^3)

Air	0.001293	Iron	7.86
Water	1.00	Copper	8.9
Carbon	2.25	Lead	11.35
Concrete	2.3–3.0	Uranium	18.7
Aluminum	2.7	Platinum (Iridium 10%)	21.5

*Values derived from several standard references.

Appendix M

BIOLOGICAL RESPONSE TO RADIATION

Dose (r)	Dose rate	Exposed area	Biological response
0.3	Weekly	Total body	Probably none.
1.5	Weekly	Hands	Probably none.
25	Single dose	Total body	Recognizable blood changes.
200	Single dose	Total body	Nausea.
300	Single dose	Local	Erythema (100 kv).
300–500	Single dose	Total body	LD_{50}.
300–600	Single dose	Ovaries	Sterilization.
400–500	10–50 r/day	Total body	Clinical recovery.
500	Single dose	Local	Erythema (200 kv).
600–800	Single dose	Testes	Sterilization.
1000	Single dose	Local	Erythema (radium).

Appendix N

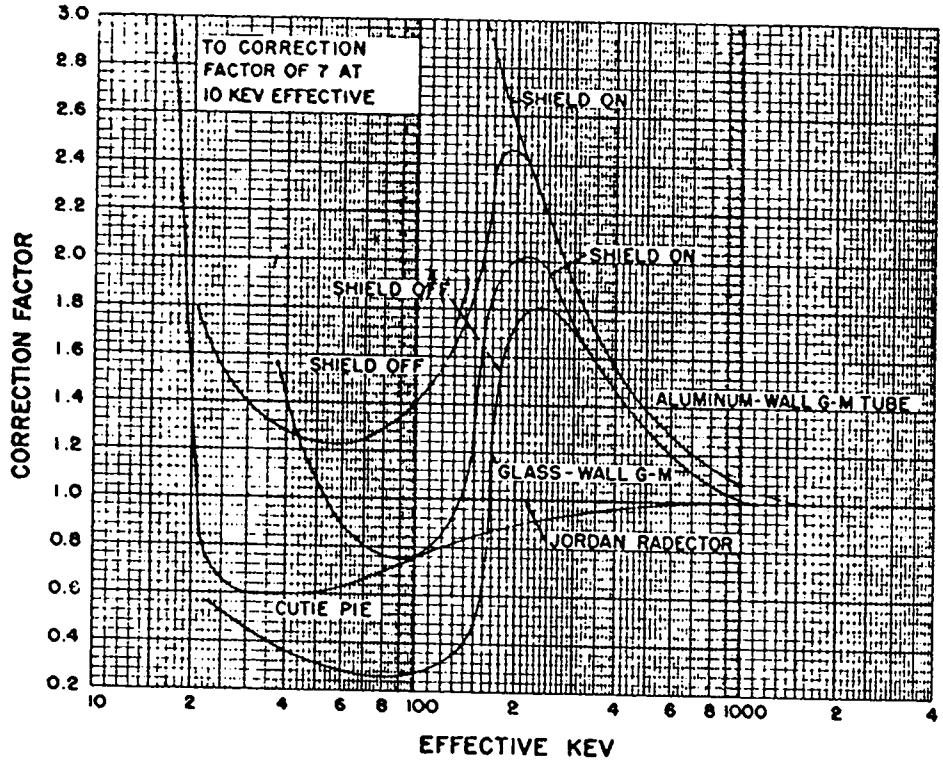
DIAGNOSTIC X-RAY DOSES*

Type of examination	Dose to examined part, r/examination	Dose to gonads, mr/examination	
		Male	Female
Chest	0.006–0.03	0–0.01	0–0.02
Chest (mini-film)	0.2–1.25	1	3
Barium enema	1.25	40–130	20–520
Gall bladder	1.0	1.8	15.6
Genitourinary	1–2	100	200
Lumbar spine	1–2	0–24	40–225
Teeth (whole mouth)	3–5	5	1
Fluoroscopy (small field)	7.5 r/min (some much higher).	2,000 normal examination.	2,000 normal examination.

*The dosages in this table are given for comparison purposes. The values are limits or averages of reported values and are not necessarily typical.

Appendix O

ENERGY DEPENDENCE CORRECTION FACTORS FOR MONITORING INSTRUMENTS



Multiplying by the proper correction factor corrects the instrument to air or tissue response. Values are approximate averages of data from various NBS reports and HW-31781. Pocket dosimeters demonstrate curves similar to the Cutie Pie curve.

Appendix P

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Appendix Q

GLOSSARY

The definitions included in this Glossary are from several sources including the *Glossary of Terms in Nuclear Science and Technology*. Many definitions have been specifically created for this handbook and are not necessarily complete or accurate for other than monitoring purposes.

Absorbed Dose (rad). The absorbed dose of any ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest.

Absorbed Dose Rate (rads/unit time). The absorbed dose per unit time.

Absorption. Often used when attenuation is meant. Although its manifestation is similar to attenuation (and certainly attenuation often involves absorption processes), absorption refers specifically to processes by which radiation disappears or is transformed.

Adsorption. The adhesion of one substance to the surface of another. Tritium is often adsorbed on zirconium accelerator targets.

Air Dose (free air dose). A dose of radiation measured in air at the point of interest in the absence of patient (or phantom) or other object, thus excluding secondary radiation apart from that arising from the air or associated with the source.

Alpha Particle (α). A helium nucleus consisting of 2 protons and 2 neutrons with a double positive charge. Mass about 4 amu.

Associated Corpuscular Emission. The full complement of secondary charged particles (usually limited to electrons) associated with an X- or γ-ray beam in its passage through air. The full complement of electrons is obtained after the radiation has traversed sufficient air to bring about equilibrium between the primary photons and secondary electrons. Electronic equilibrium with the secondary photons is intentionally excluded.

Atom. The smallest particle of an element which is capable of entering into a chemical reaction.

Atomic Number (Z). Number of orbital electrons in a neutral atom, or the electric charge on the nucleus of an atom, or the number of protons in the atomic nucleus.

Atomic Mass Unit (*amu*). $\frac{1}{16}$ of the mass of one neutral O^{16} atom.

Atomic Weight (A). The relative weight of an atom of an element compared with the weight of one atom of oxygen taken as 16. A multiple of $\frac{1}{16}$ of the weight of an atom of oxygen.

Attenuation. The process by which primary quanta or particles are reduced in number on passing through some medium.

Background (*B.G.*). Normally refers to radiation due to cosmic rays, radioactive materials in earth or building materials, and the slight radioactive contamination of the instrument materials.

Backscattered Radiation. Radiation normally proceeding in a direction so as not to be detected, that is, scattered or reflected into the detector from source backings (as in accurate scaler counting), from the body (as on a film badge), etc. The magnitude of the effect is dependent on the type and energy of the radiation, the geometrical arrangement, and the scattering material.

Beta Particle (β). A singly charged particle emitted from the nucleus of an atom and having a mass at rest equal in magnitude to the electron at rest.

Betatron. A circular electron accelerator providing a pulsed beam of high energy electrons or X rays.

Body Burden, Maximum Permissible (q). The amount of radioactive material in the critical organ so it is receiving 0.3 rem/wk; or in the case of an α or β emitter that deposits in the bone, body burden is derived from the long established maximum permissible body burden of radium, 0.1 μc, adjusted for possible less uniform deposition. See Section 10.

Bremsstrahlung. The production of electromagnetic radiation by the deceleration of a charged particle, usually an electron, while passing through matter. Examples are the continuous spectrum from an X-ray tube, and the electromagnetic radiation often noted from pure β emitters such as P^{32} and Sr^{90}.

Chain Reaction. A chemical or nuclear process in which some of the products of the process or energy generated by the process proceed to continue or magnify the process.

Characteristic (discrete) Radiation. The essentially monochromatic radiation emitted by an atom when an orbital electron is removed or following excitation of the atom. Each element may emit a number of characteristic radiations, each of a constant wavelength and different from the characteristic radiations of all other elements.

Collimation. Confining a beam of particles or rays to a defined cross-section.

Collision. A close approach of particles or photons during which there is an interchange of energy, momentum, or charge.

Collision, Elastic. A billiard ball type collision in which energy and momentum are conserved and in which there is no change in the internal energy of the colliding objects.

Collision, Inelastic. A collision in which there are changes in both internal energy and kinetic energy of the colliding systems.

Compton Effect. The interaction of a photon with matter wherein part of the photon energy is transferred to an orbital electron of an atom, the photon proceeding with altered direction and diminished energy. The electron is excited and ejected from the atom. The Compton effect is an important effect in the attenuation of X or γ rays, being especially effective for low and intermediate energy photons and for light shielding materials.

Cosmic Rays. Penetrating ionizing radiation, both particulate and electromagnetic, originating in outer space. Secondary cosmic rays, formed by interactions in the earth's atmosphere, add to the general background radiation and contribute perhaps 1 rad or more to the gonads of each individual of the general population in 30 years.

Count (as in counts/minute). The external indication of a device numerating ionizing events. The term is often used incorrectly to mean a disintegration.

Counting Error. Specifies the reliability of a measurement.

Counting Rate Meter. A device which gives a continuous indication of the average number of ionizing events detected. Most

survey instruments have a counting rate meter incorporated with a suitable detector.

Critical Organ. The body organ receiving the radionuclide that results in the greatest over-all damage to the body. Usually, but not necessarily, it is the organ receiving the greatest concentration or the organ receiving the greatest damage.

Critical Size. The minimum amount of a fissionable material which will support a chain reaction.

Curie (*c*). Amount of radioactive material defined as the quantity of any radioactive material in which the number of disintegrations per second is 3.700×10^{10}.

Cyclotron. A device for accelerating charged particles to high energies by means of an alternating electric field between electrodes placed in a constant magnetic field.

Decay Constant (λ). The fraction of the number of radioisotope atoms which decay in unit time. Decay constant is $0.693/T_r$ where T_r is the half-life.

Decay Product. A nuclide resulting from the radioactive disintegration of a radionuclide or series of radionuclides. A decay product may be either stable or radioactive.

Decay, Radioactive. Disintegration of the nucleus of an atom by the spontaneous emission of a particle or a photon.

Densitometer. An instrument to measure the blackening of photographic film. Used in the evaluation of personnel film dosimeters.

Density (*photographic*). A measure of the degree of darkening of photographic film.

Density (*physical*). The weight of a substance per unit volume; e.g., g/cm^3 or lb/ft^3.

Depth Dose. The radiation dose delivered at a depth below the surface of a body or phantom. Often expressed as a percentage of surface dose or air dose.

Deuterium (*D or* $_1H^2$). A heavy, stable isotope of hydrogen having 1 proton and 1 neutron in the nucleus.

Deuteron (*d*). The nucleus of a deuterium atom. Mass about 2 amu.

Disintegration. Process of spontaneous breakdown of a nucleus of an atom resulting in the emission of a particle and/or a photon. The rate of disintegration of a quantity of any

radioactive nuclide is a function of the number of atoms present and a disintegration or decay constant characteristic of the nuclide concerned.

Disintegration Constant. See *Decay Constant.*

Dose. A quantity of radiation.

Dose Rate. Radiation dose received per unit time.

Dosimeter. Instrument that measures radiation dose. The term usually intimates an integrating device to be worn by an individual.

Effective Atomic Number. A number calculated from the composition and atomic numbers of a compound or mixture. An element of this effective atomic number would interact with photons in the same way as the compound or mixture.

Efficiency. A factor used to convert the counting rate of a detector to the disintegration rate of the radioactive material counted. Since usage and factors involved vary considerably with different detectors, it is well to ascertain which factors (window transmission, sensitive volume, energy dependence, etc.) are included in a stated efficiency.

Electron. Negatively charged particle of 0.000548 amu. A fundamental constituent of atoms. Rest mass approximately 1/1836 of the hydrogen atom. Has an electric charge of 4.8×10^{-10} esu.

Electron Capture. A mode of radioactive decay in which an orbital electron merges with the nucleus. Process is followed by emission of an electron or photon.

Electron Volt (ev). Unit of energy. The change in kinetic energy of an electron when it is accelerated through a potential difference of 1 volt.

Electromagnetic Radiation. For purposes of this Glossary, X or γ rays.

Electronic Equilibrium. The condition in which as many electrons are stopped as are produced in a slice of material when the material is under irradiation by photons.

Element. Substance consisting entirely of atoms of the same atomic number. Cannot be decomposed by ordinary chemical means.

Emulsion, Nuclear. A photographic emulsion designed to permit microscopic examination of tracks produced by ionizing par-

ticles. Counting proton recoil tracks yields measure of personnel fast neutron exposure.

Energy. The ability to do work. Energy (E) is the force (f) acting on a body to produce motion, multiplied by the distance (S) through which the force acts and the cosine of the angle (θ) between the direction of force and the direction of motion. $E=fS\cos\theta$. *Potential energy* is energy due to relative position, for example an elevated weight. *Kinetic energy* is energy due to motion, a speeding auto or electron. Energy is measured in ergs, joules, ev, Mev, etc.

Energy Dependence. The characteristic response of a radiation detector to a given energy as compared with some standard response. For γ survey instruments, radium or Co^{60} is often used as standard.

Enriched Uranium. Uranium in which the abundance of U^{235} (and also U^{234}) is increased above normal. Oralloy (Oy) is enriched uranium.

Erythema. An abnormal redness of the skin caused by a variety of agents including ionizing radiations.

Exposure Dose (r). A measure of the X or γ radiation at a certain place based upon its ability to produce ionization. The unit is the roentgen (r).

Exposure Dose Rate (r/unit time). The exposure dose per unit time.

Extrapolation Ionization Chamber. An ionization chamber designed to arrive at a value of surface dose or zero volume dose by a series of measurements approaching the desired values as a limit.

Extremities. The hands and forearms, and, with restrictions, the head, feet and ankles. Permissible exposures in these regions are generally greater as they contain less blood-forming material and have smaller volume for energy absorption than other body parts.

Film Dosimeter. A pack of photographic film and appropriate filters used for the detection of ionizing radiation exposure to the individual wearing the dosimeter.

Fission, Nuclear. The division of a heavy nucleus into two approximately equal parts. Fission is usually induced by neutrons but can be induced by photons or charged particles.

Some very heavy elements undergo *spontaneous fission*, i.e., fission without particles or photons entering from the outside.

Fluorescence. Phenomenon involving the absorption of radiant energy by a substance and its re-emission, during the period of radiation excitation, as visible or near visible light.

Flux. A rate of flow of radiation across a unit area normal to the direction of flow. For example, neutron flux is measured in the number of neutrons that cross 1 cm^2 each second.

Free Air Ionization Chamber. An ionization chamber for standardization of X-ray beams (5 to 400 kev) in which the beam passes through the chamber without interactions with electrodes or other internal parts of the equipment.

Frequency. Number of cycles, revolutions, or vibrations completed per unit time.

Fusion (thermonuclear reaction). A nuclear reaction characterized by joining together of light nuclei to form heavier nuclei, the energy for the reactions being provided by kinetic energy derived from violent thermal agitation of particles at very high temperatures. If the colliding particles are properly chosen and the agitation violent enough, there will be a release of energy from the reaction. The energy of the stars is believed to be derived from such reactions.

Gamma Ray (γ). High frequency (short wave length) electromagnetic radiation emitted by the nucleus of an atom. Identical in nature with X rays of the same wave length.

Geiger-Müller (G–M) Tube. A gas-filled chamber operated with a voltage such that a discharge triggered by a primary ionizing event will spread over the entire anode.

Genetic Effect of Radiation. Inheritable changes (mutations) produced by the absorption of ionizing radiations, particularly by the gonads. Effects are apparently additive with no recovery.

Gram-Rad. The unit of integral absorbed dose. One gram-rad = 100 ergs.

Grenz Rays. X rays produced at voltages of 5 to 20 kv.

Half-Life, Biologic (T_b). The time required for the body to eliminate half of the material taken into the body by natural biological means.

Half-Life, Effective (T). Half-life of a radioactive isotope in a biologic organism resulting from a combination of radioactive

decay and biologic elimination. It is related to radioactive half-life (T_r) and biologic half-life (T_b) by

$$T=\frac{T_b \times T_r}{T_b+T_r}$$

Half-Life, Radioactive (T_r). The time required for a radioactive substance to lose one-half of its activity by decay. It is related to the mean life (τ) and its disintegration constant (λ) as follows:

$$T_r=\frac{\ln 2}{\lambda}=\frac{0.693}{\lambda}=0.693\tau$$

Half-Value Layer (*HVL*). Amount of shielding material necessary to reduce radiation level by a factor of 2. One HVL is equivalent to 0.3 TVL.

Homogeneous Radiation. Beam or flux of radiation consisting of same kind and energy.

Induced Radioactivity. Radioactivity that is produced by nuclear reaction, often by neutron bombardment.

Integral Absorbed Dose. The energy imparted to matter by ionizing particles in a certain region of interest. The unit is the gram-rad and is equal to 100 ergs.

Intensity of Radiation (*radiant flux density*). The energy per unit time entering a small sphere of unit cross-sectional area centered at the place of interest. The unit may be ergs/cm²-sec or watts/cm².

Internal Conversion. A mode of radioactive decay in which the γ rays from excited nuclei cause the ejection of orbital electrons from the atom.

Ion. Atomic particle, atom, or chemical radical (group of chemically-combined atoms) bearing one or more electron charges of either sign.

Ionization. The process wherein ions are produced.

Ionization Chamber. An instrument for measuring quantity of radiation as a function of the ionization produced by the radiation and associated corpuscular emission in a defined volume of gas, usually air.

Ionizing Radiation. Electromagnetic radiation (X- or γ-ray photons or quanta) or corpuscular radiation (α particles,

β particles, electrons, positrons, protons, neutrons, and heavy particles) capable of producing ions by direct or secondary processes.

Isobar. One of several nuclides having the same number of nucleons in their nuclei, and hence having about the same atomic masses. For example, P^{32} and S^{32} are isobars.

Isodose Curve. A curve depicting points of identical radiation dosage in an area or medium.

Isomer. One of several nuclides having the same mass and atomic numbers but existing for measurable times in different energy states. The lowest energy state is called the ground state; those of higher energies are *metastable states.*

Isotone. One of several nuclides having the same number of neutrons in their nuclei. For example, K^{39} and Ca^{40}.

Isotope. One of several nuclides having the same number of protons in their nuclei and hence belonging to the same element but differing in the number of neutrons and therefore in mass number (A). For example, C^{11}, C^{12}, C^{14}.

K-Electron Capture. The process wherein an electron in the K-shell of an atom is captured by the nucleus during a nuclear reaction. In the process, a characteristic X ray is emitted.

Kilo-. Prefix indicating 1,000 as in kilogram, kilocurie, kilometer.

LD–50 or LD_{50} Dose. Dose of radiation required to kill, within a specified period, 50% of the individuals in a large group of animals or organisms.

Lead Equivalent. The thickness of lead affording the same protection under specified conditions as the material in question.

Linear Absorption Coefficient. A factor expressing the fraction of a beam of radiation absorbed in unit thickness of material. In the expression $I = I_o e^{-\mu x}$, I_o is the initial intensity, I the intensity after passage through a thickness of material x, and μ is the linear absorption coefficient. The coefficient may be divided into a number of components, one for each of the γ-ray absorption processes. If x is in cm, μ is in cm^{-1}.

Linear Accelerator. A device for accelerating particles employing alternate electrodes and gaps arranged in a straight line, so proportioned that when their potentials are varied in the proper amplitude and frequency, particles passing through them receive successive increments of energy.

Linear Energy Transfer (*LET*). The linear rate of loss of energy (locally absorbed) by an ionizing particle traversing a material medium. It may be expressed in kev/μ.

Mass Absorption Coefficient. The linear absorption coefficient in cm^{-1} divided by the density of the absorber in grams per cc. It is frequently expressed as μ/ρ, where μ is the linear absorption coefficient and ρ the absorber density.

Mass Number (*A*). The number of nucleons (neutrons and protons) in the nucleus of an atom.

Maximum Permissible Accumulated Dose (*MPD*). For occupational exposures, MPD$=5(N-18)$ where N is the age greater than 18 years. See Section 9.

Maximum Permissible Concentration (*MPC*). The concentration of an isotope in air (MPC_a) or water (MPC_w) that results under equilibrium conditions in the maintenance of a body burden of the isotope in the body except in the case of submersion in a radioactive gas. See Section 10.

Mean Free Path. The average distance a particle or photon travels between collisions. Mean free path$=$HVL/0.693.

Mean Life (τ). The reciprocal of the decay constant (λ).

Meson. Short-lived particle, charged or uncharged, having a mass in multiples of the electron mass.

Metastable State. See *Isomer.*

Moderator. Material used to moderate, i.e., slow down neutrons from high to lower energies. Moderators are used in reactors and with the converted PeeWee neutron instrument.

Molecule. Ultimate unit quantity of a chemical compound which can exist by itself and retain all the properties of the original substance.

Momentum. Quantity of motion as measured by the product of mass and velocity.

Monitoring. Periodic or continuous determination of the amount of ionizing radiation or radioactive contamination present in an area.

Monochromatic Radiation. Electromagnetic radiation of a single wavelength in which photons are all of the same energy.

Neutron (*n*). Elementary nuclear particle with a mass approximately the same as a hydrogen atom (about 1 amu) and carrying no electric charge.

Nucleon. A constituent of the atomic nucleus; according to present theory, a proton or neutron.

Nucleus. The heavy central part of an atom in which most of the mass and the total positive electric charge is concentrated.

Nuclide. A species of atom having a specific mass number (A), atomic number (Z), and energy state.

Pair production. An absorption process for X and γ radiation in which the incident photon is annihilated in the vicinity of the nucleus of the absorbing atom, with subsequent production of an electron and positron pair. This reaction does not occur for incident photon energies of less than 1.02 Mev.

Permissible Dose. Dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime.

Phantom (Radiology). A volume of material behaving in essentially the same manner as tissue, with respect to the radiation in question, used to simulate a portion of the human body, and into which radiation measuring devices may be placed. Measurements made in a phantom permit the determination of the radiation dose delivered to the skin and points within the body. Materials commonly used are water, Masonite pressed-wood (unit density), and beeswax.

Phosphorescence. Emission of radiation by a substance as a result of previous absorption of radiation of shorter wavelength. In contrast to fluorescence, the emission may continue for a considerable time after cessation of the exciting irradiation.

Photoelectric Effect. A process by which a photon ejects an electron from an atom. All the energy of the photon is absorbed in ejecting the electron and in imparting kinetic energy to it. This effect as an absorption process is large for low energy photons impinging on high Z elements.

Photon. Corpuscular (quantum) manifestation of electromagnetic radiation.

Photoneutron. A neutron released from a nucleus in a photonuclear reaction.

Photoneutron Source. Source of neutrons in which the nuclear reaction is induced by a γ ray or X ray impinging on a light element such as beryllium or deuterium.

Plateau. The range of counter-tube voltage (especially G–M tubes) for which there is an essentially constant counting rate.

Positron. Particle equal in mass, opposite in charge, to the electron.

Primary Radiation. Radiation arising directly from the target of an X-ray tube or from a radioactive source.

Prompt Gamma. γ radiation emitted at the time of fission of a nucleus.

Prompt Neutrons. Neutrons emitted during fission process.

Proton (*p*). An elementary particle with a positive charge having a mass of about 1 amu.

Quality. In radiography, the penetrating power of radiation and therefore a function of energy. Units are ergs/cm^2 or watts-sec/cm^2. Often expressed in terms of half-value layers of copper, aluminum, or lead.

Quantum. The smallest quantity of energy constituting a photon of electromagnetic radiation which can be associated with a given phenomenon.

Rad (*rad*). The unit of absorbed dose. It is 100 ergs/g of any material.

Radioactive Equilibrium. Among the members of a radioactive series, the state which prevails when the ratios between the amounts of successive members of the series remain constant. *Secular Equilibrium:* If a parent element has a very much longer half-life than the succeeding ones, so that there is no appreciable change in its amount in the time interval required for the later products to attain equilibrium, then, after the condition is reached, equal numbers of atoms of all members of the series disintegrate in unit time. This condition is never actually attained, but is essentially established in such a case as radium and its series through radium C. The half-life of radium is 1,622 years, of radon 3.82 days, and of each of the subsequent members, a few minutes. After about a month essentially the equilibrium amount of radon is present, and then for a long time all members of the series disintegrate the same number of atoms per unit time. *Transient Equilibrium:* If the half-life of the parent is sufficiently short, so that the quantity present decreases appreciably during the period under consideration, but is still longer than that of

successive members of the series, a stage of equilibrium will be reached, after which all members of the series decrease in amount exponentially with the period of the parent. An example of this is radon, with a half-life of 3.82 days, and the successive members of the series through radium C.

Radioactivity. Spontaneous disintegration of an unstable nuclide with emission of a particle or a photon to form a different nuclide.

Range (of α or β particles). The distance a particle will penetrate a given material before all its ionizing power is spent.

RBE Dose. The product of the absorbed dose in rads and an agreed conventional value of RBE with respect to a particular form of radiation effect. The standard of comparison recommended by the International Commission on Radiological Units and Measurements (ICRU) is X or γ radiation with a LET in water of 3 kev/μ delivered at a rate of about 10 rads/min. The unit of RBE dose is the rem. The RBE dose in rem = rads $\times$ RBE.

Reactor, Nuclear. A device in which nuclear fission may be sustained and controlled in a self-supporting nuclear reaction. The varieties are many, but all incorporate certain features including fissionable material or fuel, a moderating material (unless reactor is operated on fast neutrons), a reflector to conserve escaping neutrons, provision for removal of heat, measuring and control elements, and provision for personnel protection.

Relative Biological Effectiveness (RBE). The appropriate value of biological effectiveness of the radiation in question relative to that of X rays with an average specific ionization of 100 i.p./μ in water for the particular biological system and effect under consideration and for the condition under which the radiation is received.

Rem (rem). Rem = rads $\times$ RBE.

Rep (rep). Obsolete unit representing the amount of ionizing radiation that will result in the absorption in tissue of 93 ergs/g. The rad is now used in place of the rep, their magnitudes for monitoring purposes being the same.

Roentgen (r). An exposure dose of X or γ 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.

Scaler. An electronic device that produces an output pulse whenever a prescribed number of input pulses have been received.

Scattered Radiation. Radiation whose direction has been altered by an interaction with matter.

Scintillation Counter. The combination of a phosphor (converts ionizing particle energy to light pulse), a photomultiplier (converts light pulse to many electric pulses), and associated circuitry for counting the electric pulses.

Secondary Radiation. Radiation, electromagnetic or particulate, originating as the result of radiation attenuation in matter. *Examples:* Secondary cosmic rays, photoelectrons, recoil protons from neutron-proton collisions, and bremsstrahlung from radioactive isotopes.

Self-Absorption. Absorption by source material or material with which the radioactive atoms are closely mixed.

Sensitive Volume. The portion of a counter tube or ionization chamber that responds to a specific radiation.

Specific Activity. The total radioactivity of a given isotope per gram, given in c/g or d/s-g.

Specific Ionization. The number of ion pairs formed per unit path length of an ionizing particle passing through a medium. For example, i.p./μ of tissue, i.p./cm of air.

Surface Dose. The dose measured at the surface of a body. It is the sum of the air dose plus the dose due to backscatter from the object.

Tenth-Value Layer (TVL). Amount of shielding material required to reduce radiation level by a factor of 10. One TVL is equivalent to 3.3 HVL.

Tissue Dose. Absorbed dose when the irradiated medium is tissue.

Tissue Equivalent. Material which produces ionization essentially equivalent to that characteristic of tissue when irradiated.

Track. Microscopically visible manifestation of the path of an ionizing particle in a nuclear emulsion.

Tritium (T or ${}_1H^3$). A radioactive isotope of hydrogen having 1 proton and 2 neutrons in the nucleus.

Triton (*t*). The nucleus of a tritium atom. Mass about 3 amu.

Unit (*mrhM*). For shipping regulations, 1 mr/hr measured at 1 meter.

Van de Graaff Generator. An electrostatic generator which employs a system of conveyor belt and spray points to charge an insulated electrode to a high potential.

Wave Length. The distance between any two similar points of two consecutive waves. Expressed in several units including Angstrom units (Å) and cm.

X Ray. (1) Penetrating electromagnetic radiation less than about 100 Å produced by electrons striking a target, giving rise to bremsstrahlung (continuous X-ray spectrum). (2) Transitions of atoms from orbital energy states to lower energy states, giving rise to characteristic X rays. Differ from γ rays of similar energy only by origin.

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