STANFORD UNIVERSITY INTERDEPARTMENTAL MEMORANDUM

Date: July 16, 1992

To: Potential X-ray Defraction (XRD) Machine Users

From: Sorcha Dennison, Health Physics, Telephone# 3-4723

Subject: Extract from the 1989 Stanford Radiation Protection Manual

It has been the practice since the publication of the 1989 manual to send a copy to all potential XRD users to help them complete the certification questionnaire. However, only a small portion of the manual is applicable to certification and the supply of manuals is limited. It has been decided to make an extract from the manual and give a copy to each candidate for certification. Such a copy is attached to this memorandum.

Please read the extract and complete questionnaire enclosed. Return to Health Physics for correction and certification. It is advisable to call for an appointment if the exam is hand carried to Health Physics for correction. The viewing of a safety film (30 minutes) is also required to complete certification.

Sorcha Dennison, Health Physicist
Health Physics Office
A19, ESF, Oak Road, 8006

II RESPONSIBILITIES AND ADMINISTRATION OF RADIATION CONTROLS

GENERAL

A fundamental precept of radiation safety is that the individuals must assume the responsibility not only for their own safety, but must ensure that their actions do not result in hazards to others. It is not possible to define the myriad of responsibilities which may arise in the performance of research. However, some of the most common responsibilities are outlined below.

Radiation Safety
Depends on <u>YOU</u>

INDIVIDUALS

Each individual is responsible for:

1. Following generally accepted procedures of safe practice such as those specified in this manual.

2. Knowing and adhering to the sections of this manual which are specifically applicable.

3. Knowing and adhering to specific laboratory safety procedures as documented in the Hazards Evaluation for the project or as may be posted in the area.

4. Keeping all exposures to radiation as low as reasonably achievable.

5. Wearing appropriate film badges and dosimeters and strictly following the monthly badge change schedule.

6. Immediately reporting to Health Physics any suspected exposure in excess of the permissible limits.

7. Employing proper shielding to minimize exposure.

8. Wearing appropriate protective clothing.

9. Surveying hands for radioactivity and removing contamination before leaving the lab.

10. Cleaning up contamination for which you are responsible.

11. Posting and labeling radiation producing machines and radionuclides for which you are responsible.

12. Maintaining required use logs.

13. Packaging and labeling contaminated articles for waste disposal and maintaining records of such disposals.

14. Furnishing information to Health Physics concerning new activities in the area, particularly alterations of operations which might lead to personnel exposures or contamination.

15. Performing no modifications, repairs, or alterations on the x-ray producing equipment which could increase the hazards or exposure levels without approval of the cognizant committee.

16. Informing Health Physics of any changes in the location or disposal of any machine under a CRA.

17. Returning film badges, dosimeters, and safety manuals to the supervisor upon terminating employment or association with the University.

18. Reporting wounds involving radiation or radioactive materials, inhalation or ingestion accidents and spills promptly to Health Physics.

Application to Obtain or Fabricate a Device

Any person who plans to fabricate, purchase, or acquire such a radiation-producing device shall submit the following information in a memorandum to the Health Physics Department prior to obtaining the device.

1. A description of the device. Specify the types, energies, and levels of radiation anticipated.

2. Indicate typical energies, beam currents, work load (i.e. hours per week), and a description of how the device will be used. Include a copy of operating and safety procedures. These procedures must be posted or distributed to all operators.

3. A sketch of the facility (room). Include shielding specifications (calculations), beam directions. Specify occupants of adjacent areas (above and below?). Provide information (circuit diagrams) about interlock systems, warning devices, installed monitoring systems, etc. How is device secured against unauthorized use? If portable shielding is to be used, describe same.

4. Indicate portable monitoring instruments which are available. (Each project is expected to provide any necessary survey instruments.) Specify type of personal monitoring devices (film badges, finger dosimeters) which will be used.

5. A brief but explicit resumé of the responsible persons' and operators' pertinent training and experience. Each user is required to complete appropriate radiation protection training. X-ray diffraction and certain other machine users must be certified in radiation safety practices. Medical x-ray users must be certified by the State of California.

Health Physics will review the proposed plans and the facilities for safety and compliance to regulations. After review, Health Physics will prepare a hazards analysis which will be sent via the applicant to the appropriate Local Control Committee. When approved by the Committee, the Director of Health Physics will assign a Controlled Radiation Activity Number (CRA No.).

The CRA No. should appear on all correspondence related to obtaining the device. Purchase requisitions should include the following statement:

"RADIATION SOURCE, CRA NO. (enter number here)"

Send a copy of the purchase requisition to the Health Physics Department. The requisition may be processed simultaneously through customary Procurement channels.

Final Approval to Operate (Use) a Radiation Producing Machine

The approval to obtain or build a proposed device is a conditional approval. Final approval to use the device can be granted only after appropriate inspections and surveys have been made. It is the responsibility of the user to schedule appropriate surveys with the Director of Health Physics as soon as the device is capable of producing radiation.

Renewals (Resurveys) of Source Authorizations

The CRA approval to operate is generally granted for a one-year term. However, the project director is responsible for informing Health Physics of changes in procedures or personnel, or modifcation in the device or facilities which would affect radiation safety. Each year a form will be sent to the project director providing the opportunity of updating and renewing the application.

Health Physics will conduct appropriate surveys and inspections periodically to assure safety and compliance.

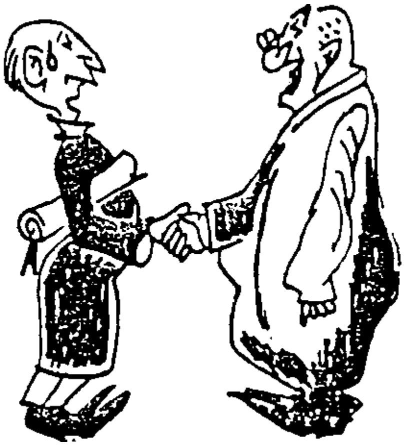
Whenever it becomes apparent, through overexposure or injury to personnel or whenever survey data indicates that continued operation poses a present danger to any person, the Director of Health Physics may restrict, modify, or terminate such use pending review by appropriate Local Control Committee or the Panel on Radiological Hazards.

Registration of Machines

All radiation-producing machines must be registered with the State of California. Health Physics registers the machine on behalf of the University, with the using department paying the associated fee. Call Health Physics for particulars concerning registration.

Termination or Moving of a Controlled Radiation Project

Project Directors are to notify Health Physics at least two weeks in advance of moving or termination of a project. All radioactive sources are to be properly transferred or disposed of. Rooms, facilities and apparatus used by the project are to be decontaminated so that they are free from contamination as measured by Health Physics. When surveys have been completed, Health Physics will remove signs from rooms and equipment and will terminate the project, if appropriate. Note that Investigators or Departments are responsible for costs attendant to "decommissioning" of a project.



The License

ACCOUNTABILITY REQUIRED FOR MACHINES

Disposal of Machines

Notify Health Physics in advance of the disposal of radiation-producing machines. The University must notify any recipient that registration of the device is required by the State. The State regulations also require the University (Health Physics) to notify the California Department of Health of each transaction.

Records and Operating Logs

Each individual user must maintain a laboratory safety journal in which pertinent records are permanently filed and readily retrievable. This journal should be contained in as small a number of laboratory notebooks as will meet the needs of the project. This journal must be accessible to all persons who work with radiation sources under the project. The journal must include, but is not limited to, the following records:

1. Correspondence with Health Physics and the Local Control Committee.

2. List of authorized users.

3. Results of radiation surveys. When performed by the laboratory staff, specify the date, the person making the survey, the instrument used and the location and levels of radiation. (It is important that a statement regarding the average exposure reading encountered in work areas be included in the record even when this value is essentially instrument background). Causes of high survey readings should be determined (with the assistance of Health Physics when necessary) and eliminated.

4. Log indicating a record of machine usage, dates/times, energies and current, other parameters, e.g. target, port used, and user's name.

5. Instrument calibration records.

6. Additional miscellaneous entries in the journal should include the addition or deletion of personnel from the project staff, significant instruction or information programs carried out for students or assistants, and description of any accidents together with a description of corrective efforts.

7. Repairs or modifications (these require safety committee prior approval if they may affect radiation exposure or safety circuits and devices.)

LOSS OF SOURCES OR RELEASE OF MATERIALS

Health Physics must be notified at once whenever radiation sources (materials or machines) have been lost, stolen, or misplaced or whenever materials are released into the environment in excess of limits.

V. RADIATION PROTECTION—RADIONUCLIDES

GLOSSARY

The following is a list of some of the terms and units which are basic for understanding and applying principles of radiation protection.

A: Symbol for Mass number.

Absorbed dose: The amount of energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest (see rad, gray).

Absorption: The process by which radiation imparts some or all of its energy to material through which it passes.

Absorption coefficient: The fractional decrease in the intensity of a beam of X rays or gamma radiation.

linear absorption coefficient - per unit length
mass absorption coefficient - per unit mass
atomic absorption coefficient - per atom

due to the absorption of energy in the absorber.

Alpha particles: These are equivalent in mass (~4 atomic mass units (amu)) and charge (2 positive units) to helium nuclei. They are emitted primarily during decay of heavy nuclides including uranium, thorium, radium and elements in the trans-uranium series. Alpha particles are emitted with discrete energies characteristic of the radionuclide. The energies for alpha particles emitted from typical nuclides are in the 3-6 MeV range. Alpha particles, because of their large mass, have a relatively low velocity. This velocity and the double positive charge mean that alpha perticles interact strongly with matter, producing intense ionization as they dissipate their kinetic energy in very short distances. Alpha particles with an energy of 5 MeV will penetrate about 50 microns in tissue and produce $(20-60)\mathrm{x}10^{3}$ ion pairs per centimeter in air. In general, alpha particles can travel only short distances (~8 cm) in air and can be stopped by a thin sheet of paper, although the highest energy alpha particles can penetrate to the living basal epidermal cells. When nuclides which emit alpha particles become deposited within a person's body, those cells within a fraction of a millimeter of the site of depostion will receive very large doses of radiation.

Anode: Positive electride; electrode to which negative ions (or electrons) are attracted.

Atomic mass: The mass of a neutral atom of a nuclide is usually expressed in atomic mass units (amu) which is 1/12 the mass of the neutral carbon-12 atom.

Atomic number: The number of protons in the nucleus of a atom of a nuclide (symbol Z).

Attenuation: The process by which a beam of radiation is reduced in intensity as it passes through a material. This is the combination of absorption and scattering processes which leads to a reduction in the number of photons per unit area per second (flux density) in a beam passing through the material.

The three principal processes involved in attenuation are

- photoelectric absorption - a process whereby a photon is absorbed by an orbital electron of an atom. This results in the ejection of the electron from its orbit. All of the energy of the photon is accounted for in the process of ejection and the kinetic energy of the electron.

- Compton scattering - a process whereby a photon interacts with an orbital electron of an atom to produce a recoil electron and a scattered photon of energy less than the incident photon.

- pair production - a process whereby a photon is annihilated in the vicinity of the nucleus of an atom in an absorber producing a pair of electrons, one positive, the other negative. The minimum energy which a photon must have to produce such a pair may be calculated by $E = mc^2$ and equals 1.02 MeV.

Attenuation coefficients: The fractional reduction in the number of photons in a beam traversing a material due to the processes of attenuation.

Barriers: Barriers of radiation absorbing materials, concrete, lead, iron, etc. used to reduce radiation exposure

- primary protective - barriers sufficient to attenuate the usefu beam to the required degree.

- secondary protective - barriers sufficient to attenuate stray radiation to the required degree.

Beta particles: These are emitted from the nucleus and are identical to orbital electrons in mass (1/1840 amu) and charge (1 negative unit). As the result of the emission of a beta particle (negative), a neutron is converted to a proton in the nucleus so that the atomic number is increased by one. The atomic mass number remains the same. Beta particles are more penetrating than alpha particles. A beta particle will produce 50-200 ion pairs per centimeter of track length in air. Beta particles are emitted in a spectrum of energies; the average energy is 1/3 of the maximum.

Bequerel (Bq): The basic unit of radioactivity in the meter-kilogram-second system. It is that amount of radioactivity which is undergoing nuclear transformations at a rate of one per second.

Bremsstrahlung: Electromagnetic radiation (like X rays) produced when charged particles decelerate in matter. The production of bremsstrahlung depends directly upon the energy of the particle and the atomic number of the absorber. This means that large activity, high energy beta sources require shielding with sufficient thickness of low atomic number substances such as plastic. The fraction of energy converted to bremsstrahlung approximately equals ZE/1000, where Z is the atomic number of the absorber and E is the average of energy of the beta particles.

Characteristic X rays: Characteristic X rays are produced when electron vacancies are produced in the inner orbital electron shells of atoms to which outer electrons can be transferred. (Also see X rays.)

Controlled area: A defined area in which occupational exposure of personnel to radiation or radioactive materials is under the supervision of a radiation safety officer. This implies that a controlled area requires control of access, occupancy, and working conditions for radiation safety purposes. (See legal definition in Section VI.)

Curie: The curie (abbreviated Ci) is the unit which describes the quantity of radioactivity, i.e. the number of nuclear transformations (or disintegrations) per unit time. One curie of activity equals $3.7x10^{10}$ nuclear transformations per second. The curie is a relatively large unit; most of the quatities of radioactivity used on campus are at the millicurie (mCi) or microcurie (μCi) level (i.e. 1/1000th or 1/1,000,000th of a curie, respectively). One curie equals 3.7×10^{10} bequerel.

Dose equivalent (DE): A quantity used in radiation protection. It expresses all radiations on a common scale for calculating the effective absorbed dose. It is defined as the product of absorbed dose (in rads or grays) and certain modifying factors. The unit is the rem or sievert.

Electron volt (eV): The unit of energy equivalent to energy gained by an electron passing through a potential difference of 1 volt (a very small unit of energy) 1 eV = 1.6 x 10^{-12} ergs. Usually multiples are used keV = 1000 eV and MeV = 1,000,000 eV.

Gamma rays and X rays: These are part of the electromagnetic energy spectrum which also includes radio waves, visible light, and ultraviolet light, etc. X rays and gamma rays have very high energies; they have short wavelengths and readily penetrate matter. Gamma rays and X rays differ only in their source. Gamma rays arise from the atomic nucleus while X rays arise from orbital electron energy transitions.

Both of these radiations interact with matter mainly by transferring energy to orbital electrons of absorber atoms causing ionization. The ejected orbital electrons then decelerate and lose energy, in the same manner as beta particles. Because the photons have no mass or electrical charge the probabilities of interaction are small and the radiations are difficult to attenuate. Dense materials with high atomic numbers, i.e. lead, uranium, etc. make the best shields against these radiations.

Gray (Gy): The unit of absorbed dose in the meter-kilogram-second system; absorption of 1 joule in a kilogram of absorbing medium. One gray equals 100 rads. (See rad.)

Half-life: The half-life of a radionuclide is the period of time required for half of the atoms in a sample of that nuclide to undergo nuclear transformation.

Half-value layer (HVL): The thickness of a material which if placed in a radiation beam, for example a shield, will reduce the intensity of the beam by half.

Ionization: The process by which a neutral atom or molecule acquires a positive or negative electrical charge.

Leakage radiation: All radiation coming from a source housing except the useful beam.

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

Monitoring: Periodic or continuous determination of the levels of radiation or radioactivity present in a region.

Neutrons: Electrically neutral particles with a mass of ~1 amu. They may be produced from nuclear interaction when high-energy particles interact with nuclei (especially when deuterium ions are accelerated) or by nuclear fission. Neutrons interact with matter in several ways: (1) being captured by nuclei, transmuting the nucleus to another isotope which can subsequently give off alpha, beta and/or gamma radiations, or (2) by collision with nuclei, especially protons (hydrogen nuclei), transferring kinetic energy to the proton. The latter has an electrical charge and causes ionization as it dissipates its kinetic energy in matter. Such proton recoils are the most important dose considerations in the interaction of neutrons with tissue (which has many hydrogen atoms). Because of the large mass of the proton compared with the electron, the proton with the same kinetic energy will have a lower velocity and will lose its energy over a shorter unit length producing dense ionization along its track, similar to alpha particles. Neutron sources are frequently stored behind shields which contain large amounts of hydrogen atoms, such as water, parafin, etc.
Since neutrons also interact with nuclei and transmute stable nuclides into radioactive nuclides special precautions may be required around sources where neutrons are being produced to protect against the induced radioactivity in the shielding, air, etc.

Positrons: These are positively charged beta particles (equivalent in mass to electrons). They are emitted from the nucleus in the same manner as negatively charged electrons. The process results in a proton being transformed to a neutron. The resulting nucleus will have one less positive charge and the same mass number as the original nucleus. Positrons are emitted in a spectrum of energies. When the positron collides with a negative electron, both particles are annihilated. The masses of the positron and electron (each of which has a mass 1/1840 of an atomic mass unit) are totally converted to energy in accordance with formula $E = mc^2$; two photons with energies of 0.511 MeV are produced. Since the annihilation radiations have the same characteristics as gamma rays, positron sources require shielding like that for gamma sources.

Quality Factor (QF): Number by which absorbed doses are to be multiplied to obtain dose for radiation protection purposes. It is a quantity that expresses on a common scale the radiation harm incurred by exposed persons. It is selected based upon review of human and animal exposure data for various kinds of radiation. Quantitatively, QF is related only to linear energy transfer of the radiation. The QF for X rays, gamma rays and beta particles is approximately one.

Rad: The unit of absorbed dose. One rad is the dose when any ionizing radiation deposits 100 ergs per gram (0.01 joules per kilogram) in any material. Since one R of exposure in the energy range of 0.1 to 3 MeV dissipates 87 ergs per gram of air (or 96 ergs per gram in soft tissue), the units are said to be nominally equivalent.

Rem: The unit of dose equivalent which is used for radiation protection purposes. It is the product of the absorbed dose (in rads) and a factor which relates it to the harmfulness to man. This latter factor is termed the Quality Factor (See Quality Factor above).

Roentgen (R): The unit of exposure; the amount of X ray or gamma radiation which will produce one electro-static unit (esu) of charge (approximately 2 billion electrical charges of either sign) per cc of air at standard temperature and pressure.

What happens during exposure of matter to 1 R of radiation

2.082×10^{9} ion pairs/cm^{3} are produced in air (density 1.293 mg/cm^{3})

1.610×10^{12} ion pairs/cm^{3} are produced in water

3.34×10^{-10} Ampere per 1 R/s in 1 cm^{3} air

5.56×10^{-12} Ampere per 1 R/min in 1 cm^{3} air

~84 erg/cm^{3} water

~5×10^{-6} (= 1/200,000) °C heating of water

~1800 ion pairs/cell (assumed cell size: 10 x 10 x 10 µm = 1000 μm^{3})

~225 ion pairs/cell nucleus (assumed size of cell nucleus: 125 μm^{3})

~3.5×10^{8} ionizations per second, in a body of 70 kg, due to exposure to background radiation of 0.1 R/year (~180 ionizations per cell per year.)

Scattered radiation: Radiation which during the passage through a material undergoes a change in direction. (The radiation may also undergo a change in energy.)

Secondary barrier: (See Barrier - secondary.)

Sievert (Sv): The unit of dose equivalent in the meter-kilogram-second system. One sievert equals 100 rems (See Rems).

Stray radiation: The sum of leakage and scattered radiation.

Tenth Value Layer TVL): The thickness of a substance which if introduced into a beam of radiation (for example, as a shield) will reduce the intensity of the beam by a factor of 10.

X Rays: Part of the electromagnetic energy spectrum which also includes radio waves, visible light, and ultraviolet light, etc. X rays and gamma rays have very high energies; they have short wave lengths and readily penetrate matter. Gamma rays and X rays differ only in their source. Gamma rays arise from the atomic nucleus while X rays arise from orbital electron energy transitions. X rays produced by machines usually have two components — bremsstrahlung and characteristic X rays.

Both of these radiations interact with matter mainly by transferring energy to orbital electrons of absorber atoms causing ionization. The ejected orbital electrons then decelerate and lose energy, in the same manner as beta particles. Because the photons have no mass or electrical charge the probabilities of interaction are small and the radiations are difficult to attenuate. Dense materials with high atomic numbers, i.e. lead, uranium, etc. make the best shields against these radiations.

Z: Symbol for atomic number.

Adopting the Appropriate Film Badge

The Health Physics Department will prescribe the appropriate type of monitoring device for the conditions to be encountered.

Two types of film badges are used to monitor whole body exposure: beta-gamma/x-ray, and neutron plus beta-gamma/x-ray. Thermoluminescent (TLD) ring dosimeters are used for monitoring exposure to hands. TLD dosimeters are required for persons who routinely handle millicurie quantities of gamma emitters or high energy beta emitters such as P-32, or whose hands may be exposed to X rays. All dosimeters are processed monthly. In certain areas where low level high energy photon exposure occurs a thermoluminescent body dosimeter may be issued each quarter as part of the regular service. Failure of employees to wear dosimeters in areas where they are required will result in appropriate disciplinaryy action.

*NOTE: A badge or dosimeter should be processed immediately whenever serious exposure is suspected. Call Health Physics, 7-3201, if such circumstances arise.

Proper Use of the Film Badge

1. Only the person who is assigned a dosimeter should wear it. Do not loan a badge or use it for monitoring an area. Badges for the latter purpose are available from Health Physics upon request.

2. It is essential to monitor the portion of the body receiving the highest exposure to which whole body limitations apply. For example: radioisotope technicians who wear lead aprons, should wear film badges outside, not under, the apron, because the dose to the head is the limiting factor.

3. Ring dosimeters should be worn when there is a possibility of significant exposure to the hand. It is important to wear ring dosimeters on the finger which is nearest the

radiation source. Usually the index finger receives the greatest exposure.

4. The film packet must be placed in the plastic badge in order to make it possible to interpret the exposure. Always place the film in the holder in the same manner (so the name label is visible through the front of the holder).

5. Wear badge whenever working with or around radiation sources; however, do not wear badges when undergoing personal medical or dental diagnosis or therapy, since occupational dose limits are not applicable.

6. Use care when removing aprons and lab coats, so that badges are not left in exposure areas such as an x-ray room or near radioactive materials. If a badge is exposed in this manner, the film should be changed immediately since the additional dose should not be ascribed to the wearer. Return the film to Health Physics with an explanatory note.

7. The film must be promptly returned for processing. Delay in returning film results in considerable extra work and correspondence in follow-up. A film which is returned late cannot be processed with the control badge supplied with the shipment. In addition, the accuracy of the film badge result is impaired by film fogging and image fading which increase with time. Note that films are also heat sensitive and should not be stored or left in high temperature areas such as inside an automobile on sunny days.

How to Obtain Dosimeters

A Film Badge Service Request Form is available from Health Physics. The department must supply to the Health Physics Office the following information concerning each wearer so that proper records may be kept.

1. Full name of wearer.
2. Social Security Number.
3. Birthdate.
4. Campus Department or Laboratory Affiliations.

The cost of the service is normally paid from the individual user's funds (department or project).

Obtaining Records of Exposure

Upon written request to the Health Physics Office, any individual may obtain a record of their radiation exposure data and the results of any measurements, analyses or calculations of radioactive materials deposited or retained within their body. A written request needs to include the name of the individual, social security number, the department where the individual worked, and the dates during which such exposure was measured. Such requests must be signed.

Current month's film badge results including quarterly, yearly and exposures from other California employers are on computer print-outs distributed to the various campus departments which issue badges. These should be posted in a place where employees can check their exposures. Employees should be encouraged to check results.

Investigation

Health Physics investigates exposures which are at a level which could lead to exceeding the University Guideline or legal limits, i.e. greater than 10 percent of the Guideline or limits in a month.

Hand Dose and Extremity Monitoring Techniques

When measuring hand exposure using finger dosimeters (either TLD or film rings), it is very important to wear the dosimeter on the proper finger. Using a hand phantom and a 20 mCi sample of Tc-99m — 2 cc in volume in a syringe, Health Physics measured the exposure to the hands. The maximum exposure at the point nearest the source was 22,000 mR/hr at the tip of the index finger. When dosimeters were placed elsewhere the measured exposure varied by large factors (See Figure 5.1).

In general, the data suggest wearing the dosimeter on the index finger, probably at the middle or base of the finger would be most workable. The dosimeter should be worn under gloves to protect it against contamination.

Direct Reading Devices

On occasion it is useful to wear a dosimeter which can give an immediate indication of the exposure. Direct reading electrometers and personal GM type counters are useful for such purposes. The latter usually gives an audible signal for each fraction of an mR of exposure. Some have registers for integrating dose. This audible signal can be used as a warning of high radiation areas or procedures which contribute to exposure. Health Physics can advise on selection of these devices. Such monitors can provide very useful data identifying the specific procedures which result in exposure. They can also help one maintain exposure at acceptable levels in areas where the exposure potential is great.

VI. POLICIES, LIMITS, AND REGULATIONS

BIOLOGICAL EFFECTS

It was recognized early after the discovery of X rays and radioactivity that exposure to ionizing radiations could have detrimental effects on biological systems. The detrimental effects against which protection is required are both somatic and genetic. The "somatic" effects are those which become manifest in the exposed individuals; the genetic (or hereditary) effects are those which affect the descendants of the exposed individuals.

The harmful effects may be classified also as to whether the effects vary in **severity** as a function of dose (called non-stochastic effects) or vary in probability of occurrence (with similar severity) as a function of dose (called stochastic effects). **Non-stochastic effects** are those usually associated with high dose, such as radiation burns or radiation sickness. Non-stochastic effects exhibit a "safe" threshold dose and would not be expected to occur in individuals exposed to levels within occupational limits. **Stochastic effects**, such as genetic mutation and carcinogenesis (causing of cancer) exhibit no threshold. This means that all exposure to radiation bears **some** risk of genetic harm or of increasing the risk of cancer in the exposed individual. Minimizing stochastic effects is now the main concern of radiation protection.

The radiation dose limits have been established so essentially no non-stochastic (threshold) effects would occur even if a person were exposed to the limit over his entire working life. Limiting the stochastic effects (especially cancer induction) is achieved by keeping all justifiable exposures AS LOW AS REASONABLY ACHIEVABLE (ALARA). Different dose limits have been set for various organs in the body because of varying sensitivity of tissues or organs to stochastic damage. Also, young individuals are more sensitive than adults to damage from ionizing radiation. This is especially true if an embryo or fetus is exposed **in utero**. For this reason, occupational exposure is more restricted (by a factor of 10) for individuals below the age of 18. Also, it is recommended that pregnant individuals restrict their occupational exposure so that a fetus does not receive more than 1/10 the yearly dose equivalent limit for workers.

On the Stanford campus, the Panel on Radiological Hazards and the Health Physics Department have implemented an ALARA program to reduce unnecessary exposure. Toward this end, a whole body (i.e. trunk of body) exposure guideline of 500 mrems/year (1/10 of the legal limit) was established for radiation workers. Adherence to the guideline will reduce, proportionately, the risk of producing cancer of all exposed individuals. Also, no fetus would then receive a dose of more than 500 mrems (the recommended limit). In approximately 8 years of observing this guideline, it has been found that all research and clinical activities on the campus and at affiliated institutions could be conducted without impairment.

Radiation dose rates in uncontrolled areas are to be restricted to less

In comparison, the average dose to persons living in the San Francisco Bay Area from natural background radiations is about 100 mrems per year and the average medical exposure is also about 100 mrems per year.

RISKS FROM EXPOSURE TO IONIZING RADIATION

It is generally accepted by the scientific community that exposure to ionizing radiation causes biological effects that may be harmful. These effects are classified into two general categories. These categories are:

SOMATIC effects, i.e., effects occurring in the exposed person which, in turn, may be divided into two classes:

> PROMPT effects that are observable soon after a large and acute dose (e.g. 25 rems or more in a few hours or very high high doses, i.e, >100 rads to the skin, to the hands, gonads, or single organs. Such effects could be erythema, skin burns, epilation, temporary or permanent sterility, cataracts, or other injuries.
>
> DELAYED effects such as cancer that might occur years after exposure;

and GENETIC effects, i.e., abnormalities that might occur in the children of exposed individuals and in subsequent generations.

Concerns about these biological effects have resulted in stringent controls on radiation sources and in efforts to control and minimize the doses to the workers.

Regulatory action has recently focused more attention on implementing the philosophy of maintaining occupational radiation exposure at levels that are AS LOW AS REASONABLY ACHIEVABLE (ALARA). A clear understanding of what is known about biological risks of radiation exposure is the first step for a radiation worker seeking to minimize his/her own dose and that to co-workers.

COMMON QUESTIONS ABOUT RISKS ASSOCIATED WITH RADIATION EXPOSURE

(Reference: NRC Regulatory Guide OH 902-1, May 1980.)

What is meant by risk?

Risk can be defined in general as the chance (probability) of injury or death resulting from some activity. The intent of this document is to estimate and explain the possible risk of injury, illness or death resulting from occupational radiation exposure.

What are the possible health effects of exposure to radiation?

Some of the health effects that exposure to radiation may cause are cancer (including leukemia), inherited birth defects in children of exposed parents, and cataracts. These effects (with the exception of genetic effects) have been demonstrated in studies of medical radiologists, radium workers, and radiotherapy patients who have received excessive doses in the early part of this century. Studies of people exposed to radiation from atomic weapons have also provided data. In addition, radiation effects studies in laboratory animals have provided a large body of data.

All of the studies mentioned, however, involve levels of radiation exposure that are much higher than those permitted occupationally today. Studies have NOT shown a clear cause and effect relationship between health effects and current levels of occupational radiation exposure.

What is meant by prompt effects and delayed effects?

Prompt effects are observable shortly after a very large dose of radiation in a short period of time. For example, a dose of 450 rems to an average adult will cause vomiting and diarrhea within a few hours; loss of hair, fever and weight loss within a few weeks; and about 50 per cent chance of death within about 1 month without medical treatment. Delayed effects such as cancer and cataracts may occur years after exposure to radiation. (Note: Cataracts are not likely to be caused by doses of X rays, gamma rays, or beta particles within the occupational limits.)

What about potential effects to the children of workers who are exposed to radiation?

Genetic effects occur when there is radiation damage to the germ cells carried by the parents, due to radiation exposure to the gonads of either parent. These effects may show up as birth defects or other conditions in the offspring of the exposed parents and succeeding generations. These effects have been demonstrated in animal experiments, although they have not been shown in human populations. The risks of producing serious genetic effects is about one third of the risk of producing cancer. (The risk of producing genetic harm is about 1 in 10,000 per rem of dose to the parent's gonads.) Genetic effects should not be confused with damage to an embryo or fetus due to exposure to radiation while still in utero, which is discussed below.

As radiation workers, which effects should concern us most?

Immediate or prompt effects are very unlikely since large exposures would normally occur only if there were a serious radiation accident. In fact such exposures could not occur in the typical radioisotope laboratory, because only limited quantities of radionuclides are present. The probability of serious genetic effects in the children of workers is estimated to be about one third of the other delayed effects. The probability of harm to a foetus due to occupational exposure of the pregnant mother is one major area of concern (see discussion in a section below.) Probably the greatest concern to the worker for most of his/her working life is the possibility of the delayed incidence of cancer. The chance of delayed cancer is believed to depend on how much radiation a person receives; therefore, every reasonable effort should be made to keep exposures low. Of course, genetic effects are also a concern to those persons who are at, or below, reproductive age.

What is the difference between acute and chronic exposure?

Acute radiation exposure, which causes prompt effects and may also cause delayed effects, refers to a LARGE dose of radiation received in a SHORT time, for example, 450 rems received in a few hours or less. The effects of acute exposures are well known from studies of radiotherapy patients, atomic bomb casualties, and accidents that have occurred. Chronic exposure, which may cause delayed effects but not prompt effects, refers to SMALL doses received over LONG time periods, for example, 20-100 millirems per week every week for several years. Concern with occupational radiation risks is primarily focused on chronic exposure to low levels of radiation over long time periods.

How does radiation cause cancer?

How radiation causes cancer is not well understood. It is impossible to tell whether a given cancer was caused by radiation or by some other of the many apparent causes. However, most diseases are caused by interaction of several factors. General physical condition, inherited traits, age, sex, and exposure to other cancer-causing agents such as cigarette smoke are a few possible interacting factors. One theory is that radiation activates existing viruses in the body which then attack the cells causing them to grow rapidly. Another is that radiation reduces the body's normal resistance to existing viruses which can then multiply and attack cells. Radiation is known to damage chromosomes in a cell. Since the chromosomes carry the genes which provide the information regulating cell growth, the damage could result in the cell's being directed along abnormal growth patterns. What is known is that in groups of HIGHLY exposed people a higher than normal incidence of cancer is observed. An increased risk of cancer has not been shown at radiation dose levels within occupational limits...Stanford's guideline being 10% of those limits. Studies of groups who receive occupational doses of radiation are still incomplete.

If I receive a radiation dose, does it mean I am certain to get cancer?

Not at all; everyone gets a radiation dose every day but most people do not get cancer. Even with doses of radiation far above legal limits, most individuals will experience no delayed consequences. There is evidence that the human body will repair some of the damage. The danger from radiation is much like the danger from cigarette smoke. Only a fraction of the people who breathe cigarette smoke get lung cancer, but there is good evidence that smoking increases a person's chances of getting lung cancer. Similarly, there is evidence that large radiation doses increase one's chance of getting cancer.

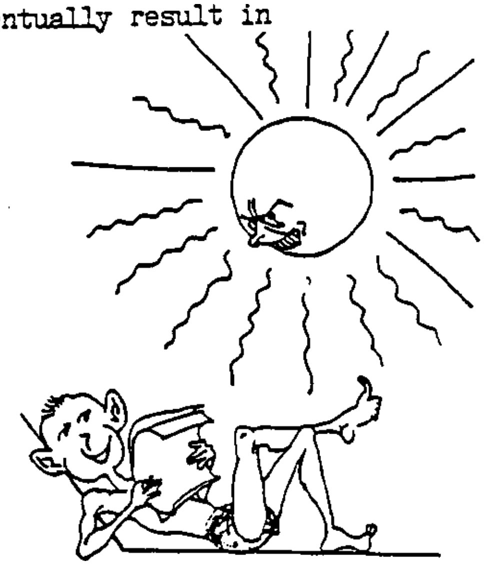
Radiation is like most substances which cause cancer in that the effects can only be observed at large doses. Still, it is prudent to assume that smaller doses also have some chance of causing cancer. (For example, you may recall the debate about saccharin.) This assumption is applied to natural cancer-causers such as sunlight and natural radiation as it is for those that are man-made such as smog, cigarette smoke, and man-made radiation. As even very small doses may have some risk, it follows that no dose should be taken without a reason. Thus it is a time-honored principle that doses should be kept as low as reasonably achievable.

We don't know exactly what the chances are of getting cancer from a radiation dose, but we have good estimates. The estimates of radiation risks are at least as reliable as estimates for the effects from any other important hazard. Being exposed to typical occupational radiation doses is taking a chance, but that chance is small and reasonably well understood.

It is important to understand the probability factors here. A similar question would be: if you select one card from a full deck, will you get the ace of hearts? This question cannot be answered with a simple yes or no. The best answer is that your chances are 1 in 52. However, if 1000 people each select one card from full decks, we can predict that about 20 of them will get the ace of hearts. Each person will have 1 chance in 52 of drawing the ace of hearts, but there is no way of predicting which persons will get the right card. The issue is further complicated by the fact that in 1 drawing only 15 persons may draw the card while in the next drawing 25 persons may get the card. We can say that if you receive a radiation dose, you will have increased your statistical chances of eventually developing cancer or some other radiation-related injury. The more radiation exposure you get, the more you increase your chances of cancer.

Clearly, there is no simple answer to the question. The best we can do is to provide estimates, for large groups, of the increased chances of cancer or other radiation injury resulting from exposure to radiation.

A reasonable comparison involves exposure to the sun's rays. Frequent short exposures provide time for the skin to repair. An acute exposure to the sun can result in painful burning, and excessive exposure has been shown to cause skin cancer. Whether exposure to the sun is short term or spread over time, some of the injury is not repaired and may eventually result in skin cancer.



The effect upon a group of exposed workers may be an increased incidence of cancer over and above that which would be expected in that population. Each exposed individual has an increased probability of incurring subsequent cancer. We can say that if 10,000 workers each receive 1 rem (1000 mrems) in a year, that group is more likely to have a larger incidence of cancer than 10,000 people who do not receive the additional radiation (all other factors being equal.) An estimate of the increased probability of cancer from low radiation doses delivered to large groups is one measure of occupational risk.

What are the estimates of risk of cancer from radiation exposure?

The cancer risk estimates (developed by various scientific advisory groups) are presented in Table 6.1.

Table 6. 1

CANCER RISK ESTIMATES FROM EXPOSURE TO LOW-LEVEL RADIATION

Source of data	Number of Additional Cancers Estimated to Occur in 1 million Persons After exposure to 1 rem of Radiation
BEIR 1980	3-60 leukemias + 10-1600 other cancers
ICRP 1977	300*
UNSCEAR 1977	300*

* ICRP and UNSCEAR both estimated 100 excess delayed deaths from these 300 radiation-induced cancers. Only about one third of cancers are fatal. Note that the three independent groups are in close agreement on the risk of radiation induced cancer. BEIR 1980 has broader ranges of risk because different assumptions about how to treat the data can be and are made by experts.

To put these estimates into proper perspective, we will use the average of 300 excess cancers per million persons, each exposed to one rem. This means that if a group of 10,000 workers each receives 1 rem, three would be predicted to develop cancer because of that exposure, although the actual number could be more or less than three (including none).

The American Cancer Society has reported that about 25 percent of all adults in the 20-65 year age bracket will develop cancer at some time from all possible causes. Thus in a group of 10,000 workers not exposed to radiation on the job, we could expect that about 2500 will develop cancer. If this entire group of workers were to receive an occupational dose of 1 rem each, we would expect that three additional cancers would occur which would give a total of 2503. This means that a 1-rem dose might increase the cancer rate from 25 percent to 25.03 percent, an increase of about three hundredths of one percent.

It is important to realize that these risk numbers are only estimates. Many difficulties are involved in designing research studies which could accurately measure such small increases in cancer due to low exposures to radiation as compared to the normal incidence of cancer. There is, therefore, still uncertainty and controversy with regard to estimates of radiation risk.

The BEIR advisory committee and others feel that the largest risks shown above, which are calculated by extrapolating from high doses and high dose rates, are higher than would actually occur and represent an upper limit on the risk.

How much radiation does the average person who is not a radiation worker receive?

We are all exposed to ionizing radiations from the moment of conception. Our environment, even the human body, contains naturally occurring radioactive materials that contribute some of the background radiation we receive. Cosmic radiation originating in space and in the sun contributes additional exposure. The use of X rays and radioisotopes in medicine and dentistry contributes considerably to the population exposure.

The table below shows estimated average individual exposure in millirems from natural background and other sources.

Table 6.2
U.S. GENERAL POPULATION EXPOSURE ESTIMATES

Source of exposure	Average Individual Dose (mrem/year)
NATURAL BACKGROUND	82
MEDICAL	92
NUCLEAR WEAPONS FALLOUT	5
NUCLEAR ENERGY	< 1
CONSUMER PRODUCTS (TVs, etc)	0.5
AIR TRAVEL (COSMIC RADIATION)	0.5

Thus, the average individual in the general population receives about 180 millirems per year from sources that are part of our natural and man-made environment.

What are the health risks to children of women who are exposed during pregnancy?

Some recent studies have shown that the risk of leukemia and other cancers increases if the mother is exposed to a significant amount of radiation during pregnancy. According to the BEIR 1980 Report, the extra incidence of leukemia among children from birth to 12 years of age in the U.S. would be 300 per million if the children were exposed to 1 rem before birth. The Report also estimated that an equal number of other types of fatal cancer could result from this level of radiation. Although other scientific studies have shown a much smaller effect from radiation, it is important that women employees who work around radiation be aware of possible risk so that they can take steps they think appropriate to protect their offspring. Note: When one compares the risks of carcinogenic effects in children exposed in utero to the carcinogenic effects in the exposed adult, one observes a significant difference (the in utero being about six times more sensitive). This is one of the reasons that Stanford adopted the Guideline of 0.5 rem per year versus the legal dose limits which are 5 rems per year.

The Nuclear Regulatory Commission suggests a few alternatives that women of child bearing age who work around radiation sources might consider:

a) If you are now pregnant or expect to be soon, you could decide not to continue to work in such areas. (Note that it is possible that there may be no alternate jobs in the University in your discipline which involve no risks of exposure.) You should also note that very few (5-6) radiation workers accumulate doses at the level of 0.5 rem in a year, and that in such cases the doses to the fetus are usually much less than the doses monitored by the badge which measures the dose at the surface of the body.

b) You could in some cases take steps to reduce your exposure by decreasing the amount of time spent near radiation sources, by increasing your distance from sources, or by using better shielding. For example, in some cases lead aprons can be used.

c) If you are not pregnant you could decide to postpone pregnancy until you are no longer working in areas where you may be exposed to radiation.

Whatever course you may wish to follow, it is appropriate to reach a decision early. The fetus is most sensitive during the first three months of your pregnancy.

The University Health Physics Office will be glad to review the risks and means for reducing exposure potential on any particular project with anyone who needs such consultation.

Can radiation exposure within occupational limits cause sterility?

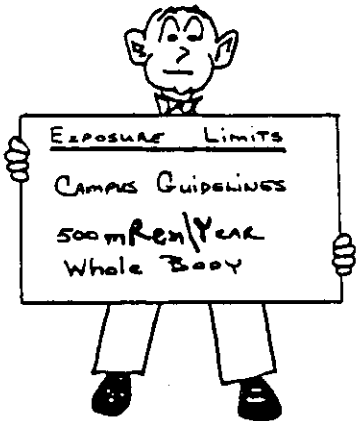
There is no need to be concerned about sterility at occupational dose levels. The dose needed to cause sterility about 100 times larger than the legal limits for occupational exposure.

Can radiation cause cataracts?

At occupational radiation dose-limit levels (for X rays, gamma rays and beta particles) the risks of inducing cataracts is believed to be vanishingly small. The most recent data from the International Commission on Radiation Protection and Measurements indicate that 40 years of doses of 15 rems per year (to the eyes) would not be expected to cause any lens opacities which could lead to deterioration of one's vision. (The legal limit is 5 rems per year.) However, it should be noted that high doses of X rays, greater than 200 rads in single doses, could cause injuries which could lead to cataracts. This is a particular reason to be sure to use proper shielding when aligning X-ray diffraction beams.

EXPOSURE LIMITS AND GUIDELINES

A thorough discussion of the mechanisms of such damage, the probability of harm and a discussion of the basis of the radiation exposure limits are contained in a report from the National Academy of Sciences entitled "Report of the Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR Report)" published in 1980. Call Health Physics for further information. (497-3201).



Except as noted in items 7 and 8, the dose limits and guidelines are for persons over the age of 18 years.

1) 500 mrems/year to trunk of body or whole body (Campus Guideline)

2) 500 mrems over full gestation period to fetus due to occupational exposure of mother (U.S.N.R.C. Guideline)

occupational exposure of mother (U.S.N.R.C. Guideline)

3) 5,000 mrems/year - 1250 mrems/quarter to head, lens of eye, or blood forming organs or gonads (when major fraction of trunk of body is not exposed) (This is the State and U.S.N.R.C. legal limit for whole body, lens of the eye, blood forming organs, or gonads.)

4) 75,000 mrems/year - 18,750 mrems per quarter to hands and forearms, feet and ankles (State and U.S.N.R.C. Limit)

5) 30,000 mrems/year - 7,500 mrems/quarter to skin when exposed to non-penetrating radiations such as very soft X rays or beta particles (State and U.S.N.R.C. Limits)

6) 15,000 mrems/year (not to exceed 5,000 mrems/quarter) to organs and tissues except those noted above. Note: Usually such a dose would result from internal deposition of a radionuclide (Recommendations of International Committee on Radiation Protection and National Council on Radiation Protection)

7) 10% of above limits to the general public or persons 18 years of age or under — State Limit - Usually exposure must be well under this limit.

8) 100 mrems/year to students 18 years of age or under (such doses resulting from educationally related activities). This guideline was established by the National Council on Radiation Protection and is followed on campus.

SELECTED RADIATION CONTROL REGULATIONS

General

The extent and form of the restrictions which apply to each laboratory are determined by Title 10 of the Code of Federal Regulations and Title 17 of the California Administrative Code. These regulations are based upon earlier recommendations of the National Council on Radiation Protection (NCRP). These regulations are binding on each person using radioisotopes or other radiation sources.

Copies of State and Federal regulations concerning radiation control and recommendations of the NCRP and other agencies may be obtained from the Health Physics Office.

The regulations applicable to use of radiation on campus may be summarized as follows:

Definition of Controlled Areas

The term is defined in Section 30258(d) of Title 17 of the California Administrative Code as follows:

"'Controlled area' means any area access to which is controlled by the user for purposes of radiation safety . . . Airborne radioactivity areas, high-radiation areas, and radiation areas shall be considered controlled areas. Controlled areas shall not include any area used as residential quarters".

As a practical guide, each area where radiation use presents the possibility of exposure of individuals to 10 per cent of occupational limits (specified above) must be treated as a controlled area, that is:

1. The area must be secured when it is not occupied by responsible personnel (or equipment must be restricted against unauthorized use).
2. The area and/or equipment must be posted with proper signs indicating the radiation zone(s) and identifying the source which is present.
3. Personnel monitoring must be provided where appropriate, as specified by Health Physics Department.
4. Surveys must be performed to maintain surveillance on the hazards which might be present, and records must be kept.
5. Personnel must receive written instructions as to the hazards present in the area (proper operating procedures and emergency procedures posted).

Permissible Levels of Radiation in Uncontrolled Areas

No user shall possess, use, or transfer sources of radiation in such a manner as to create in any uncontrolled area (from such sources of radiation in his/her possession) radiation levels which, if an individual were continuously present in the area, could result in his/her receiving a dose in excess of:

1) 2 millirem in any one hour, or

2) 100 millirem in any one week, or

3) 500 millirem in any one year

Instruction of Employees

Regulations stipulate that radiation workers must be kept informed of the hazards which they may encounter and methods by which they can provide for their own safety. The Administrative Panel on Radiological Hazards requires that research supervisors avail themselves of every opportunity to improve the technical and professional proficiency of their students and employees in the area of radiation safety. Written safety procedures approved by the Director of Health Physics must be established for each laboratory. All persons working in the laboratory will be required to familiarize themselves with these procedures. Basic standards and safeguards are outlined in this manual.

Records

The University is required to maintain the following records for inspection by licensing agencies:

1. Reports of radiation exposures of personnel.

2. Records of receipt, location, utilization, and disposal of radiation sources.

3. Reports of instrument surveys and laboratory inspections performed by the Health Physics Department.

4. Reports of radiation surveys performed by users.

5. Copies of applications for use of radiation sources plus the associated Hazards Analysis Reports originated by Health Physics.

6. Physical examination records (when applicable).

7. Copies of agenda and minutes of the University Radiological Hazards Control Committees.

Non-Compliance

It should be noted that failure to demonstrate compliance with regulations in any laboratory could result in undesirable restrictions which may affect all users of all radiation sources.

Special Requirements for High Radiation Areas Produced by Radiation Producing Machines

Except for high radiation areas caused by radiographic and fluoroscopic machines used solely in the healing arts, each entrance or access point to a high radiation area shall be:

a) equipped with a control device which shall cause the level of radiation to be reduced below that at which an individual might receive a dose of 100 millirems in 1 hour upon entry into the area; or

b) equipped with a control device which shall energize a conspicuous visible or audible alarm signal in such a manner that the individual entering the high radiation area and the licensee or a supervisor of the activity are made aware of the entry; or

c) maintained locked,except during periods when access to the area is required, with positive control over each individual entry.

VIII PROTECTION FROM MACHINE PRODUCED IONIZING RADIATIONS

Relationship between Exposure Rate and Distance from Source

$$\frac{I_1}{I_2} = \frac{(d_2)^2}{(d_1)^2}$$

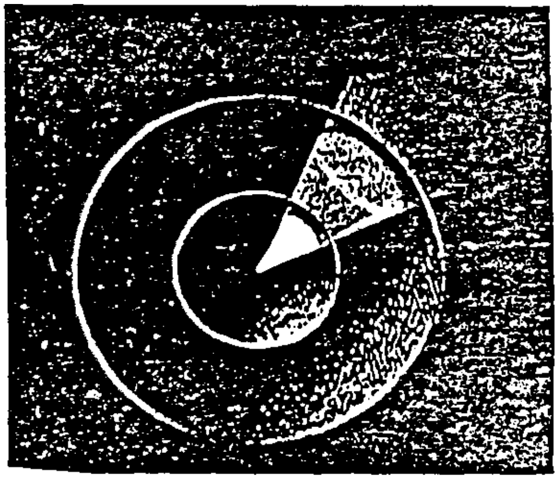
where: I_2 = exposure (dose) rate at distance d_2

where: I_1 = exposure (dose) rate at distance d_1

(the distances must be in the same units)

Inverse square rule: radiation intensity decreases inversely as the square of the distance from the source.*

Drawing from:
*Diagnostic Nuclear Medicine
E.R. Powsner, D.E. Raeside,
1971



Shielding of Radiation Sources

1) Shielding of X ray Sources

$$I = BI_0e^{-\mu x}$$

where: B = build up factor (dependent upon composition of shielding, the energy of the gamma radiations and the thickness of shield). See Radiological Health Handbook, 1970 edition, PHS Publication No. 2016.

I_0 = the original exposure rate
e = base of natural logarithm system = 2.7183...
x = the shield thickness
μ = the linear attenuation coefficient (in reciprocal units of the shield thickness)

NOTE: $\mu = \frac{\mu}{\rho} \times \rho$

where: $\frac{\mu}{\rho}$ =the mass attenuation coefficient

ρ = the density of the shielding

Mass attenuation coefficients for various energies of X rays in various materials are included in the appendices. See NSRDS-NBS Report #29 for a more complete tabulation of values.

Half-value Layer

(Approximate half-value layers obtained for the indicated tube potentials under broad beam conditions.)

Attenuating Materials	HVL for various tube potentials (in kVp, >300 in kcVp)									
	50	70	100	125	150	200	250	300	400	500
Lead(mm)	0.05	0.16	0.24	0.27	0.3	0.5	0.8	1.3	2.2	3.6
Concrete(cm)	0.51	1.27	1.8	2.0	2.3	2.5	2.8	3.0	3.3	3.6

Standards for Design of Shielding

1) Plans for shielding and shielding calculations for proposed facilities are to be reviewed and approved by Health Physics.

2) Wherever shielding is required it is to be designed to resist cold flow and mechanical damage. Due regard is to be taken of the potenial seismic effects on shielding. Portable shields are to be provided with a base structure so that the shields will not fall over or collapse in a minor quake.

3) Dose rates in uncontrolled areas shall not exceed those specified in Section VI.

Personnel Dosimetry

General requirements related to personnel dosimetry are described in Section V. However, it is useful to remind workers who wear lead aprons to wear the film badge outside of the apron at the collar.

Also, it is noted that each person who operates X-ray diffraction types of equipment is required to wear BOTH a film badge on his/her body and a finger dosimeter.

Film badges must be worn in any area where the exposure rates exceed 100 mr/hr.

Security

Radiation producing machines are to be installed in rooms (or areas) which are locked to secure the machine against unauthorized use. Alternatively the machine may be equipped with a locking mechanism to prevent its being used by an unauthorized person.

Posting and Labeling Requirements

In certain instances signs or labels are required for significant levels of radiation. These requirements are generally outlined in Section V.

Consult with Health Physics (ext. 7-3201) for proper instructions for posting or otherwise controlling areas where radiation dose rates exceed 100 mrem/hour.

The following are some of the specific requirements for signs and labels which are appropriate around radiation producing machines. Signs and labels are usually available from Health Physics.

1. "Caution - Radiation Area" Sign. This sign is used in areas accessible to personnel in which a major portion of the body could receive in any one hour a dose of 5 mrem or in any 5 consecutive days a dose in excess of 100 mrem.

2. "Caution - High Intensity X-ray Beam..Wear Finger Ring and Film Badge Dosimeters" label. This label is to be affixed to the control panel of all X-ray Diffraction types of machines.

3. "Caution Radiation - This Equipment Produces Ionizing Radiations When Energized" label. This label is affixed to all devices which produce ionizing radiations at levels requiring the machines to be registered with the State. A variant of this label adds that the equipment is "to be operated by qualified personnel only."

4. "Notice to Employees" Department of Health Services Form # 2364 is to be placed in a sufficient number of places accessible to individuals working in or frequenting a controlled area to observe the signs on

their way to or from such an area.

5. "Notice - Film Badges Required" sign. This OSHA type advisory sign is used to warn personnel that film badges are to be worn in the area. These signs are frequently placed in the areas around medical X-ray machines.

6. "Caution - X rays" sign. This sign is used to post medical X ray installations.

7. "Caution (or Danger) - High Radiation Area" sign. This sign is to be posted in areas where radiation levels exceed 100 mrems in one hour. Usually the sign will contain additional advice, " Personnel Dosimeters Required", etc.

8. Other posting requirements:

A) A list of approved operators

B) A copy of the most recent survey by Health Physics

C) Operating instructions including the statement:"Further information regarding radiation safety is available in the Radiation Protection Manual or by calling the Health Physics Office (X 73201)."

D) Emergency procedures including the following statement: "Notify Health Physics Department in the event of accident or suspected overexposure.

E) For medical machines a table indicating exposures received by patients undergoing radiological procedures on that machine is also to be posted.

Interlocks, Warning Devices, Panic Switches

Appropriate interlocks, warning devices and emergency switches are required for many types of radiation producing machine installations. Some of the general requirements are listed below. Health Physics will specify particular requirements as a part of the Hazards Evaluation for a project.

A) Where conditions require installation of a radiation producing machine (which is capable of producing a high radiation area) within a protective shielded enclosure, all access doors shall be equipped with interlocks which shall secure the entry such that to enter will interrupt the operation of the equipment causing the dose rate to be reduced below 100 mrem/hour or will trigger a warning alarm to notify the operator and the person entering the high radiation area. It shall not be possible to resume operation of the machine merely by closing the door. It shall be necessary to manually reset the machine with a suitable device near the operator's control station.

B) In enclosed protective installations a panic switch shall be placed in the enclosure to enable any person who becomes trapped within to shut off the operation of the machine. This switch shall be clearly identified and shall not be capable of being reset from outside the enclosure.

C) Each radiation machine which is capable of producing in any area accessible to individuals, a dose rate in excess of 100 mrems per hour shall be provided with a conspicuous visible or audible alarm such that any individual at or approaching the tube head or radiation port is made aware that the machine is producing radiations. Such an alarm signal shall be automatically activated only when radiation is being produced. (Such alarm signals are not required for medical radiographic or fluoroscopic installations used in the healing arts.)

D) Interlocks and warnings that are required for safety shall be of a fail-safe design which has been reviewed by Health Physics.

E) Interlocks and warning devices shall be subject to routine monthly inspection by the user, and the results of the tests maintained in a log book. If systems are found to be defective, the machine shall not be operated until repairs have been completed and reinspected by Health Physics.

ANALYTICAL X-RAY MACHINES AND SIMILAR DEVICES

Electron Microscopes

Normally these devices do not present significant radiation hazards. Operators need not wear personnel dosimeters. Health Physics performs a radiation survey every two years or when requested by the project director. These machines should not be modified in any way to increase the radiation output or reduce the shielding. (Particularly one should not change the materials in the column housing the beam or target or the viewing windows. Electron microcsopes are usually surveyed by Health Physics at two-year intervals.

These devices are posted with a special label which is variant of the "caution-this equipment produces ionizing radiations when energized" sign.

Note: Uranium salts frequently are used in electron microscopy of biological specimens. Hazards associated with uranium (naturally radioactive) are described in the Appendix.

General Safety Instructions for X-ray Diffraction Machines

1) All operators must be certified by Health Physics, and receive operational safety instructions from the project director. Use only procedures approved by manufacturer or alternate procedures approved in CRA. A training film entitled, "The Two Edged Sword" is available for training X-ray diffraction machine operators.

2) All operators are required to wear both a film badge and finger dosimeters.

3) When aligning cameras by eye be sure that the machine is turned off or that the viewing is done through a properly designed lead glass viewing window.

4) Make sure that the machine is turned off before changing samples. Check the kV and mA meters and the warning light. Never by-pass interlocks or warning systems.

5) Survey the machine to ensure that the exposure rate at the table edge is less than 0.2 mR/hr.

6) Use shielding to ensure that the above limits are satisfied. Do not remove (or move) fixed shielding from the machine.

7) Maintain direct surveillance of the machine, unless the area is secured. (Usually machines must be in a locked room.)

8) Check safety apparatus, shutters warning lights, survey meter, shields, for proper function. Report any malfunctions, defects, etc., to the project director. Do not operate a machine with a safety defect. Post the machine, "Do Not Operate", until the problems are corrected. Check safety devices monthly.

9) If any changes are made in the machine which would affect radiation output, call Health Physics for a survey.

10) Promptly report any accidental exposures or potential injuries to Health Physics and the project director.

11) Maintain a log of all operations.

Approximate Formula for Calculating Exposure Rates from Analytic X-Ray Machines (Developed by B. Lindell) Health Physics, Vol 15, pp 481-486

(Accuracy within factor of 2 for tubes with 1 mm Be window)

$$\dot{X}(\mathrm{R/sec}) = \frac{50(\mathrm{kV}) \times (\mathrm{mA}) \times Z}{\mathrm{cm}^2 \times 74} = \frac{50 \times V(\mathrm{kV}) \times I(\mathrm{ma}) \times Z}{[r(\mathrm{cm})]^2 \times 74}$$

Where Z= atomic number of the target
kV= tube potential in kilovolts
mA= tube current in milliamps

FROM ICRU REPORT NO. 17

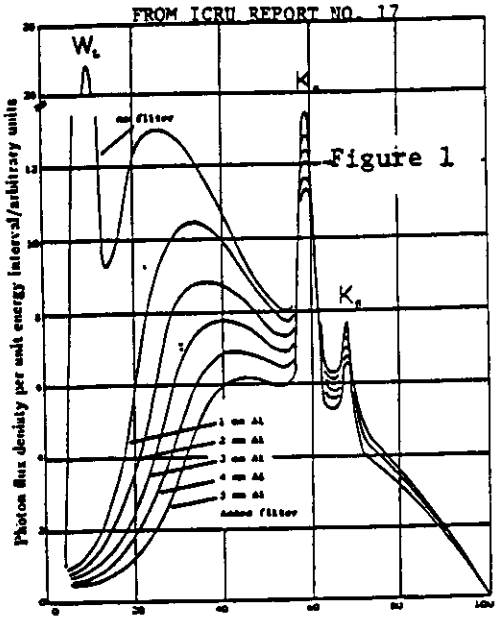


Figure 1

Spectral distributions of x rays from a tube with 1 mm Be inherent filtration operated at 100 kV and with various filters (measured after passage through 2 m of air).
[Derived from Drexler and Perzl, 1968b]

An energy spectrum for the photons produced with an X-ray tube having a tungsten target is shown in Fig. 1. Note the appearance of the two main features of the spectrum: the bremsstrahlung portion which falls approximately linearly with increasing energy and the X-ray portion consisting of three sharp peaks. The maximumm energy of the bremsstrahlung portion is 100 keV while the mean energies of the K_{alpha} and K_{beta} lines of tungsten are 58.840 and 67.596 keV (see below). The L X-ray lines fall into one peak shown at about 10 keV. The effect of adding aluminum filtration is hardening the spectrum in that the population of low-energy photons is materially reduced. In fact, the tungsten L lines completely disappear from spectrum if enough aluminum filtration is employed.

Conversion of a Measured Exposure to Absorbed Dose

The conversion of a measured exposure to absorbed dose in a medium requires a knowledge of the ratio

$$S = (\bar{\mu}_a/\rho)_{med}/(\bar{u}_a/\rho)_{air}$$

where $\bar{u}_a/\rho$ is the value of the energy absorption coefficient averaged over the photon energy spectrum. The relation between the measured exposure and the absorbed dose is

$$D(rad) = f\ X(R)$$

where f = 0.877S is tabulated for several materials in Appendix D. An example is given of calculating absorbed dose. Note: the units in the tables are in the m-k-s system.

Example:

An X-ray beam consisting of 100 R/hour of 50-keV photons is measured with a properly calibrated survey instrument. Calculate the dose equivalence rates for water, compact bone and muscle, neglecting attenuation or scatter of the radiation.

Answer: dose equivlence rates for
water: 0.89 x 100 = 89 rem/hour
compact bone: 3.62 x 100 = 362 rem/hour
and
muscle: 0.93 x 100 = 93 rem/hour

Experimental Exposure Rates in Direct and in Scattered Beams

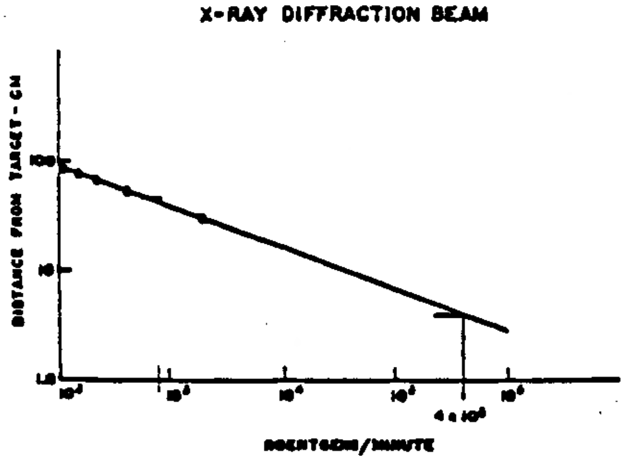
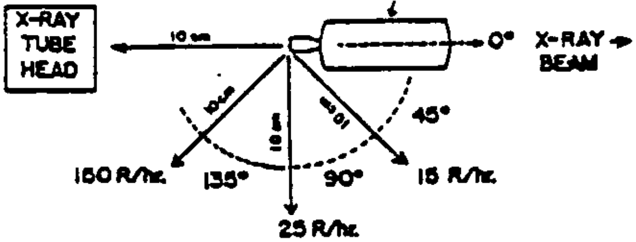


Figure 2 shows the exposure rate (R/min) which was measured at various distances from the port of an X-ray tube. An extrapolation gives 400,000 R/min at the port, a result not inconsistent, within a factor of two or so, with the result obtained in the example calculated by the Lindell formula. The addition of a 0.0007 inches of nickel filter reduced the extrapolated exposure rate to 200,000 R/min.

Fig. 3 shows the exposure rate (R/hour) measured for scattered radiation at a distance of 10 cm from a sample in front of an X-ray diffraction camera.



Both figures were taken from "Radiation Hazards from X-ray Diffraction Equipment" by J.R. Howley and C. Robbins, Radiological Health Data and Reports 8, No.5, May 1967, pp.245-249

INSTRUMENT SURVEYS AROUND RADIATION PRODUCING MACHINES

Good laboratory practice dictates that radiation surveys be made whenever an experiment is set up to ensure that sources are adequately shielded.

See also Section V, "Radiation Surveys", for general discussion of survey instruments.

Two types of portable instruments are commonly used to make radiation surveys around radiation producing machines.

1. The air filled ion chamber instruments. They are principally effective for measuring fields of radiation around gamma or X-ray sources. It is very difficult to detect less than 0.1 mR/hr on the most sensitive of these instruments. These instruments are usually goodfor survey of X-ray machines especially those which generate broad beams of X rays.

2. The Geiger-Mueller (GM) Counter is more sensitive than the ion chamber. Exposure rates as low as 0.01 mR/hr can be detected. GM instruments have detectors filled with a gas other than air, thus do not read exposure rates [roentgens(R)/hr] directly. Radiations cause electrical discharges in the GM detector tube. These discharges are converted to electronic pulses (counts) per minute (or second) and are read on a meter. The sensitivity varies markedly with energy, so that an instrument calibrated with the Cs-137 (0.662 MeV gamma) radiations (as is the practice on campus) will tend to over-respond to lower energy radiations. A GM counter used on campus should be equipped with a thin end-window GM tube to permit detection of low energy X-ray radiations. G M counters should also be equipped with a speaker or other audible indicator, to allow one to survey without watching the meter — this is a unique advantage of the pulse counting system. Most GM counters can become paralyzed in moderately high radiation fields, greater than a few R/hr. This is a serious problem when high levels of radiation are present especially when one is surveying around an X-ray diffraction machine. The paralyzed instrument may give a zero reading in such a field. The instrument which is recommended for use around X-ray machines the El Scint GSM-1. This has all of the desirable features and does not become paralyzed in fields up to 400 R/hr. Care needs to be exercised when using GM counters to survey x-ray machines. This is because the GM counters are very energy dependent. Also, the meters can respond to the frequency at which a radiation machine may be generating radiations. These factors may cause erroneous (low!) readings.

3. When using either of the above instruments make surveys with window shield in proper condition, "open" if low energy X rays are present. For low energy X rays, "point" the thin window toward the source of X rays. For low level radiations (fraction of an mR per hour) move the probe slowly. This will allow the instrument to respond to the radiations. Most instruments have a long time constant on the most sensitive ranges to allow for a good statistical estimate of the exposure rate. Keep hands out of the x-ray beam when surveying.

Be sure instrument is calibrated annually by Health Physics — or after major repairs are made. Be sure to know what the characteristics of the instrument are. Review the manual and/or check with Health

Physics. Be careful to avoid breaking the thin window of the detector. As noted above, calibration is a very important consideration in interpreting the results of a "reading." For Elscint meters open window readings for low energy X rays will be high by a factor of 2 at about 25-30 keV or significantly low if the energies are below 6 keV. Different energies of radiation require different calibration factors.

On balance, the Elsint GSM-1 survey meter is the best instrument for surveying for small radiation leaks from X-ray diffraction machines.

Corrections to Exposure Rates Measured with an Ionization Chamber

The problem is frequently encountered around an X-ray diffraction unit is poor shielding in which small-diameter beams leak out of holes in the shielding and which are much smaller than the diameter of an ionizatin chamber. Figure 4 shows such a small beam impinging on an ionization chamber. The actual exposure rate is A_2 (the area of the chamber)/A_1 (the area of the beam) times the measured exposure rate.

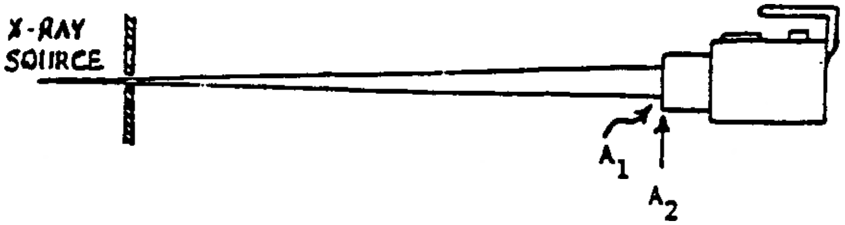


Figure 4: Correction for small beam size. In this case the exposure rate reading of the ion chamber is to be multiplied by A_2/A_1

Example:

The area, A_2, for the Victoreen Model 440 ionization chamber is about 62 sq cm . Suppose the beam comes from a point source 2 cm in back of the shielding, passes through a 1-mm hole, and impinges on the chamber 10 cm in front of the shielding. Calculate the beam area, A_1, at the chamber and the ratio A_2/A_1

Answer: $A_1 = 0.28\ \text{cm}^2$, $A_2/A_1 = 221$

One way to avoid the uncertainty in the determination of the beam area would be to move the chamber further away until the beam covers the whole end face of the chamber. This situation is illustrated in Figure

5 but now corrections have to be made for inverse-square falloff of the intensity and for air attenuation (for low energy X rays).

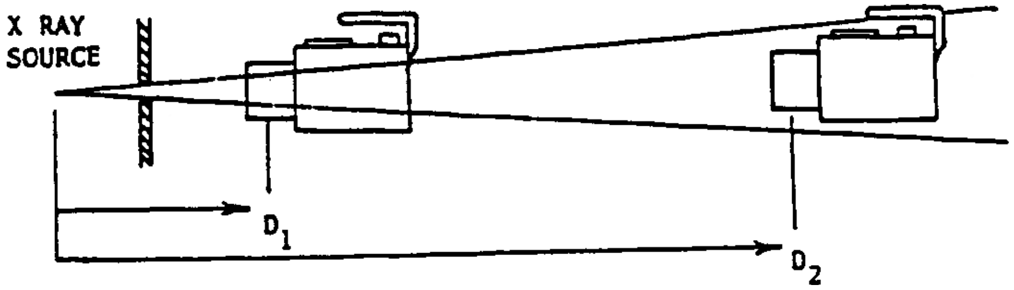


Figure 5: Correction for distance and air attenuation to find the exposure rate near the source when the measurement is far from the source. The exposure rate reading at the distant position is to be multiplied by $(D_2/D_1)^2 \exp[-\frac{\mu}{\rho}(D_2-D_1)\rho]$ to give the correct exposure rate at the near position.

Specific Exposure Hazards Associated with Analytical X-ray Machines

Accident Causes

Bo Lindell, (Health Physics, Vol. 15), notes that four types of accidents appear to be responsible for most injuries with X-ray diffraction machines. These are summarized in the table below.

Accident Causes

A. Careless Work

Missing cover plates at Head Ports not in use.

B. Routine Work

Adjustment of samples or alignment of cameras, not noticing the tube "on"

C. Equipment failure

Failure of shutter, warning lights, etc., during normal operations

D. Inadequate instruction or violation of instruction

Non-routine operations with tube "on" believed to be "off" because of ignorance

Types of Injuries

The part of the body which is primarily affected by X-rays with energies less than 50 keV is the skin, especially that on the hands, but there exists considerable lack of information on the long term effects of such soft (by medical standards) radiation - the experimental work appears to be done mostly with harder radiation. Skin damage can be classified into three categories: reversible changes, conditional reversible changes, and irreversible changes. Included in reversible changes are temporary reddening of the skin (erythema), temporary stoppage of hair growth, and temporary loss of production of sebum by the sebaccous glands (fat-producing glands). Approximately 500 R of exposure of the skin to soft X rays can cause erythema. Pigmentation involving the production of large amounts of melanin pigment in the skin is regarded as sign of a conditional reversible change because when it disappears the skin appears to be more vulnerable to radiation damage. Finally irreversible changes are produced when enough radiation is absorbed in the skin to produce permanent destruction of either hair or sweat glands, or whole skin with a resulting scar. These irreversible changes come under the heading of radiation dermatitis and radiation cancer. A second concern is potential damage to the eyes from large (greater than 200 R) accidental exposures to X rays. Such large doses may cause cataracts. The annual rate of severe radiation injuries for x-ray diffraction instuments is one in one-hundred units.

CABINET TYPE X-RAY MACHINES

Cabinet X-ray machines are machines designed to operate in enclosed, shielded, interlocked cabinets. The machine can only operate when the opening(s) is securely closed. The exposure levels at every location on the exterior must meet the levels specified for uncontrolled areas. All operators must be trained in the proper operation of the device and be certified in radiation safety associated with the device by the Health Physics Department. (Levels must be less than 0.2 mR/hr at one foot from the outside of the cabinet.)

Note: Many cabinet devices are designed for irradiation of biological samples and produce very high levels of low energy X rays, similar to the X-ray diffraction machines. Exposure to the direct beams for even a few seconds can produce injurious skin burns. Never operate such a machine if the interlocks appear to be malfunctioning. In certain cases it may be appropriate to wear a finger dosimeter as an accident dosimeter. Such dosimetry requirements will be spelled out in the Hazards Evaluation.

General Safety Instructions for Operators of Cabinet X-ray Machines

APPENDIX D

MASS ATTENUATION COEFFICIENTS* FOR SELECTED LOW-Z ELEMENTS AND COMPOUNDS MADE FROM THESE ELEMENTS

*ICRU Report 17 -- "Radiation Dosimetry: X rays Generated at Potentials of 5 to 150 kV" (June 15, 1970)

TABLE 1a—*Values of mass attenuation coefficients*

Photon Energy keV	Mass attenuation coefficient, $(\mu/\rho)/\mathrm{m^2\,kg^{-1}}$ (Multiply by 10 if $\mathrm{cm^2\,g^{-1}}$ required)											
	H	C	N	O	Na	Mg	Al	P	S	Ar	K	Ca
1	0.860	210	329	463	—	—	—	—	—	—	—	—
1.5	0.287	67.0	106	153	341	441	—	—	—	—	—	—
2	0.143	29.5	46.8	68.0	152	197	239	—	—	—	—	—
3	0.0717	8.91	14.3	20.9	48.5	63.4	76.8	114	139	—	—	—
4	0.0514	3.77	5.98	8.88	21.5	28.2	34.6	51.5	63.5	70.0	98.4	—
5	0.0445	1.91	3.06	4.59	11.4	15.1	18.5	28.0	34.4	43.0	53.6	63.3
6	0.0420	1.07	1.75	2.65	6.79	9.07	11.1	16.9	20.8	26.1	32.6	38.5
8	0.0395	0.439	0.722	1.12	2.96	4.01	5.0	7.62	9.45	11.9	14.9	17.6
10	0.0387	0.225	0.369	0.570	1.54	2.10	2.63	4.06	5.05	6.42	8.01	9.48
15	0.0376	0.0767	0.117	0.176	0.459	0.627	0.783	1.23	1.54	1.99	2.49	2.98
20	0.0369	0.0424	0.0589	0.0824	0.199	0.268	0.335	0.523	0.657	0.851	1.07	1.29
30	0.0357	0.0250	0.0297	0.0365	0.0694	0.0897	0.108	0.163	0.203	0.262	0.333	0.40
40	0.0346	0.0206	0.0225	0.0254	0.0388	0.0473	0.0549	0.0776	0.0947	0.118	0.149	0.179
50	0.0335	0.0186	0.0196	0.0211	0.0275	0.0322	0.0359	0.0474	0.0565	0.0677	0.0842	0.0998
60	0.0326	0.0175	0.0181	0.0190	0.0225	0.0253	0.0272	0.0342	0.0394	0.0454	0.0553	0.0643
80	0.0309	0.0161	0.0164	0.0167	0.0170	0.0194	0.0201	0.0231	0.0255	0.0273	0.0322	0.0362
100	0.0295	0.0151	0.0153	0.0155	0.0159	0.0169	0.0171	0.0186	0.0201	0.0187	0.0233	0.0256
150	0.0265	0.0134	0.0135	0.0136	0.0134	0.0140	0.0138	0.0144	0.0150	0.0143	0.0159	0.0168

TABLE 1b—*Values of mass attenuation coefficients*

Photon Energy keV	Mass attenuation coefficient, $(\mu/\rho)/\mathrm{m^2\,kg^{-1}}$ (Multiply by 10 if $\mathrm{cm^2\,g^{-1}}$ required)								
	Polystyrene $(C_8H_8)_n$	Perspex, Plexiglass, Lucite $(C_5H_8O_2)_n$	Polyethylene $(CH_2)_n$	Bakelite $(C_{43}H_{38}O_7)_n$	Water	Air[a]	Compact bone[a]	Muscle[a]	Fricke dosimeter solution (0.4 mol/l H_2SO_4)
1	193	277	180	242	412	—	—	—	—
1.5	61.6	89.1	57.1	77.6	135	—	—	—	—
2	27.2	39.4	25.2	34.2	60.1	—	—	—	—
3	8.21	12.0	7.63	10.4	18.5	—	—	17.9	19.9
4	3.48	5.10	3.24	4.42	7.89	7.60	—	7.90	8.63
5	1.77	2.62	1.64	2.25	4.08	3.93	13.9	4.10	4.49
6	0.990	1.49	0.922	1.28	2.36	2.28	8.34	2.38	2.61
8	0.408	0.624	0.382	0.531	0.909	0.960	3.75	1.01	1.11
10	0.211	0.322	0.198	0.273	0.516	0.496	2.00	0.524	0.576
15	0.0737	0.105	0.0711	0.0911	0.161	0.155	0.628	0.164	0.179
20	0.0420	0.0547	0.0416	0.0488	0.0773	0.0747	0.278	0.0790	0.0850
30	0.0258	0.0295	0.0265	0.0276	0.0364	0.0343	0.0058	0.0368	0.0386
40	0.0217	0.0233	0.0226	0.0222	0.0264	0.0244	0.0510	0.0265	0.0273
50	0.0198	0.0206	0.0207	0.0199	0.0225	0.0206	0.0347	0.0224	0.0229
60	0.0187	0.0192	0.0197	0.0186	0.0205	0.0187	0.0272	0.0204	0.0207
80	0.0173	0.0175	0.0182	0.0171	0.0183	0.0166	0.0208	0.0182	0.0184
100	0.0162	0.0164	0.0172	0.0160	0.0171	0.0154	0.0180	0.0169	0.0171
150	0.0144	0.0146	0.0153	0.0142	0.0150	0.0135	0.0149	0.0149	0.0150

APPENDIX D

MASS ENERGY ABSORPTION COEFFICIENTS* FOR SELECTED LOW-Z ELEMENTS AND COMPOUNDS MADE FROM THESE ELEMENTS

*ICRU Report 17 -- "Radiation Dosimetry: X rays Generated at Potentials of 5 to 150 kV" (June 15, 1970)

TABLE 2a—*Values of mass-energy absorption coefficients*

Photon Energy keV	Mass energy absorption coefficient, $(\mu_{en}/\rho)/m^2\ kg^{-1}$ (Multiply by 10 if $cm^2\ g^{-1}$ required)											
	H	C	N	O	Na	Mg	Al	P	S	Ar	K	Ca
1	0.819	209	328	459	—	—	—	—	—	—	—	—
1.5	0.250	66.9	106	152	335	430	—	—	—	—	—	—
2	0.100	20.3	46.7	67.7	150	193	233	—	—	—	—	—
3	0.0312	8.85	14.2	20.8	47.8	62.4	75.2	110	132	—	—	—
4	0.0122	3.71	5.88	8.79	21.2	27.7	33.9	50.0	60.9	73.3	88.9	—
5	0.00586	1.85	3.00	4.51	11.2	14.9	18.2	27.2	33.1	40.4	49.4	56.8
6	0.00326	1.03	1.69	2.58	6.66	8.91	10.9	16.5	20.1	24.7	30.4	35.1
8	0.00150	0.404	0.683	1.07	2.87	3.92	4.88	7.43	9.18	11.4	14.1	16.4
10	0.00100	0.194	0.338	0.534	1.48	2.02	2.55	3.94	4.89	6.16	7.61	8.91
15	0.00107	0.0515	0.0903	0.146	0.419	0.581	0.737	1.17	1.47	1.89	2.37	2.81
20	0.00131	0.0202	0.0354	0.0574	0.168	0.234	0.299	0.482	0.610	0.796	1.01	1.21
30	0.00184	0.00678	0.00979	0.0157	0.0463	0.0649	0.0830	0.135	0.173	0.231	0.296	0.358
40	0.00230	0.00296	0.00440	0.00681	0.0191	0.0263	0.0338	0.0549	0.0704	0.0945	0.122	0.149
50	0.00270	0.00217	0.00294	0.00404	0.00988	0.0136	0.0173	0.0278	0.0357	0.0477	0.0620	0.0761
60	0.00303	0.00199	0.00238	0.00301	0.00623	0.00820	0.0103	0.0165	0.0207	0.0277	0.0358	0.0439
80	0.00362	0.00199	0.00213	0.00238	0.00363	0.00451	0.00532	0.00738	0.00958	0.0124	0.0159	0.0193
100	0.00406	0.00212	0.00219	0.00232	0.00288	0.00335	0.00372	0.00496	0.00589	0.00720	0.00909	0.0108
150	0.00482	0.00241	0.00245	0.00248	0.00258	0.00276	0.00281	0.00318	0.00344	0.00370	0.00437	0.00490

TABLE 2b—*Values of the mass energy absorption coefficients and of the factor f*

Photon Energy keV	Mass energy absorption coefficient, $(\mu_{en}/\rho)/m^2\ kg^{-1}$ (Multiply by 10 if $cm^2\ g^{-1}$ required)									$\frac{f}{rad/R} = 0.869 \frac{(\mu_{en}/\rho)_{med}{}^{a}}{(\mu_{en}/\rho)_{air}}$			
										Medium			
	Polystyrene $(C_8H_8)_n$	Perspex, Plexiglass, Lucite $(C_5H_8O_2)_n$	Polyethylene $(CH_2)_n$	Bakelite $(C_{43}H_{38}O_7)_n$	Water	Air[a]	Compact bone[a]	Muscle[a]	Fricke dosimeter solution (0.4 mol/l H_2SO_4)	Water	Compact bone	Muscle	Fricke solution
1	192	275	170	241	409	—	—	—	—	—	—	—	—
1.5	61.5	88.7	57.1	77.3	135	—	—	—	—	—	—	—	—
2	27.0	39.2	25.0	34.0	59.9	—	—	—	—	—	—	—	—
3	8.15	11.9	7.58	10.3	18.4	—	—	17.8	19.7	—	—	—	—
4	3.42	5.04	3.18	4.35	7.81	7.43	—	7.77	8.51	0.913	—	0.909	0.995
5	1.71	2.55	1.59	2.19	4.01	3.84	12.8	4.01	4.39	0.907	2.90	0.907	0.995
6	0.951	1.44	0.883	1.23	2.29	2.20	7.76	2.30	2.53	0.907	3.07	0.911	1.002
8	0.373	0.584	0.346	0.493	0.950	0.912	3.53	0.961	1.06	0.905	3.36	0.916	1.009
10	0.170	0.287	0.166	0.240	0.474	0.450	1.88	0.483	0.533	0.898	3.56	0.913	1.008
15	0.0476	0.0776	0.0443	0.0645	0.130	0.127	0.576	0.134	0.148	0.891	3.95	0.917	1.012
20	0.0187	0.0306	0.0175	0.0254	0.0511	0.0504	0.244	0.0530	0.0585	0.881	4.20	0.914	1.010
30	0.00548	0.00863	0.00521	0.00722	0.0142	0.0140	0.0710	0.0148	0.0163	0.876	4.39	0.915	1.005
40	0.00291	0.00414	0.00287	0.00357	0.00631	0.00620	0.0208	0.00658	0.00715	0.884	4.18	0.923	1.003
50	0.00221	0.00281	0.00225	0.00252	0.00389	0.00378	0.0157	0.00403	0.00431	0.895	3.62	0.926	0.991
60	0.00207	0.00240	0.00214	0.00222	0.00301	0.00286	0.00971	0.00300	0.00324	0.917	2.96	0.939	0.987
80	0.00212	0.00225	0.00222	0.00215	0.00252	0.00232	0.00524	0.00254	0.00261	0.943	1.96	0.951	0.977
100	0.00227	0.00234	0.00240	0.00227	0.00252	0.00229	0.00381	0.00251	0.00256	0.957	1.45	0.956	0.972
150	0.00260	0.00263	0.00276	0.00256	0.00274	0.00247	0.00302	0.00272	0.00275	0.964	1.06	0.956	0.965