GUIDE FOR SAFE HANDLING OF RADIOACTIVE SOURCES
and
A PRIMER ON THE EFFECTS OF EXPOSURE TO IONIZING RADIATION

Exposure to "natural" radiation from cosmic rays, as well as radioactive materials in the soil and building materials, is unavoidable. The additional hazards from "artificial" radiation sources, such as X-ray machines, radionuclides, the burning of fossil fuels, nuclear power plants, airline travel, etc., are amenable to some degree of control. While it is not yet possible to say exactly how bad exposure to ionizing radiation can be to an organism, it is prudent to minimize all exposure to all ionizing radiation. The material presented here is intended to assist you in safely using radioactive sources in this laboratory. References, listed on page 6, should be consulted for a more extensive treatment. Because your exposure to significant amounts of radiation is minimal in the benign academic environment that you now enjoy, this is the time and place for you to develop good work habits and confidently accept responsibility for all decisions regarding what constitutes an acceptable risk to you. Ask questions and seek advice, but make up your own mind.

HANDLING RADIOACTIVE SOURCES:

Only sealed sources will normally be available in this laboratory. The basic details of the source construction are noted in the Inventory contained in APPENDIX A (last page). Most of the available sources can emit only γ– rays to the experiment, the impact-resistant epoxy/plastic encapsulation totally absorbing all β-ray emissions. Two exceptions are: ^{144}Ce (a welded metal capsule with a very thin aluminum exit window used with Exp. 13) and a special ^{60}Co source (a thin delicate plastic sandwich installed in Exp.17). These are β–γ-ray emitters with thin exit windows to allow emission at the lowest β–particle energy, consistent with safe confinement of the nuclide. They are delicate and must be treated carefully. They emit high energy particles that deposit large quantities of energy in nearby soft tissue. **It is vital that they be kept well away from the eyes and handled only with the forceps provided!** The stronger plastic-rod γ-ray sources are stored in cylindrical lead containers that are color coded: RED for ^{137}Cs and ORANGE for ^{60}Co. Always carry these sources in their containers to minimize exposure, especially to your hand, and always return them to their containers when not in active use. ****** ALWAYS RETURN SOURCES, IN THEIR CONTAINERS, TO THE SOURCE BOX IN 210-A *BEFORE YOU LEAVE THE LABORATORY* ! ****** Before moving a source, check with everyone in the vicinity, so as to avoid disrupting a nearby experiment. While it may be possible to reduce the dose received from a source by piling large quantities of lead shielding around it, this procedure may degrade data, or even increase the dose rate if the shielding is carelessly placed. It is usually more practical to decrease the solid angle between yourself and the source by moving away from it. For example, double the distance and reduce exposure by 4x (square law).

MONITORING INSTRUMENTS AND MEASURING TECHNIQUES

A portable radiation monitor is available for your use: become familiar with its operation and behavior. Do not hesitate to ask questions if you are unsure of anything.

JOHNSON MODEL GSM-5 Handheld Survey Meter with General Purpose Probe:

Sensitivity - 0.2, 2.0, and 20.0 milli-Roentgen/hour (mR/hr)

Accuracy of Calibration ≈ 10 % (Correction factor supplied by C.I.T. Safety Office semiannually.)

Detector Probe - lead sheathed Geiger-Mueller Tube 1.0-2.0 mg/cm^2 beryllium end window. This end window is fragile and protected with a non-removable plastic grid plus an aluminum cap. Leave the protective aluminum cap in place except when measuring α-particles or low energy β's.

Energy Response:

- **α particles**: - >1 MeV (aluminum end cap OFF)
- **β particles**: - >5 keV (aluminum end cap increases efficiency at high energies.)
- **γ, X-rays:** - >5 keV (end window, aluminum cap ON) (Turn tube axis 90^o to allow the lead sheath to increase detection efficiency >1 MeV)

This instrument provides accurate data if it is used properly. Always check the batteries immediately after turning it on. If you have any reason to question the instrument's accuracy -- test it! All the sources in the laboratory have accurate calibrations of their strength. *An inventory is provided of all available sources (their I.D. numbers, level of activity, and the date of their calibration) on the last page of this document (APPENDIX A).*

EXPOSURE LIMITS FOR IONIZING RADIATION

Maximum limits for occupational exposure of individuals to ionizing radiation have been established by the State of California, based upon the recommendations of the Nuclear Regulatory Commission (NRC), the International Commission on Radiological Protection (IRCP), and the National Council on Radiation Protection and Measurements (NCRP).

The California Institute of Technology sets, and enforces, limits that are **10 times lower than the state limits**, about 3-times higher than the unavoidable whole body background dose for residents of Pasadena. These limits are based on the non-threshold hypothesis (p. 5), even though that has not yet been proven completely correct under all circumstances. It is only common sense to follow the most conservative guidelines when there is no definitive proof that greater exposure is totally safe. The Institute philosophy is exposure must be the lowest possible, and that every situation must be evaluated to determine if the exposure involved can be justified by real benefits that significantly outweigh the potential damage .

CALIFORNIA INSTITUTE OF TECHNOLOGY LIMITS
FOR IONIZING RADIATION EXPOSURE - 1991

Body Organ	MREM /hour	REM /3 mo	REM /year
Whole body; head and trunk; blood forming organs; eyes; or gonads	0.25	0.125	0.5
Hands, forearms, feet, and ankles	3.75	1.875	7.5
Skin of whole body	1.5	0.75	3.0
The DOSE/hour (milliREM) is based on a 250 day year and 8 hour day.			
Background (24 hours): Cosmic ray flux plus ^{228}Th and ^{40}K in building walls Room 210 East Bridge	0.017	0.03	0.154
Cosmic-rays only (variable over 11 year cycle)			0.035
(This background DOSE/year is based on a 24-hour day and 365-day year.)			

Continuous guidance and oversight of safe procedures are provided by the Campus Radiation Safety Committee, the Institute's Health Physicist, and the Division's Radiation Safety Officer. All ionizing radiation sources on campus are licensed, registered, regularly inventoried, and tested by the Institute's Health Physicist in conformance with the rules of the State of California. All areas where any radiation may be encountered are prominently marked and monitored monthly with film-type dosimeters placed at strategic locations.

Compare the DOSE limits and background levels above with the *normal background* encountered in other regions of the country listed below, as well as the level of exposure encountered during common activities.

Location	Total DOSE/hour	Total DOSE/year
Normal Background:		
Room 210 East Bridge Laboratory	0.017 mREM	0.154 REM
Colorado Springs, Colorado	0.022 mREM	0.197 REM
Chicago, Illinois	0.012 mREM	0.105 REM
New Haven, Connecticut	0.008 mREM	0.073 REM
Medical and dental X-rays	20-60 mREM (desired)	to >2 REM per examination of organ!
Passenger in Jet aircraft (30,000 ft.)	5 mREM	(cf. 210 E. Bridge Lab)

PHYSICS OF INTERACTION OF IONIZING RADIATION AND THE BODY

When an ionizing particle passes through matter it transfers energy to the electrons of the atoms and molecules of that matter. As the incident particle slows down and stops, the molecules along its path are left in excited states, or in ionized states if the energy transferred to the electrons is great enough. It is this excitation, or ionization, that produces damage to the cell structure of living tissue. The amount, and type, of damage is a function of the energy of the incident radiation and the interaction cross section of the material encountered.

BIOLOGICAL EFFECTS OF RADIATION

The reactions of living tissue to ionizing radiation is complex, and as yet rather poorly understood. A human cell consists of a membrane, an aqueous material called the cytoplasm, and the tiny nucleus that contains chromosomes and nucleic acids. There are two nucleic acids; **RNA** (Ribo Nucleic Acid) that controls the synthesis of the proteins required for the health of the cell, and **DNA** (Deoxyribo Nucleic Acid) that carries the genetic code for a species. Hereditary information will be found in the genes, the components of the long thread-like assemblies of DNA called chromosomes. Most human cells reproduce by dividing, a process controlled by components of the nucleus. Any alteration of the structure of these components, by radiation or other agents, can have serious consequences. When ionizing radiation interacts with, and transfers sufficient energy to disrupt any part of the nucleus of a cell, one of several conditions may be detected:

1. The cell suffers injury, but recovers without permanent damage,
2. Slight alterations of the DNA molecules of the gonads (ovaries or testes) that carry the genetic and hereditary codes occur. Such alterations (mutations) will remain hidden, but appear in later generations,
3. Only those components of the nucleus (RNA and DNA) that control nutritional and self-reproductive functions are affected, producing uncontrollable growth and division known as cancer,
4. Damage is so great that the cells do not divide successfully,
5. The cell is destroyed immediately. Massive exposure results in serious injury, or death, to the organism.

Some human cells do not reproduce by division. The blood cells are continuously produced by special organs, principally in the bone marrow. Brain, sensory, and motor nerve cells develop only in the womb. Any that are destroyed after birth cannot ever be replaced. Cellular damage in this case is of the type described in 1 and 5 above.

Items 1, 3, 4, and 5, describe SOMATIC damage that affects only the recipient of the radiation. Symptoms may appear quickly (within hours, days, months), or may be delayed for many years (10 to 30, or more), depending upon the type and amount of radiation received, and the parts of the body most seriously damaged. Item 2 describes GENETIC or HEREDITARY effects that will afflict only the descendants of the person irradiated. It is entirely possible for the one exposure to produce both types of damage. Items 1, 2, and 3 will be seen at all levels of dosage, while items 4 and 5 are produced by large doses. Typically, a short term whole-body dose of 1 REM (Roentgen Equivalent Man) will produce no immediately detectable effects, 10 to 20 REM will cause a noticeable drop in the blood's white cell count within days, while 600 REM will produce severe disability within hours and be fatal within 2 months to 50% of those individuals so exposed. For comparison, and reassurance, you receive about 0.0004 REM/day from background radiation in Pasadena, (See below for definitions of the REM and other units.)

Debate has raged for years over the validity of the **non-threshold vs. the threshold hypothesis**. Is there a threshold dose level below which no detectable effects are produced, or will all radiation, no matter how small the dose, produce cumulative harmful effects? Data have been obtained that seem to support both hypotheses, but a clear decision is not yet available. The no-threshold viewpoint appears to be valid with respect to long term effects, both somatic and genetic, while the threshold approach has been useful in describing the short term effects of moderate to substantial exposures (medical treatments). The current belief is that if exposure to radiation is unavoidable, it is best that the dose rate be kept low over a long period of time so as to give the body a chance to repair any damage before it becomes extensive, rather than receive a short large dose. Damage will result in either case but will be different in character.

DEFINITION OF UNITS AND TERMS USED IN IONIZING RADIATION PROTECTION

ACTIVITY OF SOURCE: The System International (SI) unit is the *Bequerel (Bq).* ***1 Bq = 1 event/second.*** The older, but more widely used, unit is the Curie **(Ci; 1 Ci ≡ 3.7 x 10^{10} Bq (3.7 x 10^{10} disintegrations/second).**

RADIOACTIVE HALF-LIFE (T_r): Time for a source to decay to 1/2 of its initial activity.

BIOLOGICAL HALF-LIFE (T_b): Time required for body to excrete 1/2 of ingested material. This rate is chemically determined, and is usually a much shorter time than the radioactive half-life (T_r), and may be significantly different for different organs. For examples: ^{14}C, with a T_r = 5700 years, has a T_b = 10 days for the whole body, and a T_b = 40 days for bone. ^{239}Pu (T_r = 24,000 years) has a T_b = 175 years for the whole body and 82 years for the liver. In contrast ^{32}P has a T_r = 14.3 days, and a T_b = 257 days for the whole body and 1115 days for bone.

EXPOSURE: The Roentgen is defined as the amount of X- and/or gamma - ray radiation that produces a charge of **1 esu** (2.08 x 10^9 ion-pairs) in 1 cc of dry air (STP). **1 esu/cc dry air = 1 ROENTGEN (R).** The SI unit has not been assigned a name, and equals 1 Coulomb/kg of dry air (STP). **1 R = 2.58 x 10^{-4} C/kg air.**

DOSE: The energy deposited in any material by any type of radiation. The SI unit is the **GRAY (Gy) = 1 J/kg.** The more common older unit is the ***Radiation Absorbed Dose (RAD) = 100 erg/gm = 10 mGy.*** DOSE is related to exposure by: **1 R = 88 erg/gm = 8.8 mGy = 0.88 RAD.**

QUALITY FACTOR (Q): A multiplying factor applied to the DOSE (Gy or RAD), representing the effect of different values of Linear Energy Transfer [LET - energy deposited per unit distance in tissue] for different types of radiation. The accepted values (September 1987) for Q are:

Radiation Type	Q	Radiation Type	Q
γ rays/X rays	1	Neutrons (Energy Unknown)	10
β Particles (E > 30 keV)	1	Thermal	2.3
Electrons/Positrons	1	0.02 MeV	3.3
Protons (E < 14 MeV)	10	0.50 MeV	11
α Particles (E < 14 MeV)	20	1.00 MeV	10.6

TABLE 1. Quality Factor (Q or QF) for various types of ionizing radiation (sometimes called RBE for Relative Biological Effectiveness)

DOSE EQUIVALENT (DE): The SI unit for DOSE EQUIVALENT (DE) = Sievert (Sv = Gy x Q). The older, more common, unit for (DE) is the Roentgen Equivalent Man (REM), DE = 1 REM = RAD x Q = 10 mSv. Dose Equivalent describes biological effects, hence the values of REM's produced by several sources of different types of radiation may be added.

The type of radiation, its intensity and energy, as well as the location of the source (external to, or inside the body) must be evaluated. High-energy radiation of any type will be hazardous whether the source is internal or external to the body. All high-energy β-particle and electron emitters must be handled with caution, since they deposit large amounts of energy in soft tissue, especially the eyes. If any nuclide is ingested, its total energy is deposited in the soft tissue of the most susceptible organ, resulting in serious damage. For example: 3.7×10^{-2} Bq (1pCi) of a 6 MeV α-particle emitter external to the body produces 0 DE. If ingested, the DE is 349 REM/hour! γ-ray sources, because of their high penetrating power almost always produce whole-body doses regardless of their location. Neutrons behave in the same way, and are damaging at all energy levels.

Reference: N. Tsoulfanidis, *Measurement and Detection of Radiation*, (McGraw-Hill Book Company, 1983), Chapter 16.

ESTIMATES OF DOSE FROM RADIOACTIVE SOURCES

A realistic estimate of the DOSE EQUIVALENT (DE) from a source requires only the use of a Survey Meter and simple calculations.

EXAMPLE 1: The "240   Ci" ^{137}Cs source emits a single 662-keV γ ray, and is located 1 m away. What is the DE?

* Survey Meter reading = 0.07 mR/hr (Room background = 0.02 mR/hr)
* 0.05 mR/hr x 0.88 = 0.044 mRAD/hr

* **0.044 mRAD/hr x 1 (Q) = 0.044 mREM/hr DE**

(*Caltech limit = 0.25 mREM/hr DE)*

(**N.B.:** A safe approximation is to use 1 R ≈ 1 RAD.)

EXAMPLE 2: A 10   Ci ^{144}Ce source, emitting β particles up to 2.995 MeV through its thin exit window. What is the DE with the source 30 cm. away from the eyes?

* Survey Meter reading (**Cap OFF**) = 1.7 mR/hr (Background negligible.)
* 1.7 mR/hr x 0.88 = 1.5 mRAD/hr

* **1.5 mR/hr x 1 (Q) = 1.5 mREM/hr DE**

(Caltech limit = 0.25 mREM/hr DE!)

EXAMPLE 3: What is the total DE received during a 5 hour session at the bench for Experiment 16 in Room 207 E. Bridge . (^{252}Cf Neutron source in 1.3 m^3 H_2O)?

* Survey Meter reading for γ rays = 0.03 mR/hr (Johnson Meter) [Background - 0.02 mR/hr]
* " " " " neutrons = 0.002 mR/hr (Safety Office Neutron Monitor) [Oct.1981]
* 0.03 mR/hr x 0.88 x 1 (Q for γ rays) = 0.026 mREM/hr
* 0.002 mR/hr x 0.88 x 2.3 (Q for Thermal Neutrons) = 0.004 mREM/hr

* **(0.026 mREM/hr + 0.004 mREM/hr) x 5 hr = 0.15 mREM/5 hr DE!**

(Caltech limit = 1.25 mREM/5 hr DE!)

APPENDIX : RADIOACTIVE SOURCE INVENTORY, 8 September 97

GAMMA-RAY SOURCES: (β-rays emitted are completely absorbed by the encapsulation material.)

CALIBRATION DISC TYPE:	Calibrated Activity	Half-life	Calibrated	C.I.T. I. D.
^{137}Cesium (^{137}Cs)	1 Ci ± 2.5 %	30.07 y	1 FEB 1978	2800/2801
^{60}Cobalt (^{60}Co)	1 Ci ± 2.5 %	5.271 y	1 FEB 1978	2798/2799
^{60}Cobalt (^{60}Co)	1 Ci ± 2.5 %	5.271 y	1 FEB 1987	1708
^{22}Sodium (^{22}Na)	487 Ci ± 10 %	2.602 y	1 FEB 1975	2775
^{22}Sodium (^{22}Na)	500 Ci ± 10 %	2.602 y	1 DEC 1980	2772

ACRYLIC PLASTIC ROD TYPE:				
^{137}Cesium (^{137}Cs)	250 Ci ± 15 %	30.07 y	1 FEB 1987	1710/1711
^{137}Cesium (^{137}Cs)	50 Ci ± 15 %	30.07 y	1 FEB 1987	1707
^{137}Cesium (^{137}Cs)	50 Ci ± 15 %	30.07 y	1 FEB 1978	2796
^{60}Cobalt (^{60}Co)	50 Ci ± 15 %	5.271 y	1 FEB 1978	2793/2794
^{22}Sodium (^{22}Na)	10 Ci ± 15 %	2.602 y	1 FEB 1978	2797

STEEL SCREW with EPOXY/ACRYLIC CAP TYPE:				
^{137}Cesium (^{137}Cs)	30 Ci ± 10 %	30.07 y	1 JAN 1963	2577
^{137}Cesium (^{137}Cs)	90 Ci ± 10 %	30.07 y	1 JAN 1963	2566
^{137}Cesium (^{137}Cs)	240 Ci ± 10 %	30.07 y	1 JAN 1963	2567

X-RAY FLUORESCENCE EXPERIMENT SOURCES:

^{57}Cobalt (^{57}Co) (Calibration)	2 mCi ± 15 %	271.8 d	1 MAR 1991	1716
^{57}Cobalt (^{57}Co) (Working)	0.6 mCi ± 15 %	271.8 d	9 MAR 1995	1748

ANNIHILATION EXPERIMENT SOURCE: (Permanently installed - Room 210 E. Bridge)

^{22}Sodium (^{22}Na)	900 Ci ± 10 %	2.602 y	1 MAR 1997	1819

ANNIHILATION EXPERIMENT CALIBRATION SOURCE: (Mounted in RED LEAD HOUSE)

^{22}Sodium (^{22}Na)	900 Ci ± 10 %	2.602 y	1 FEB 1987	1709

NEUTRON ACTIVATED PAIR-PRODUCTION SOURCE: (NaF powder in Polyethylene Bottle)

^{24}Sodium (^{24}Na)	<0.1 Ci	14.959 h		

BETA / ELECTRON SOURCES: (^{106}Ru - 0.002" Al Window; ^{144}Ce - 0.002" Al Window)

^{106}Ruthenium (^{106}Ru)	7 Ci ± 15 %	373.6 d	1 OCT 1995	1802
^{106}Ruthenium (^{106}Ru)	10 Ci ± 15 %	373.6 d	18 FEB 1983	2596
^{144}Cerium (^{144}Ce)	10 Ci ± 15 %	284.9 d	30 DEC 1988	1728

CAUTION: HANDLE ONLY WITH FORCEPS PROVIDED, KEEP AWAY FROM EYES!

NEUTRON FISSION SOURCE: FOR ACTIVATION ANALYSIS - (Room 207 E. Bridge.)

^{252}Californium (^{252}Cf)	10.1 mCi ± 10 %	2.645 y	30 NOV 1993	1768