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FUNDAMENTALS OF RADIATION SAFETY FOR NERVA TEST OPERATIONS PERSONNEL

April 1967

Westinghouse Electric Corporation
Jackass Flats, Nevada

and

Aerojet-General Corporation
Jackass Flats, Nevada

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FUNDAMENTALS OF RADIATION SAFETY

APRIL 1967

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NERVA Test Operations
Nuclear Rocket Development Station
Jackass Flats, Nevada

TABLE OF CONTENTS

SECTION I	CHARACTERISTICS OF NUCLEAR RADIATION-----	1
A.	THE ATOM AND ITS PARTS-----	1
B.	IONIZATION-----	5
C.	NATURAL RADIOACTIVITY-----	6
D.	NATURAL RADIOACTIVE DECAY-----	8
SECTION II	MEASUREMENT OF RADIATION-----	13
A.	ACTIVITY UNITS-----	13
B.	DOSE UNITS-----	13
C.	DOSE RATE MEASUREMENT-----	15
D.	FORMULAS AND PROBLEMS-----	15
SECTION III	BIOLOGICAL HAZARDS OF RADIATION-----	18
A.	EXCITED AND IONIZED MOLECULES-----	18
B.	DAMAGE TO CELLS-----	19
C.	DAMAGE TO ORGANS-----	22
D.	EFFECTS OF ACCIDENTAL EXPOSURE-----	25
E.	RADIATION SICKNESS-----	27
F.	MINIMUM DOSES-----	29
G.	MAXIMUM PERMISSIBLE DOSES-----	29
H.	BACKGROUND RADIATION-----	30
SECTION IV	PRINCIPLES OF RADIATION DETECTION-----	32
A.	SURVEY INSTRUMENTS-----	32
B.	PERSONNEL MONITORING DEVICES-----	39
C.	CHARACTERISTICS OF RADIATION DETECTION INSTRUMENTS-----	43
D.	OPERATION-----	45
SECTION V	PROTECTION FROM RADIATION-----	51
A.	DISTANCE-----	51
B.	PRINCIPLES OF SHIELDING EFFECTS-----	51
C.	HALF-VALUE LAYERS-----	52

PERIODIC CHART OF THE ATOMS

APPENDICES

APPENDIX A	X-RAYS-----	A1
APPENDIX B	CRITICALITY ACCIDENT REPORTS-----	B1
APPENDIX C	HISTORICAL BACKGROUND OF NUCLEAR PHYSICS-----	C1
APPENDIX D	RADIATION STANDARDS-----	D1

SECTION I

CHARACTERISTICS OF NUCLEAR RADIATION

A. THE ATOM AND ITS PARTS

Elements - Atomic Compounds

1. An element is a substance that contains only atoms with the same chemical properties. There are over one hundred identified elements. Some of the better known are carbon, sulfur, oxygen, gold, and copper.

2. Atom - The smallest particle of an element that can exist by itself and still represent the element is an atom. For example, the smallest particle of helium is a helium atom, shown in Figure 1.1, and this is one of the simpler atoms of all the elements.

Figure 1.1

Helium Atom

3. The atom contains a dense central portion called the nucleus, and an outer region where much less massive particles called electrons move about the nucleus in orbits.

4. The mass of the atom is contained in the nucleus, yet the nucleus is only 1/100,000 of the total volume of the atom. The great density of this nucleus is the result of the presence and number of nuclear particles called protons and neutrons.

5. The volume of the atom depends upon the orbiting electrons. One should not form the mental image of space-point occupation of the electrons orbiting about the nucleus as the planets orbit about the sun. Because orbital electrons travel at great velocities, they form a space "cloud" rather than occupy space points. An atom, then, may be considered an electron cloud around a nucleus.

6. Protons - Protons are very dense particles, each with a positive electric charge. The mass of one proton is considered as 1.007594 MASS UNITS. Each element has a different number of protons in the nucleus. Since the elements can be differentiated by the number of protons, each element is assigned a number which corresponds to the number of protons in the nucleus. This is known as the ATOMIC NUMBER. The symbol for the atomic number is Z.

7. Neutrons - Neutrons are also contained in the nucleus. They are particles having no charge and may be considered as the combination of a proton (positive charged particle) and an electron (negative charged particle), the electrical sum of which is neutral. The nuclear designation for the neutron is ${}^1_0\text{n}$. The subscript indicates the atomic number (or number of protons in the nucleus) and the superscript indicates the mass number (or the total of protons plus neutrons in the nucleus). Since a neutron has, practically speaking, the same mass as a proton, each is considered a mass unit. A common experience is that a given volume of lead will weigh more than the same volume of aluminum. To a large degree, this is dependent upon the total mass units of the atomic species. For example, the total of mass units in lead atoms exceeds the total of mass units in aluminum atoms and, therefore, lead per unit volume weighs more than aluminum. Since both a proton and a neutron are the equivalent of a mass unit, the MASS NUMBER, symbol A, is the sum of the number of protons and neutrons in the nucleus. For example, oxygen has 8

protons and 8 neutrons with a mass number of 16. By previous definition it also has an atomic number (Z) of 8 protons in the nucleus.

Mass Number = total protons + total neutrons

$$A = Z + \frac{1}{0}n$$

$$\begin{matrix} \text{(Mass No.)} & A & \\ \text{(Atomic No.)} & Z & \end{matrix} X \quad \text{(Element)}$$

Representation of Neutrons ($\frac{1}{0}n$) and Protons (+) in Atomic Nuclei

Element	$\frac{1}{1}H$	$\frac{4}{2}He$	$\frac{7}{3}Li$	$\frac{9}{4}Be$
Mass No. (Neutrons plus Protons)	$A = 1$	$A = 4$	$A = 7$	$A = 9$
Atomic No. (No. of Protons)	$Z = 1$	$Z = 2$	$Z = 3$	$Z = 4$
Number of Neutrons	0	2	4	5

When the atomic number and either the number of protons or neutrons is known, the other can be determined. Hydrogen, for example, can have different numbers of neutrons in the nucleus. The nuclear properties are different due to the different number of neutrons contained in the nucleus. However, the chemical properties of the hydrogen isotopes are the same.

The three hydrogen species are described below:

	HYDROGEN	DEUTERIUM	TRITIUM
Nuclear Designation	$\frac{1}{1}p$	$\frac{1}{1}p + \frac{1}{0}n$	$\frac{1}{1}p + \frac{1}{0}n + \frac{1}{0}n$
Number of Protons (+)	1	1	1
Number of Electrons (-)	1	1	1
Number of Neutrons	0	1	2
Mass Number (A)	1	2	3
Atomic Number (Z)	1	1	1

	<u>HYDROGEN</u>	<u>DEUTERIUM</u>	<u>TRITIUM</u>
Nuclear Designation	${}^1_1\text{H}$	${}^2_1\text{H}$	${}^3_1\text{H}$
% of Abundance	99.9844	0.0156	Probably not found naturally
Stability	Stable	Stable	Unstable, $\frac{1}{2}$ life 12.5 years

Elements having a different mass number but the same atomic number are called ISOTOPES. Obviously, if the atomic number (identical to the number of protons in the nucleus) remains constant, the isotopes are created by the different number of neutrons found in the nucleus. A system of nuclear designation is as follows:

- a. Write symbol of the element H, He, Be
- b. In lower left hand corner write atomic number
 ${}^1_1\text{H}$, ${}^2_2\text{He}$, ${}^4_4\text{Be}$
- c. In the upper left hand corner show the mass number
 ${}^1_1\text{H}$, ${}^4_2\text{He}$, ${}^9_4\text{Be}$

8. Electrons - Electrons orbit about the nucleus as a space charge. When the atom is in an unexcited state the electrons move in definite orbits. Only a fixed number of electrons may inhabit an orbit. The great physicist, Neils Bohr, postulated that electrons in any particular orbit can have only fixed amounts of energy. The distance from the nucleus, at which the electron orbits, is determined by that fixed amount of energy the electron has. This energy within an electron is termed its quantum state.

The distances from the nucleus, determined by the energy in the electron, are called Electron Shells and are labeled as shown in Figure 1.2.

ELECTRON SHELLS

Figure 1.2

B. IONIZATION

It is very common for electrons to be removed from an orbit. The proton/electron balance is thus destroyed and the remainder of the atom (called an ion) assumes a positive charge. Ionization caused by radiation is shown in Figure 1.3.

Figure 1.3

When an atom is excited (by heat, ultraviolet radiation, etc.), the quanta of the electrons increase. As the electron's orbital position has determined its quantum state, a quantum increase will change the electron's position, causing it to leap from one shell to the next shell of higher energy. This activity excites the atom and increases its tendency to react. Some of the more important ions are:

<u>Ion</u>	<u>Symbol</u>	<u>Designation</u>	<u>Nucleus</u>	<u>Comment</u>
Hydrogen	${}^1_1\text{H}^+$	Proton	1 Proton	Free proton, found in vast clouds in outer space. Emits radio waves at 21cm.
Deuterium	${}^2_1\text{H}^+$	Deuteron	1 Proton 1 Neutron	Useful as a "bullet" in particle accelerating devices.
Tritium	${}^3_1\text{H}^+$	Triton	1 Proton 2 Neutron	Probably not found naturally.
Helium	${}^4_2\text{He}^{++}$	Alpha Particle	2 Protons 2 Neutrons	Helium nucleus; heavy, strong, short-range ionization properties.

C. NATURAL RADIOACTIVITY

The discovery of radioactivity by Becquerel in 1896 was quickly followed by the Curies' discovery of other radioelements (thorium, polonium, radium, and actinium). Simultaneous discovery by Becquerel and others showed that some radiations from radioelements could be deflected by a magnetic field. Rutherford added additional insight when he discovered that certain "rays" (alpha) could be shielded out by thin sheets of aluminum, while another "ray" (beta particles) required a somewhat thicker sheet to prevent penetration. Other discoveries were made concerning the properties of radioactive elements. The properties of the basic types of radiation are summarized by Figure 1.4.

Studies of both natural and artificially produced radioactivity have greatly increased man's knowledge of the atom. When the nucleus of an atom spontaneously gives off particles (beta, alpha, etc.), it is undergoing the process called NUCLEAR DECAY and it becomes a new isotope. It was found that the process of nuclear decay could not be altered by physical means, i.e., temperature, pressure, ultraviolet radiation, etc.

Radiation	Typical Energy	Mass AMU	Descrip.	Air Range	Typical Emitter	Effective Shield	Interaction Process(es)
Alpha	4-8 Mev	4.0	He ⁺⁺	5-10 cm	²²⁶ Ra	Sheet of Paper	Ionization by inelastic collisions
Beta	0-3 Mev	1/1845	e ⁻	0-10 m	¹⁴ C, ⁴⁰ K	$\frac{1}{2}$ inch Lucite	Ionization by inelastic collisions
Gamma	0-3 Mev	None Measurable	Wave	100's m	⁶⁰ Co	Dense Materials (Pb, Fe)	Photoelectric effect Compton effect Pair Production
Neutrons (Thermal)	0.025 ev	1.0	Neutral	10's m	Reactor	Boron Cadmium Hafnium	Capture
Neutrons (Fast)	0.5 to 10 Mev	1.0	Neutral	100's m	Reactor Pu-Be Source	H ₂ O (CH ₂) _x	Inelastic collisions-recoil protons-recoil nuclei

PROPERTIES OF RADIATION

Figure 1.4

For some reason not fully understood, not all of the atoms of a radioactive element decay at one time. The time for one-half of the atoms present to undergo this process is called the HALF-LIFE. The remaining one-half of the original element will again be reduced by one-half in the same time period. One pound of ^{60}Co in 5.25 years will form one-half pound of nickel. The other one-half pound remains as ^{60}Co . Each radioisotope has its own characteristic half-life. Half-lives may be very short (seconds), or millions of years. Those with the very long half-lives often appear to be stable. An interesting observation was made on nuclear stability and neutron/proton ratios: a study of isotopes reveals that nuclei containing even numbers of protons and neutrons are much more common than any other; nuclei with an odd number of protons and an even number of neutrons and vice versa are equally common, while those containing odd numbers of both protons and neutrons are rare. It appears that nuclei containing even numbers of both protons and neutrons are the most stable, whereas those with odd numbers of both are very unstable. There are exceptions to this observation. It should be noted that all elements with an atomic number greater than 83 are radioactive. Many of the elements with atomic numbers less than 83 have radioactive isotopes, such as $^{14}_6\text{C}$.

D. NATURAL RADIOACTIVE DECAY

Prior to presenting some decay series, it might prove helpful to provide a chart of radiation emission and the resultant effect upon the atom. Radioactive decay is accompanied by the emission of either an alpha particle or a beta particle. Many times a gamma ray may accompany particle emission. The gamma ray emission is a means whereby the atom rids itself of excess energy.

RADIOACTIVE DECAY

			Effect of Emission		
			Atomic No.	Mass No.	Typical Equation
Alpha Particle	${}^2_2\text{He}$	2 protons and 2 neutrons (i.e., helium nucleus)	Decrease by 2	Decrease by 4	${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^4_2\text{He}$
Beta Particle	${}^0_{-1}\beta$ or ${}^0_{-1}e$	High speed electron	Gain 1	No Change	${}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^0_{-1}\beta$
Gamma Ray	γ		No Change	No Change	${}^{65}_{30}\text{Zn} \rightarrow {}^{65}_{30}\text{Zn} + \gamma$

Now let us look at some natural radioactive decay. The example given is the Uranium Decay Series. It is called a series since it begins with uranium and decays into stable lead. There are several other long decay series. Often, artificially produced radioelements may decay by a one-step process into a stable nuclide. It will prove helpful to the reader if he will follow the progress of the decay series on the chart on page 12.

Uranium 238 emits an alpha particle. An alpha particle consists of two protons and two neutrons. Thus, when the alpha particle is emitted, two protons and two neutrons are lost. The atom has 90 protons and 144 neutrons. The nucleus now contains 234 mass units, and since the number of protons has been changed, it is no longer uranium, but thorium.

Thorium 234 does not emit an alpha particle but does emit a beta particle. Where does the beta particle come from? Remember that neutrons are electrically neutral. We know that an electrically neutral state can be reached when positive and negative charges balance one another. Let us consider that a neutron consists of a proton with an electron tightly bound onto it. The negative charge of the electron balances the positive charge of the proton, so we have a neutron. When this negatively charged electron is emitted as a beta particle,

the remainder is no longer electrically neutral, but now has a positive charge, so a neutron has been changed to a proton. In effect, the change is one proton added and one neutron subtracted. We now have 91 protons and 143 neutrons. The mass is still 234, but since we have changed the number of protons, we have changed the nature of the element, and it is now an atom of protactinium.

Protactinium 234 also emits a beta particle so we add 1 proton and subtract 1 neutron, leaving 92 protons and 142 neutrons. Its mass is 234, but our element is, of course, again uranium.

Uranium 234 emits an alpha particle, so we subtract 2 neutrons and 2 protons, and we now have 230 particles in the nucleus. Since the number of protons is 90, we have thorium 230.

Thorium 230 emits an alpha particle. Subtract 2 protons and 2 neutrons. We now have a mass of 226, and since we have only 88 protons in the nucleus, we now have the element radium.

Radium 226 emits an alpha particle, we lose 2 neutrons and 2 protons and have 86 protons and 136 neutrons. Our element is now radon 222, which is a gas.

Radon 222 emits an alpha particle, leaving us with 84 protons and 134 neutrons. Again we have a different element - polonium 218.

Polonium 218 emits an alpha particle, which leaves us with 82 protons and 132 neutrons, lead 214.

Lead 214 emits a beta particle which increases our number of protons by one and decreases our number of neutrons by one, leaving us with 83 protons and 131 neutrons. This gives us bismuth 214.

Bismuth 214 emits a beta particle which adds 1 proton and subtracts 1 neutron leaving us 84 protons and 130 neutrons. This is polonium 214.

Polonium 214 emits an alpha particle which subtracts 2 neutrons and 2 protons bringing us down to 82 protons and 128 neutrons for an atomic mass of 210. The element is lead 210.

Lead 210 emits a beta particle resulting in 83 protons and 127 neutrons. This is bismuth 210.

Bismuth 210 emits a beta particle resulting in 84 protons and 126 neutrons. This is polonium 210.

Polonium 210 emits an alpha particle which results in lead 206.

Lead 206 is stable and no further decay will occur.

Note: Gamma radiation is emitted in some of these reactions - a means for some daughter elements to lose surplus energy.

The preceeding sequence is summarized by Figure 1.5.

Another interesting transmutation and decay is that of cobalt 60. Cobalt 60 is an unstable isotope with a half-life of 5.25 years. With such a short half-life, the isotope would not be found naturally. Cobalt 60 must be produced in a nuclear reactor where cobalt 59 is bombarded with neutrons. The reaction is of the neutron capture type.

Cobalt 60 is an unstable isotope and undergoes decay to a stable isotope of nickel through beta decay, accompanied by gamma emissions.

Excess energy of ${}^{60}\text{Ni}$ is released by gamma emissions. These gamma emissions are similar to X-rays and are utilized in many ways.

Figure 1.5
Radioactive Decay Series
for
Uranium 238 to Stable Lead 206

Element and Atomic Weight	Type of Radiation Emitted		Number of	
	Name	Symbol	Protons	Neutrons
URANIUM-238	Alpha Particle	${}^4_2\text{He}$	92 -2	146 -2
↓ THORIUM-234	Beta Particle	${}^0_{-1}\beta$	90 +1	144 -1
↓ PROTACTINIUM-234	Beta Particle	${}^0_{-1}\beta$	91 +1	143 -1
↓ URANIUM-234	Alpha Particle	${}^4_2\text{He}$	92 -2	142 -2
↓ THORIUM-230	Alpha Particle	${}^4_2\text{He}$	90 -2	140 -2
↓ RADIUM-226	Alpha Particle	${}^4_2\text{He}$	88 -2	138 -2
↓ RADON-222	Alpha Particle	${}^4_2\text{He}$	86 -2	136 -2
↓ POLONIUM-218	Alpha Particle	${}^4_2\text{He}$	84 -2	134 -2
↓ LEAD-214	Beta Particle	${}^0_{-1}\beta$	82 +1	132 -1
↓ BISMUTH-214	Beta Particle	${}^0_{-1}\beta$	83 +1	131 -1
↓ POLONIUM-214	Alpha Particle	${}^4_2\text{He}$	84 -2	130 -2
↓ LEAD-210	Beta Particle	${}^0_{-1}\beta$	82 +1	128 -1
↓ BISMUTH-210	Beta Particle	${}^0_{-1}\beta$	83 +1	127 -1
↓ POLONIUM-210	Alpha Particle	${}^4_2\text{He}$	84 -2	126 -2
↓ LEAD-206	Stable Atom	---	82	124

SECTION II

MEASUREMENT OF RADIATION

This discussion of radiation measurement deals with various letter designations such as REP, REM, RAD, etc. These measurements have been originated, one succeeding another, as more comprehensive means of evaluating total effects were needed.

A. ACTIVITY UNITS

Radiation cannot be measured directly. Instead, it is measured by its secondary effects on other materials. A basic unit of radioactivity is the curie. The measurement expressed by this term was redefined in 1953 and is now established to be the quantity of a radioisotope undergoing 37 billion disintegrations in one second. This standard was based upon the number of disintegrations occurring in one gram of radium each second. Smaller units are used representing smaller amounts of active material. Two of these are the millicurie (1/1000 curie) and the microcurie (1/1,000,000 curie). The curie (abbreviated c) then, is a measure of activity and does not indicate the energy of radiation.

B. DOSE UNITS

A roentgen (abbreviated R) is that quantity of X-rays or gamma rays which will produce, as a result of ionization, one electrostatic unit of electricity of either sign in one cubic centimeter of dry air measured at standard conditions. This quantity can also be expressed in terms of ion pairs: 1R produces 2.083×10^9 ion pairs per cm^3 of air. This represents 83 ergs of energy which is absorbed by one gram of air. The roentgen measures only ionizing radiation in the air.

1. Roentgen (R). Roentgens are used as a measure of DOSE which is the amount of radiation delivered to a specified volume. The DOSE RATE is the rate at which radiation dose is delivered, the common rate is roentgens per hour (R/hr). Since roentgens are based upon X or gamma rays, a unit to describe the similar biological effects caused by ionization from alpha and beta particles was needed and the roentgen equivalent physical (REP) was established.

2. Roentgen Equivalent Physical (REP). This unit is defined as that dose of any ionizing radiation which produces an energy absorption of 93 ergs/gm of tissue. The increase of 93 is a more accurate representation of the energy absorbed per gram of tissue which has received a dose of 1R of hard X-rays or gamma rays. However, the REP is not useful for estimates of whole body irradiation due to the high proportion of hard tissue. The REP has been replaced by more easily defined units such as the RAD.

3. Radiation Absorbed Dose (RAD). The RAD is defined as the absorbed dose of any ionizing radiation in any medium equivalent to 100 ergs of energy per gram of absorbing material.

4. Roentgen Equivalent Man or Mammal (REM). The absorption of quantities of different ionizing radiation which provide the same amounts of energy may not have a comparable biological effect upon the body. To compensate for this observed phenomenon, a newer unit, the Roentgen Equivalent Man (abbreviated REM) was proposed and is designated as that quantity of radiation which produces the comparable biological effect in man as one RAD of X or gamma radiation. The REM is thus intended to take into account the relative biological effectiveness (RBE) of different types of radiation. Such factors, however, vary not only with the properties of the radiation but also with the biological effects. It became customary, therefore, to regard the REM as a biological unit of dose; dose in REM equals dose in RAD x RBE, where for a given biological action the RBE values are stated as inverse ratios of the energy absorption of different radiations which produce equal biological effects. The REM is not officially listed as a unit, but in the recommendations of the International Commission of Radiological Protection it is suggested that this unit should be used when it is necessary to add the doses of different radiation received. The REM is then defined in relation to the RAD. Dose in REM equals dose in RAD x RBE. Practically speaking, the REM is simply the RAD adjusted or compensated in terms of the relative biological effectiveness. The actual biological effectiveness of ionizing radiation is difficult to measure because of the numerous variables that effect the biological damage produced by ionizing radiation (i.e., tissue, depth and distribution of radiation, energy, etc.).

5. Summary of Basic Units

- a. Curie: Used to measure radioactivity in terms of the numbers of emissions per second.
- b. Roentgen: Used to measure the dose of X or Gamma rays.
- c. REM: Used to measure the biological dose to human beings from radioactive sources. This is a more comprehensive measure of the effects of radiation dose than the roentgen.

C. DOSE RATE MEASUREMENT

Radiation dose is the total amount of ionizing radiation absorbed. Generally, the dose is initially reported in roentgens, milliroentgens or REMs. Radiation dose rate, on the other hand, is a measure of how rapidly the radiation dose is being accumulated by the animal. Time controls the total radiation dose received.

If we received 200-500 REM of total body radiation in a very short time, we may die. Should we receive 25 roentgen doses at 8 different times over a period of many years, there would probably be no adverse effect. Thus, the importance of knowing the dose rate is of vital importance.

Time can also be used to control dosage in a situation where there is but one single radiation source. Assume that the source is located in a room with a radiation level of about 20 mR per hour. Assume furthermore that it is necessary to limit the radiation dosage of any individual entering the room to 100 mR/week. To limit the dosage to a per-day basis, we divide the $100 \text{ mR} / 5 = 20 \text{ mR/day}$. Since the dose rate of the source is 20 mR/hr, the maximum daily dose would occur in one hour of exposure.

D. FORMULAS AND PROBLEMS

The following formulas may be utilized in approximate calculations for the problems to follow:

1. The dose rate in R/hr can be computed at one foot from a point source of gamma radiation.

$$\text{R/hr at 1 ft} = 6CE$$

where:

- C = the intensity of the parent nuclide in curies
E = the total gamma energy in million electron volts of the rays emitted. When more than 1 gamma ray is emitted per disintegration, "E" is the sum of the gamma energies, i.e., $E = \text{Mev}_1 + \text{Mev}_2 + \text{Mev}_n$.

2. To compute the dose rate in R/hr at a distance greater than one foot, we utilize the above formula with the addition of the factor of distance. We know that the radiation intensity is inversely proportional to the square of the distance. Mathematically, this would be expressed as:

$$\text{Intensity} = \frac{1}{\text{Distance}^2}$$

Combining the formulas:

$$R/\text{hr} = \frac{6CE}{D^2}$$

Problem #1:

Cobalt 60 is an example of the radioelement that emits gamma radiation of two energies; gamma emission of 1.17 Mev and gamma emission of 1.33 Mev. A 1,000 curie source of ^{60}Co is used for radiographic inspection of rocket motors at Aerojet. Compute the dose rate in roentgens per hour at one foot from the unshielded source. Compute the dose rate at 100 feet from the unshielded source.

Solution:

- a. (1) $R/\text{hr} = 6CE$ C = intensity 1,000 curies - given
(2) $R/\text{hr} = (6)(10^3)(2.5)$ E = since the parent nuclide has two gamma emissions, E is the summation of the two emissions or 1.17 Mev + 1.33 Mev = 2.50 Mev.
(3) $R/\text{hr} = 15,000$ at 1 foot

- b. (1) $R/hr = \frac{6CE}{D^2}$
- (2) $R/hr = \frac{(6)(10^3)(2.5)}{10^4}$
- (3) $R/hr = 1.5$ at 100 feet

Problem #2:

From the information in Problem #1, compute the following: A ^{60}Co source of unknown intensity was introduced into the inspection operation. An operator monitored a dose rate of 3.21 R/hr at 100 feet from the unshielded point source. What is the approximate intensity of the source in curies?

Solution:

- (1) $R/hr = \frac{6CE}{D^2}$
- (2) $C = \frac{R/hr}{6} \frac{D^2}{E}$
- (3) $C = \frac{3.21 (10^4)}{(6) (2.5)}$
- (4) $C = .214 (10^4)$
- (5) $C = 2140$ curies

Problem #3:

Assume that a workman spent six minutes at 100 feet from the 2140 curie ^{60}Co source mentioned above. Calculate the dose.

Solution:

Dose rate at 100 feet was given at 3.21 R/hr. The workman remained in the area 6/60 or 1/10 of an hour. Hence, his dose was (1/10 hr) (3.21R/hr) = 0.321R or 321 mR.

SECTION III

BIOLOGICAL HAZARDS OF RADIATION

The purpose of this section is to describe the processes by which radiation can damage the human body.

A. EXCITED AND IONIZED MOLECULES

If the molecules of the body were to absorb energy only as heat from radiation, the biological hazards of radiation would be insignificant. However, the passage of radiation subjects the molecules of the body to brief but intense electrical forces. These electrical forces either excite the molecules by forcing electrons into orbits at a different energy level, or ionize the molecules by releasing planetary electrons from their orbits. The vast majority of biological damage results from the latter process.

In Figure 3.1, a schematic representation of the effects of a charged particle, only one electron is shown for each atom.

Figure 3.1

The excited and ionized molecules are much more reactive than those unaffected. Along this path of disrupted molecules many reactions may take place; the freed electrons can collide with the electrons of normal molecules

and cause further secondary ionization. Water molecules, for example, may be excited or changed to hydrogen ions and hydroxyl radicals. These units may then recombine into hydrogen molecules (H_2), oxygen molecules (O_2), and hydrogen peroxide molecules (H_2O_2).

Some possible breakdown products from water are illustrated in Figure 3.2.

Figure 3.2

Water has been used as an example because it comprises about 75% of the body cells, and the peroxides and free radicals formed from its ionization are among the most bio-toxic agents resulting from radiation exposure.

Although the effects of radiation are similar in all molecules, they are more devastating in substances such as water and proteins, where molecules are oriented by the unequal distribution of charge within them.

B. DAMAGE TO CELLS

The cell is the fundamental unit of biological structure and function in organisms. A typical cell is shown in Figure 3.3.

1. Oxidation. The very active oxidizers such as hydrogen peroxide, resulting from ionized water molecules, react with neighboring molecules. These altered molecules produce end products that are strange to the chemistry of the cell, and thereby enlarge the scope of the injury.

2. Molecular Breakdown. The valence bonds of excited atoms may be altered to the point that they no longer will hold the atoms in their molecules. The electrically charged molecular fragments will react immediately, while the uncharged particles may or may not react. In nearly every case,

DIAGRAM OF A TYPICAL CELL

FIGURE 3.3

however, the results are molecules which are foreign to normal body chemistry; these may produce toxic effects upon the whole body.

3. Cell Division. The very reactive oxidizers formed when water ionizes can break down complex protein molecules such as enzymes. The process of cell division which is controlled in part by the enzymes, can thereby be disrupted. The rate of cell division can be lowered or stopped entirely or the cell can be killed outright. Cells undergoing division (mitosis) are particularly susceptible to injury or death.

A non-dividing cell may grow until its size becomes abnormal. If the cell does divide, its offspring may be subject to the defects shown in Figure 3.4.

Figure 3.4

Normal Cell Division

Irradiated Cells

Irradiated Cells

a. Irradiated Cell

b. Cell Division

c. Damaged Daughter Cells

4. Damage to Cell Walls. Protein molecules of the cell wall act as selective filters to permit only the passage of vital materials in and out of the cell. Radiation can damage these filtering molecules directly or by producing toxic by-products.

5. Radiosensitivity of Cells. Biologists have demonstrated that the following conditions make cells more sensitive to radiation damage:

- a. Rapid cell production; children are therefore more sensitive than adults.
- b. High cell activity or metabolism; resting or inactive cells are less sensitive.
- c. Cells well supplied with blood and food; undernourished cells are less sensitive than normal cells.
- d. Degree of maturity; immature cells are more sensitive than mature cells.

C. DAMAGE TO ORGANS

The organs are discreet groups of cells having definite functions to perform in the body. Radiation damage to an organ may result in an increase or decrease in its functions, alteration of its growth, or death of the organ. Unless the organ is extensively damaged, repair will begin at once. The normal functions of the organ may be suspended during repair and the body may be deprived of vital products. Therapy of radiation sickness is often designed to provide the body with these products of the organs.

The following list of body structures and their reactions to radiation are arranged in increasing order of radiosensitivity:

1. Lymphatic System. The lymphatic system consists of a network of capillaries for the circulation of lymph. Lymph is a body fluid comprised primarily of lymphocytes which also constitute an important part of the blood. The system carries tissue debris and invading bacteria to the lymph nodes where the undesirable products are filtered out and lymphocytes are replenished. The spleen, located below the left lung and in front of the left kidney, is the largest of the lymph organs.

Lymphocytes are among the most radiosensitive cells of the body and are often used as indicators of radiation injury. Lymphocytes are also a type of white blood cell.

Since the lymph nodes filter out foreign substance, they show the first stages of hemorrhaging and infection after an acute exposure to radiation. The destruction of lymphocytes permits bacteria to multiply and infection to spread. The results of overexposure to the lymphatic system are reduced if a great portion of the lymph nodes and particularly the spleen, can be shielded.

Experiments in lymph transfusions in the treatment of radiation sickness have been promising.

2. Blood and Bone Marrow. The red blood cells (erythrocytes), platelets and part of the white cells (granulocytes) are formed by the marrow of the bones. These blood cells are relatively resistant to radiation damage when mature, but are highly sensitive when being formed.

The erythrocytes are the transport agents for the body's supply of food and oxygen. The granulocytes combat certain infections by absorbing foreign substances in the blood. Platelets contain blood clotting agents.

An acute exposure to radiation starts a series of undesirable events in the blood. The lymphocyte count drops first and is followed in a few days by the granulocyte count. The reduction of the white cell count makes the body susceptible to an ordinarily harmless number of bacteria. Within a week after the exposure the supply of platelets is reduced so that the blood will

not properly clot and wounds will not heal. About seven weeks after exposure the erythrocyte count drops, resulting in anemia, pallor, shortness of breath, fluttering of the heart and general weakness.

3. The Reproductive System. The reproductive organs themselves are also particularly radiosensitive, requiring several hundred roentgens (or REM) to produce temporary sterility. Conception after irradiation of the reproductive organs introduces a genetic hazard, proportional to the dose.

Inherited characteristics are controlled by the genes carried by the sperm and ova. Radiation of the genes can cause mutations; i.e., changes from the parents in the inherited characteristics of the child. In human beings, almost all mutations are undesirable, resulting in miscarriages, stillbirths, or abnormalities. It should be noted, however, that most defects are not genetically caused. Mutations occur normally in about 2% of all births. A dose of 20 roentgens increases the chance to about $2\frac{1}{2}\%$, and a dose of about 80 roentgens raises the chances to about 4% (doubling dose).

4. The Skin and Hair. The skin reacts to ionizing radiation and will redden after a dose of about 100 roentgens of 0.250 Mev X or gamma rays. If the area involved in a single exposure was small, healing usually begins immediately with no serious consequences. Skin cancer, however, has resulted from cases of chronic overexposure.

Radiation damage to the hair follicles may cause temporary baldness (epilation) at dose levels of several hundred R.

5. The Alimentary (Digestive) Canal. The alimentary canal consists of the mouth, stomach, intestines, and connecting plumbing. Highly specialized cells along the 30 feet of the canal carry on the process of digestion in many complex ways. These cells are highly radiosensitive.

The first symptom of damage to the alimentary canal is nausea and vomiting. The irritation of the damaged intestinal walls by the digestive juices produces convulsions of the intestine and diarrhea. Damage to the surface tissue also produces ulcers.

6. The Lungs. As air enters the lungs it passes through smaller and smaller tubes to tiny air sacs with permeable membranes where oxygen is absorbed into the blood and carbon dioxide and water are released to be exhaled.

Radiation may damage these very delicate membranes allowing blood to enter the lungs. This may occur from extreme doses penetrating external radiation, but the greatest lung hazard is from inhaling radioactive dust, fumes, or smoke such as would be present in the event of a fire involving radioactive materials.

7. Connective Tissues. These are the structural tissues which support the organs and other specialized tissues.

8. Muscles. Muscles are relatively radioresistant.

9. Bones. Mature bone cells are radioresistant; growing bones are moderately radiosensitive.

10. Nerve Tissues. The nerve cells, including the brain, are among the most resistant members of the body to radiation.

D. EFFECTS OF ACCIDENTAL EXPOSURE

Organisms vary widely in their ability to withstand radiation, Figure 3.5. In general, the more complex the organism the more radiosensitive it is. Plants, insects and bacteria will withstand several thousands of roentgens; a lizard will survive a few thousand R; the median lethal dose to man is about 500 REM.

1. Effects During Exposure. In most cases of radiation exposure there is little or no indication of trouble during the exposure. Occasionally, in cases of severe exposure, a tingling or itching of the skin is reported during exposure.

2. Lethal Doses (LD).

a. Measurement of Lethal Dose. Individuals show some variation in their ability to withstand radiation dose. Because of this variation, the amount of radiation that will be fatal to 50% of the exposed individuals within 30 days is usually considered to be the lethal dose and is abbreviated as LD₅₀. For human beings the acute LD₅₀³⁰ is about 500 REM.

b. Conditions of Lethal Dose. A large single burst of radiation has a more lethal effect than the cumulative damage of chronic exposures.

Figure 3.5

LD₅₀ FOR VARIOUS SPECIES

<u>Organism</u>	<u>Dose (REM)</u>
Man	500
Mammals	200 - 1,000
Fish	700
Frog	700
Tortoise	1,500
Lizards	3,000
Snails	10,000
Yeast	30,000
Insects	60,000
Paramecia	300,000

In general, the more complex the organism, the greater the radiosensitivity.

Much higher doses of radiation can be tolerated if only part of the body is exposed. The effect depends on the amount and kind of tissue, its radiosensitivity, and its role in the vital processes of the body. A man can withstand several hundred REM to his hands or feet without permanent damage, but the same dose received to the chest and abdomen may be fatal. Cancer patients have received thousands of roentgens by radiotherapy to a diseased organ without excessive damage to the rest of the body.

3. Early Effects. The first symptoms of acute doses over the whole body are:

<u>Dose in REM</u>	<u>Symptoms</u>
0 to 25	No apparent injury.
25 to 50	Possible blood changes.
50 to 100	Blood cell changes, some injury; no disability.
100 to 200	Injury, possible disability.
200 to 400	Injury and disability certain; possible death.
500	Fatal to 50%.
800 or more	Probable LD ₁₀₀

E. RADIATION SICKNESS

1. Symptoms. The first symptoms of a dose of 100 or more REM are nausea, vomiting, and lassitude. This may be followed by bleeding from the gums or nose and, in about 10 days, by loss of hair. These symptoms do not seem to depend on damage to specific organs but can result from any intensive exposure whether it is accidental or deliberate as in the case of cancer therapy. The symptoms suggest a general intoxication resulting from the release of substance from the cells to the bloodstream. Radiation sickness and deaths have been biologically categorized in Figure 3.6.

2. Treatment. Radiation sickness is combated by treating the symptoms.

a. Gastrointestinal Disorders. Nausea, vomiting, and diarrhea are treated with antispasmodics. The diet offered is soft and bland, high in calories, liquids and vitamins.

ACUTE RADIATION SURVIVAL CURVE

FIGURE 3.6

b. Bacterial Infections. Bacterial infections are treated by antibiotics only when they become obvious to avoid development of drug-resistant strains of bacteria. The white cell count may be too low for the body to provide any of its own protection.

c. Hemorrhaging and Anemia. Fresh whole blood transfusions may be used to replace platelets necessary for blood clotting and red cells to fight anemia. Transfusions of normal bone marrow may have been successful in saving individuals who have received fatal doses of radiation.

F. MINIMUM DOSES

Intensive research has been carried out to determine the minimum dose that can cause damage to human beings. At the present time a few tests indicate that all radiation exposure is damaging while most tests seem to indicate a threshold dose below which no damage can be detected. Because the threshold damage is genetic, it is extremely difficult to evaluate.

G. MAXIMUM PERMISSIBLE DOSES

With all the foregoing factors taken into account, maximum permissible dose rates have been established that are well below the point of observed or suspected damage. No one may be employed in the radiation field until the age of 18. Then one may receive an exposure up to 5 REM per year. This is the limit for whole body exposure while the less sensitive extremities and skin have higher limits. The maximum permissible doses, also called radiation safety guides, or radiation standards are shown in Appendix D.

Individuals who occasionally receive their maximum allowable dose or even exceed it slightly should not regard themselves as on the brink of injury. They should, however, make quite sure a situation cannot arise that might lead to a repetition of the exposure.

Maximum permissible doses have recently been decreased, not primarily because of new evidence of damage, but because better handling techniques which permit less exposure have been devised.

H. BACKGROUND RADIATION

Natural radioactivity has been part of the environment of our planet since its creation. Uranium and thorium, with their decay products, comprise the main source of natural radioactivity. Occasionally, they occur in high concentrations, apparently without significant harm to the inhabitants of the area. One out of every 10,000 potassium atoms is the radioisotope potassium ⁴⁰ which emits beta particles. Cosmic rays are constantly bombarding the earth with highly ionizing particles. Naturally occurring radiation may range from a maximum of a few roentgens per year in areas of uranium ores to a minimum of about 80 mR per year on sedimentary soils. An average of 100 mREM per year might be a good estimate for most areas.

Man-made radiation has become a commonly accepted part of our lives and ranges from 40 mR per year from a wristwatch to several roentgens caused by each X-ray of fluoroscope examination. Background radiation averages have been summarized in Figure 3.7.

Figure 3.7

BACKGROUND RADIATION

I. From natural sources (estimated):

<u>Source</u>	<u>Millirem (Annually)</u>
Cosmic Rays	30 - 75
Terrestrial Gamma Rays	25 - 75
^{40}K (in body)	20
^{14}C (in body)	1.5
^{226}Ra (in body)	5 - 15 (2 to gonads)
Sub-Total	80 - 195

In addition, the lungs may receive an additional dose of from 125 to 1,500 millirem per year from radiation given off by building structures.

II. From man-made sources (estimated excluding fallout):

<u>Source</u>	<u>Millirem</u>
Medical (exposure of patients)	
Diagnostic X-rays	40 - 240
Therapy	12
Internal (isotopes)	1
Occupational	20
Environs	5
Other (luminous dials, TV, etc.)	2
Sub-Total	80 - 280

III. Fallout: 5 - 10

SECTION IV

PRINCIPLES OF RADIATION DETECTION

Human and animal senses are insensitive to all but the very narrow spectrum of electromagnetic radiation between 4,000 angstrom units and 7,700 angstrom units which is the range of visible light. Gamma radiation, for example, has a wave length 100 times shorter than violet light (i.e., 10^{-10} cm for gamma radiation vs. 10^{-8} cm for violet light). However, man has been able to supplement the inadequacies of his sensory abilities with instruments that can detect radiation.

Radiation detection equipment is based upon the principle that particles or photons of radiation transfer energy to matter. Most radiation detection devices utilize one of two energy transfer mechanisms: ionization and scintillation. Let us limit our present discussion to the phenomenon of ionization.

Ionization normally means an ion pair: a positively charged atom (ion) and a negatively charged free electron. Radiological detection devices such as the Geiger-Muller counter, ionization chambers and electroscopes (like the pocket dosimeter), actually measure this secondary ionization produced by the radiation and not the actual radiation itself.

A. SURVEY INSTRUMENTS

Ionization detection instruments are chambers containing an easily ionized gas between two electrodes. Penetration of the chamber by a radiation particle or photon will ionize the gas along its path, causing the tube to be momentarily conductive, showing a dose rate or registering as a count rate. Figure 4.1 illustrates the effect of increasing the voltage of the electrodes. In Region I of Figure 4.1, an increasing number of radiation penetrations are counted as the voltage is increased. In Region II, (Ion Chamber Region) the voltage is high enough to count all radiation penetrations of the tube. The current passed by each ionized path, however, is quite low and the instrument is relatively insensitive. It is, therefore, useful in fields of high radiation intensity. In Region III the voltage is high enough to accelerate some of the ions to velocities that will cause secondary

ionization. This effect is known as gas multiplication. In this proportional region, particles or photons of the same type but differing in energy level can be identified. In Regions I through IV, the effects of high and low energy radiation are shown by lines A and B. In Region V, any penetration will cause the entire tube to become conductive through gas multiplication. Region V, therefore, is quite sensitive even in fields of low dose rate. In Region VI, the high voltage overcomes the insulation of the gas and completely ionizes the tube without any radiation. The instrument, then, cannot detect radiation.

1. Geiger-Muller Counter. The Geiger-Muller counter (often abbreviated to "Geiger Counter" or "G-M Counter") consists of a tube with a metallic coating inside which serves as the cathode and a thin wire which traverses the axis and serves as the anode. These electrodes are insulated and connected to the prongs in the base. The tube is filled with a gas under reduced pressure to help produce the avalanche or "gas amplification" effects. The space inside the metal coated cylinder of the tube is the "active volume."

When the tube is connected to a voltage source and an electrical counter or meter is included in the circuit to register the pulses or counts, we have all the elements of a Geiger counter. Under proper conditions, each and every ionizing event occurring within the tube will be counted. The voltage applied to the tube can be regulated from zero to 1,500 volts. Up to several hundred volts may be applied with no noticeable effect. In this range, the avalanche or "gas amplification" effect is not great enough to produce pulses with enough intensity to register. But by increasing the voltage, a point will soon be reached where a few counts will be detected. The voltage at which pulses are first detected is the "starting potential" for the counter. These counts are produced by the more densely ionizing particles. As the voltage is increased over a considerable range, little or no effect is indicated in the counting rate. This is the "G-M range" where all particles are counted. By plotting the count rate against the applied voltage, a curve such as shown in Figure 4.2 is obtained. The G-M region is called the plateau because it corresponds to the relatively flat part of the curve. Each individual G-M tube has a characteristic curve and its own plateau region. To function properly the G-M tube must be operated at a voltage that is within the plateau of the curve. For practical reasons discussed later, the best operating voltage

is near the lower end of the plateau. The voltage that represents the beginning of the plateau is "threshold" voltage. Increasing the voltage beyond that of the plateau causes spurious discharges and counts that are meaningless and harmful to the tube.

Because G-M tubes have walls that absorb alpha particles, they are seldom used for alpha work. The counter will count each beta particle that enters the tube. It will also count a small but definite proportion of the gamma rays that penetrate the tube. The gamma rays may occasionally produce an ion pair by interaction with the gas molecules, but by far the most ionization is formed when the gamma rays strike the atoms in the walls of the tube. Some of the electrons thus formed traverse the active volume of the tube and produce a count. The vast majority of the gamma rays will penetrate both the gas and the tube walls without producing any effect at all. To distinguish between beta and gamma rays, a separation must be made outside the tube. This is accomplished by equipping the G-M tube with a movable metal shield that will absorb beta particles. Measurements are then made with and without the shield. The shield measurement is the gamma measurement; the differences between the two is the beta measurement.

It should be noted that the G-M tube requires a little time to make each count. When an avalanche is started by one particle, the discharge will continue for some time. If another particle enters before the discharge is completed, the pulse it produces will be confused with the preceeding one and so on for subsequent pulses. Too many particles "jam" the counter and can result in an erroneous low reading. This is the reason why G-M counters are not used to measure high intensity radiation fields since the counter can become "saturated" and erroneously indicate a low reading.

To count each particle, the avalanche ionization must be stopped and the tube cleared of ions after each pulse. This action is known as quenching.

The electrical pulses from the G-M tube are fed to a counting circuit. In some cases a scaler is used to actually count and totalize individual pulses. Others use a count-rate meter which integrates the pulses and gives a meter reading in terms of counts per minute. A schematic of the Geiger counter is shown in Figure 4.3.

Figure 4.1

Figure 4.2

GEIGER COUNTERS (Schematic)

A particle or gamma ray entering the tube dislodges electrons from atoms encountered. The negative electrons, attracted to the positively charged wire, brush off other electrons in their rush to the wire. There is a veritable avalanche of electrons to the wire. This produces an electrical pulse. This pulse is then amplified and sent into one of a variety of counting or recording devices.

Figure 4.3

2. The Ionization Chamber. The essential features of an ionization chamber shown in Figure 4.4 consist of a closed vessel containing gas and equipped with two high voltage electrodes. The electrodes may be in the form of parallel plates or one electrode may be the chamber itself with the other inside and insulated from it. Ionizing radiation produces ion pairs within the ion chamber. The ion pairs are attached to the electrodes of opposite charge which produces an electron flow. The electron flow is measured and shown on a meter.

Ionization chambers are capable of measuring gamma, beta, and alpha radiations. Ionization chambers operate at lower voltages than the G-M tubes, which means that ionization chambers are somewhat insensitive to low level radiation, but are fully operative well beyond the upper dose rate limit of a G-M counter.

Figure 4.4

IONIZATION CHAMBER (Schematic)

When a charged particle of high velocity traverses the chamber, it ionizes molecules of the gas. A voltage across the two plates attracts positive ions to one plate and negative ions to the other. The resulting current is indicated on a meter.

TYPICAL IONIZATION CHAMBER

B. PERSONNEL MONITORING DEVICES

1. The Electroscope or Dosimeter. Electroscopes are among the most sensitive of all radiation devices. Their construction is rather simple; however, they have a drawback in that they are not a "rugged" instrument. The dosimeter is one of the more common electroscope type instruments used in laboratory monitoring situations and is much less sensitive to rough handling.

The electroscope is based upon the effect of electrostatic repulsion. We have all observed the action of paper placed in the electrostatic field of a pocket comb that has been run through hair. In this case, the comb picks up free electrons from the hair and become negatively charged. When bits of paper are placed in the negative field, they jump to the comb. As they touch the comb they pick up electrons and become negatively charged. Once they become negatively charged, they are repelled by each other since bodies of a similar charge repel.

The electroscope consists of a glass enclosed center post to which is attached a thin gold leaf. A negative charge is placed upon the leaves through a surplus of electrons. The thin leaf, capable of movement, is repelled from the center post. Ionizing radiation passing through the glass chamber produces ion pairs. The positively charged particles are attracted to the negatively charged post where they pick up the free electrons. The result is that the filament is repelled less by the center electrode through a reduction in charge and then falls back towards the center pole. The distance traveled by the filament can be directly converted into roentgens. Naturally, the free electrons formed are repelled by the poles and do not enter into the reaction.

The dosimeter (Lauritsen Electroscope) is a very rugged yet sensitive electroscope that utilizes a quartz fibre rather than a gold leaf. The operator must read the scale with a small microscope mounted in the dosimeter tube. Careless handling of a dosimeter can spoil the insulating qualities of the electrodes and give false readings. The operator should give his dosimeter every care so that it will provide him with accurate information necessary to his well being. If an operator does not plan on using his dosimeter, he should store it in a radiation-free environment with the dose recorded. This should then be compared with the final recording. Any sufficient increase of the reading (mR or mREM) could indicate the dosimeter has been damaged.

2. The Film Badge. A film badge represents one of the oldest methods for detection of radioactivity. In the early days of atomic physics, photographic film was the only means known of detecting radioactivity. Nowadays, specially sensitized emulsions have been developed that represent a great advance over the early photographic emulsions.

The principle of photosensitivity might be understood if we examine some of the basic conditions in the process. If one exposes a freshly prepared precipitate of silver chloride to light energy, the precipitate will change from its original white color to a black color. The longer it is exposed to light energy, the darker it will become. A chemical treatment can be rendered to the precipitate that will "fix" or prevent the chemical from becoming darker. The ability of light energy to cause a chemical change is not unusual when one realizes that heat or kinetic energy is often used to cause chemical reactions: (i.e., the practice of heating certain reactions to hasten their reactivity). However, in photochemical reactions, light energy is utilized instead of heat energy.

A photographic emulsion consists of a piece of celluloid upon which is placed an emulsion of silver salt. An emulsion is like a finely divided precipitate suspended in another media. Photographic emulsions have been developed so that the photochemical reactions will occur only to light energy or other electromagnetic radiations of definite energy or frequency.

Photographic emulsion has been greatly improved in sensitivity so that highly accurate measures of radioactivity can be made of X, gamma, and beta radiations. Just as with common photographic film, the developed emulsion turns black where hit by electromagnetic radiation. Again, just as with ordinary photographic film, the development of the film plays an important roll in the density of the negative. Exposed film badges are always developed under exacting standards. They are always developed in the same way so that the changes in density will not result through variables in process development, but only through variables in exposure. Since the variables of development are controlled, any change of negative density can be attributed to the incident exposure.

Negative density standards are prepared by exposing film to known amounts of radiation and developed by controlled procedures. The exposed film badge densities can then be compared to the densities of the known standards.

The densities of the films are checked with an instrument called a densitometer. The principle of densitometer operation is simple. Light is passed through the film and then measured with a small light meter. The greater the negative density, the less the amount of light recorded by the light meter. The reading of the densitometer is calibrated in dose. Dose can then be recorded on the individual's film badge record.

Film badges utilize the principle of shielding as a means of interpreting the energy of the radiation. For example, beta-ray measurements normally obtained from unshielded portions of the film are difficult to interpret because identical results can be obtained with very low doses of soft X or gamma rays. In practice, however, beta radiation is distinguished from low energy X-rays by making readings under both the plastic and open window regions. The plastic is sufficiently thick to attenuate all beta rays, while at the same time being virtually transparent to X-rays except at very low energies.

The high sensitivity of film to X or gamma ray energies requires the use of special measuring techniques when low energies are encountered. This is done by density ratios of the open window, the aluminum and cadmium filters. The lead filter is used in determining higher energy X or gamma radiation. The effects of combining films and filters are shown in Figure 4.5.

Film badges are a very inexpensive and yet highly accurate means of determining radiation exposure. Special consideration should be given by the wearer to assure that the film badge is properly worn. Do not carry the badge in a pocket since there is danger of shielding by coins, keys, etc. Finger tab versions of film badges are worn as a ring. They are used by workers who may expose their hands, fingers, or wrists to radiation.

Remember that a film badge will record radiation whether it is worn or not. When not in use, take care not to store your badge in a radiation field.

Figure 4.5

TYPICAL FILM BADGE SENSITIVITY SPECTRUM

C. CHARACTERISTICS OF RADIATION DETECTION INSTRUMENTS

Alpha particles are normally monitored with a gas proportional counter or a scintillator-photomultiplier combination. Beta, gamma, and X-radiation are measured with ion chambers, Geiger tubes or scintillation detectors. Neutrons can be measured with BF_3 proportional counters (moderated-fast, bare-thermal), scintillation devices, and fission chambers. The output from these detectors is read on a dose-rate or count-rate meter. Each instrument type has its own advantages and limitations. The portable radiation detectors in use at NRDS are summarized in Table 4.1.

1. Geiger-Muller Instruments. G-M devices are widely used for low level (less than 20 mR/hr) monitoring of beta/gamma radiations and beta/gamma contamination. They have advantages of small size, ruggedness, rapid response, and high sensitivity to beta radiation. They have several limitations. One is energy dependence; i.e., the instrument response is not the same as that of air or tissue for all radiation energies. Another is low gamma sensitivity. Temperature extremes can effect the operation of G-M tubes or battery characteristics, causing instrument failure or erratic operation in only moderately cold temperature. Saturation may appear as a lowering of the dose rate as a G-M tube is moved into a radiation field higher than the tube and circuits were designed to handle. Although this effect should require dose-rates several times full scale, much lower intensities can cause saturation in a tube that is near the end of its life.

With the beta shield open, a G-M tube will detect beta particles with energies sufficient to penetrate the tube walls. Beta readings with a G-M instrument are not normally in units of dose-rate (RADs/hr). In certain cases, however, conversion factors can be applied to change the reading to RADs/hr (or mRADs/hr). With shield closed, the G-M will measure gamma alone (mR/hr).

The Geiger counter used at NRDS for low level radiation monitoring is the Eberline Model E-510 (Figure 4.6).

2. Ion Chamber Instruments. Ion chamber instruments are normally issued for measuring higher radiation intensities than G-M devices. This is partly attributable to the fact that ion chambers are less sensitive than are G-M detectors.

METER FACE
EBERLINE MODEL-E510 GM
FOR TRAINING USE ONLY

FIGURE 4.6

Ion chambers show energy response characteristics comparable to those of air and tissue and therefore, require little or no correction for energy variations. Most ion chamber instruments are equipped with beta filters and hence can measure beta plus gamma dose-rates or gamma dose-rates alone.

Some of the deficiencies to be expected with ion chambers include battery failure at low temperatures, zero drift, and relatively long warmup time.

Instruments of this type for portable radiation monitoring at NRDS are the Victoreen Cutie Pie, Model 740C (Figure 4.7); Technical Associates Junos (normal and range types) (Figure 4.8); and the Victoreen Rad Gun (Figure 4.9).

3. Scintillation Counters. Scintillation counters are used to measure fast neutrons, alpha particles or gamma rays. Their advantages include high or variable sensitivity, wide measurement range, energy discrimination, and energy determination. Disadvantages include complexity, high cost, and sensitivity to rough handling. Scintillation counters in use at NRDS are the Eberline Gadora gamma detector and the Precision Model P111B gamma detector.

4. Proportional Counters. Proportional counters are principally used to measure neutrons or alpha particles. Most scintillation devices operate in the proportional region where energy discrimination is possible.

Disadvantages are similar to those of scintillation and G-M counters.

Proportional counters in use at NRDS include the Eberline Model PAC-3G alpha detector (Figure 4.10) and the Eberline Model PAD-1 neutron detector.

D. OPERATION

1. Meters. The meters of radiation detection instruments consist of either a linear or a logarithmic scale.

a. Linear Meter Scales. A linear scale begins with zero and is divided into equal segments. Each instrument has a selector switch which changes the direct reading by the factors indicated. These factors may be indicated by multipliers to be applied to the readings or may be indicated by full-scale value for each setting. Readings between numbers must be interpolated. Examples of linear meter scale systems and readings are shown in Figures 4.6, 4.7, 4.8, and 4.10.

CUTIE PIE
VICTOREEN MODEL 740
FOR TRAINING USE ONLY
46

FIGURE 4.7

JUNO MODEL 7
FOR TRAINING USE ONLY

FIGURE 4.8

b. **Logarithmic Meter Scales.** Logarithmic scales begin with some value greater than zero. As shown in Figure 4.9, the spacing of the marks is repeated identically through each ten-fold increase in readings. Thus, the spacing of the marks from 0.05 to 0.5 is identical to that from 0.5 to 5 or from 5 to 50. These major divisions are called decades. Within any decade the spacing of the marks decreases logarithmically. This also takes place between whole numbers and thus the space from 1.5 to 2 is less than 1.0 to 1.5 so that a reading of 1.5 is about 75% of the distance between 1 and 2 rather than half way as it would be on a linear scale. For the smaller spacings interpolation becomes more linear.

The Victoreen Rad Gun is an example of a radiation detector in use at NRDS with a logarithmic scale (Figure 4.9).

2. **Calibration.** To help insure adequate personnel protection, all portable radiation survey instruments are calibrated monthly by Pan American Radiation Services. Radiation sources of known activity are used to calibrate all instruments in use at NRDS. Each instrument bears a label showing date of last calibration and maintenance.

3. **Maintenance.** All portable radiation survey instruments in use at NRDS are maintained monthly, or more frequently if required. Normally, the instruments are recalled monthly, maintained, and then calibrated.

METER RANGES

MR / HOUR

R / HOUR

KR / HOUR

METER FACE

VICTOREEN RAD - GUN

FOR TRAINING USE ONLY

FIGURE 4.9

METER FACE
EBERLINE MODEL PAC-3G
FOR TRAINING USE ONLY

FIGURE 4.10

MANUFACTURER	MODEL NUMBER	RADIATION(S) DETECTED	DETECTOR TYPE	MEASUREMENT RANGES	CALIBRATION POINT(S)
Eberline	PAC-3G	Alpha	Gas Proportional	0-1,000, 0-10,000, 0-100,000 counts/minute	1/3 and 2/3 Full Scale on each range.
Eberline	Gadora 1B	Gamma	Scintillation	0-5, 0-50, 0-500, 0-5K R/hr	1/3 and 2/3 Full Scale on each range.
Eberline	E-510	Beta and Gamma	G-M	0-012, 0-2, 0-20, 0-200 mR/hr	1/3 and 2/3 Full Scale on each range.
Victoreen	Rad Gun AGB-10KG-SR	Beta and Gamma	Ion Chamber	0.01-10mR/hr, 0.01-10 R/hr, 0.11-10KR/hr	Mid-scale on each range plus built-in check source.
Victoreen	Cutie Pie 740	Beta and Gamma	Ion Chamber	0-100, 0-1000, 0-10,000, 0-100,000 mR/hr	1/3 and 2/3 Full Scale on each range.
Technical Associates	Juno's SRJ-7 HRJ-7	Beta and Gamma	Ion Chamber	50, 500, 5000 mR/hr Full Scale 250, 2500, 25,000 mR/hr Full Scale	1/3 and 2/3 Full Scale on each range.
Victoreen	440	Beta and Gamma	Ion Chamber	0-3, 0-10, 0-30, 0-100, 0-300 mR/hr	1/3 and 2/3 Full Scale on each range.
Precision	P-111B	Gamma	Scintillation	0-0.025, 0-0.25, 0-2.5, 0-0.05, 0-.5, 0-5	1/3 and 2/3 Full Scale on each range.
Eberline	PNC-1	Neutrons (Fast and Slow)	BF ₃ Proportional	0-500, 0-5000, 0-50,000, 0-500,000 E/M	1/3 and 2/3 Full Scale on each range.
Victoreen	488A	Neutrons (Fast and Slow)	BF ₃ Proportional	0-800, 0-8,000 0-80,000, 0-800,000	1/3 and 2/3 Full Scale on each range.

PORTABLE RADIATION DETECTORS IN USE AT NRDS

TABLE 4.1

SECTION V

PROTECTION FROM RADIATION

Personnel can be protected from harmful radiation by limiting the time of exposure, increasing the distance between the source and the personnel, and placing an energy-absorbing material between the source and the personnel to be protected. It has been shown in Section II that the dose accumulated is directly proportional to the length of time of the exposure. This section, then, will cover the effects of distance and shielding.

A. DISTANCE

The effectiveness of distance in furnishing protection from gamma radiation exposure is startling. The intensity of radiation decreases by the square of the distance from a point source. For example, if at a distance of one foot from a source, the dose rate is 1000 R/hr, doubling the distance will divide the dose rate by 2^2 or 4, reducing it to 250 R/hr; multiplying the distance by 3 will divide the dose rate 9 to give 111 R/hr. This law holds true for almost any distance. At 1000 feet, for example, the dose rate would be down to 1 mR/hr. The formula for this effect is:

$$\frac{I_1}{I_2} = \frac{D_2^2}{D_1^2}$$

Where I_1 and D_1 represent a known intensity and distance and I_2 and D_2 represent another intensity and distance.

B. PRINCIPLES OF SHIELDING EFFECTS

The energy of nuclear radiations are absorbed by the materials through which they pass. Thus, various materials may be used as shielding against radiation. Each type of radiation has unique shielding requirements.

1. Alpha Shielding. Alpha particles can be stopped very easily by a sheet of paper or ordinary clothing. Examples of alpha emitters are radium, polonium and uranium. The skin absorbs the energy from alpha emitters on its surface.

2. Beta Shielding. Beta particles are not emitted from ^{60}Co sources as long as the source encapsulation is intact. In the event of a fire or explosion, however, ^{60}Co dust or vapors could be released and beta particles would become a hazard. Beta particles are stopped by their reactions with orbital electrons so that they have a range of only a few yards in air. Geiger counters are provided for monitoring beta radiation in the event of damage to source capsules. Aluminum and lucite are the standard beta shielding materials. They stop the beta particles without giving rise to gamma rays by bremsstrahlung. Other examples of beta emitters are ^{14}C Carbon and ^{90}Sr Strontium. Beta particles can penetrate several centimeters of tissue.

3. Gamma Shielding. The gamma radiation of ^{60}Co can penetrate to great depths even in dense material. It is this property which makes it valuable as an inspection tool yet difficult to shield. Gamma radiation is attenuated by interacting with orbital electrons as shown in Figure 5.1.

The best gamma shielding materials have high densities and high atomic numbers, such as gold, tungsten, and lead. Iron and lead are the most effective commonly used gamma shielding materials.

C. HALF-VALUE LAYERS

Since gamma rays cannot be completely stopped by any thickness of a shielding material, the effectiveness of shielding materials is rated by the thickness required to reduce the level of radiation by one-half. This thickness is called the half-value layer. The half-value layer of lead for 2 Mev gamma radiation is one-half inch. Figure 5.2 illustrates why sources of high activity do not require proportionately heavy shielding. In this case, doubling the shielding would permit increasing the activity of the source by eight, to maintain the desired radiation level on the outside of the source.

Figure 5.1

ATTENUATION OF GAMMA PHOTONS

PHOTOELECTRIC EFFECT

COMPTON EFFECT

PAIR PRODUCTION

Figure 5.2

ATTENUATION OF ^{60}Co GAMMA RAYS BY HALF-VALUE
LAYERS OF LEAD

Note that three layers will give a reduction of eight times or 2^3 , while six layers give a reduction of 64 times or 2^6 . The half-value thickness of any material is dependent upon the energy of the gamma photons and the density of the shielding material.

Revised Edition
1963

PERIODIC CHART OF THE ATOMS

Designed in 1924 by
Henry D. Hubbard
Revised frequently since 1940 by
William F. Meggers

The Atoms Grouped According to the Number of Outer [Valence] Electrons										Planetary electrons in the completed shells		PERIODS ↓ RADIAL QUANTA
PERIODS ↓ RADIAL QUANTA	Planets ↓ VALENCE	GROUP I ns ¹	GROUP II ns ²	GROUP III ns ² np ¹	GROUP IV ns ² np ²	GROUP V ns ² np ³	GROUP VI ns ² np ⁴	GROUP VII ns ² np ⁵	GROUP VIII ns ² np ⁶	Total Atom No. = 2(1 ² + 2 ² + 3 ² + 4 ² + 5 ² + 6 ²)		
1	0 n Neutron 1.00898	1 × H 1.00797								2 = 2	End of the 1st Period	1
2	2 He	3 × Li 6.939	4 × Be 9.0122	5 × B 10.811	6 × C 12.0115	7 × N 14.0067	8 × O 15.9994	9 × F 18.9984	10 × Ne 20.183	10 = 2 + 8	End of the 2nd Period	2
3	10 Ne	11 × Na 22.9898	12 × Mg 24.312	13 × Al 26.9815	14 × Si 28.086	15 × P 30.9738	16 × S 32.064	17 × Cl 35.453	18 × Ar 39.948	18 = 2 + 8 + 8	End of the 3rd Period	3
4	18 Ar	19 × K 39.102	20 × Ca 40.08	21 × Sc 44.956	22 × Ti 47.90	23 × V 50.942	24 × Cr 51.996	25 × Mn 54.9380	26 × Fe 55.847	27 × Co 58.9332	28 × Ni 58.71	4
		29 × Cu 63.54	30 × Zn 65.37	31 × Ga 69.72	32 × Ge 72.59	33 × As 74.9216	34 × Se 78.96	35 × Br 79.909	36 × Kr 83.80	36 = 2 + 8 + 18 + 8	End of the 4th Period	4
5	36 Kr	37 × Rb 85.47	38 × Sr 87.62	39 × Y 88.905	40 × Zr 91.22	41 × Nb 92.906	42 × Mo 95.94	43 × Tc 99	44 × Ru 101.07	45 × Rh 102.905	46 × Pd 106.4	5
		47 × Ag 107.870	48 × Cd 112.40	49 × In 114.82	50 × Sn 118.69	51 × Sb 121.75	52 × Te 127.60	53 × I 126.9044	54 × Xe 131.30	54 = 2 + 8 + 18 + 18 + 8	End of the 5th Period	5
6	54 Xe	55 × Cs 132.905	56 × Ba 137.34	57 × La 138.91	58 × Ce 140.12	59 × Pr 140.907	60 × Nd 144.24	61 × Pm 145	62 × Sm 150.35	63 × Eu 151.96	64 × Gd 157.25	6
		79 × Au 196.967	80 × Hg 200.59	81 × Tl 204.37	82 × Pb 207.19	83 × Bi 208.980	84 × Po [210]	85 × At [210]	86 × Rn [222]	86 = 2 + 8 + 18 + 32 + 18 + 8	End of the 6th Period	6
7	86 Rn	87 × Fr [223]	88 × Ra [226]	89 × Ac [227]	90 × Th 232.038	91 × Pa [231]	92 × U 238.03	93 × Np [237]	94 × Pu [242]	95 × Am [243]	96 × Cm [247]	7
		104	105	106	107	108	109	110	111	112	113	7
6	★58-71 Rare Earths Type 4f	58 × Ce 140.12	59 × Pr 140.907	60 × Nd 144.24	61 × Pm 145	62 × Sm 150.35	63 × Eu 151.96	64 × Gd 157.25	65 × Tb 158.924	66 × Dy 162.50	67 × Ho 164.930	6
		114	115	116	117	118	119	120	121	122	123	6
7	★90-103 Rare Earths Type 5f	90 × Th 232.038	91 × Pa [231]	92 × U 238.03	93 × Np [237]	94 × Pu [242]	95 × Am [243]	96 × Cm [247]	97 × Bk [249]	98 × Cf [251]	99 × Es [254]	7
		124	125	126	127	128	129	130	131	132	133	7

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APPENDIX A

X-RAYS

X-rays were discovered on November 8, 1895, by Professor Wilhelm Konrad Roentgen. While experimenting with a glass vacuum tube through which he was passing an electronic current Roentgen noticed that a plate of barium platinocyanide crystals on a nearby table was glowing. The vacuum tube was covered with a black paper so Roentgen knew no light from the electrical discharge escaped to cause the crystals to glow. After further research Roentgen concluded that some unknown type of ray produced in the vacuum tube had caused the crystals to fluoresce. To these rays, the cause and nature of which he could not then determine, Roentgen gave the name X-ray.

X-rays are a form of radiant energy, like visible light. Their distinguishing feature is an extremely short wavelength, about $1/10,000$ or less than the length of visible light waves. Ordinary light is reflected or absorbed by most surfaces but X-rays, because of their short wavelength, penetrate these materials. Because X and gamma rays are so different in this way from other forms of radiant energy they are considered separately. Figure A.1 shows their location in the electromagnetic spectrum.

X-rays are produced when electrons traveling at high speed collide with any form of matter. An X-ray tube is usually made of an incandescent filament which supplies electrons and forms the cathode or negative

electrode of the tube. When high voltage is applied to the tube, electrons are driven to the anode. The sudden stopping of the electrons as they strike the anode produces X-rays. As the energy of the bombarding electrons is increased the radiated frequencies increase, overlap, and may extend beyond the gamma ray region. Gamma rays, which after emission are identical to X-rays of the same wavelength, are emitted from radioactive nuclei.

Figure A.1

THE ELECTROMAGNETIC SPECTRUM

Figure A.2
DIAGRAM OF AN X-RAY TUBE

Figure A.2 is a schematic diagram of the essential parts of an X-ray tube. The filament is heated by a current of several amperes from a low voltage source, generally a small transformer. The FOCUSING CUP serves to concentrate the stream of electrons on a small area of the target, called the FOCAL SPOT. This stream of electrons constitutes the TUBE CURRENT, and is measured in MILLIAMPERES.

The higher the temperature of the filament, the greater is its emission of electrons, and the larger the resulting tube current. Other conditions remaining the same, the X-ray output is proportional to the tube current.

Most of the energy applied to the tube is transformed into heat at the focal spot, only a small portion being transformed into X-rays. The efficiency of the target material in the production of X-rays is proportional to its atomic number. The high atomic number of tungsten, in combination with its high

melting point, makes it a most suitable material for the target of an X-ray tube. In the absence of provision for liquid cooling, the use of copper for the main body of the anode provides high heat conductivity, while radiating fins on the end of the anode outside the tube transfer the heat to the surrounding oil or air.

X-ray generating apparatus comprises, aside from the X-ray tube, the following principal components: a high-voltage transformer; an autotransformer; a rectifier; and a power supply for the X-ray tube filament.

APPENDIX B

CRITICALITY ACCIDENT REPORTS

1. Accidental Radiation Excursion at the Y-12 Plant
2. Los Alamos Criticality Accident
3. Nuclear Incident at the Idaho Chemical Processing Plant

ACCIDENTAL RADIATION EXCURSION AT THE Y-12 PLANT

(Excerpts)

SUMMARY

"The site of the accidental nuclear excursion was in the C-1 Wing of Building 9212 in a 55-gallon stainless steel drum."

"A portion of enriched (~90% U-235) uranium-bearing solution, containing approximately 50 gm U-235/liter, flowed through a valved pipeline from an extraction product "safe" tank in B-1 Wing into C-1 Wing."

"Following the initial nuclear burst, which did not discharge the contents of the drum, the nuclear system appears to have oscillated. The reaction was ultimately stopped by the additional water flowing into the drum. Based upon an examination of the chart taken from a recording monitor located in another building and other indicative information, it is believed that the nuclear reaction lasted approximately twenty minutes."

"Eight Y-12 employees were in the vicinity of the drum at the time of the incident. The five men exposed to what has been described as a medium dose of radiation by Dr. Marshall Brucer, Chairman, Medical Division, Oak Ridge Institute of Nuclear Studies, were:

Employee "A", Chemical Operator - Age 40; 365 rad - 461 rem
Employee "B", Electrician - Age 32; 270 rad - 341 rem
Employee "C", Maintenance Mechanic - Age 39; 339 rad - 428 rem
Employee "D", Electrician - Age 51; 327 rad - 413 rem
Employee "E", Maintenance Mechanic - Age 35; 236 rad - 298 rem

FINDINGS

"This temporary arrangement of old facilities combined with part of a new installation was a compromise between the customary detailed design planning of valving, instrumentation, and other safeguards, and a requirement for maintaining production during this interim phase. Also, the responsibility for the uranyl nitrate to uranium tetrafluoride operation was thereby split among three different supervisors in three physically separated areas, instead of being under a single supervisor as would be the case in the completed B-1 Wing. Communications were considerably complicated by this situation."

"At the time of the incident the uranium processing areas had been concerned with the required monthly accounting of uranium in inventory, which necessitated a stoppage of operations. However, all operations were not stopped or started at the same time due to the complexity of the installation. The method of taking inventory varied with the form and concentration of the uranium. For example, where equipment contained dilute homogeneous solutions of uranium, a satisfactory accounting could be made by taking samples and computing the content of known volumes."

"Certain routine duties, such as the mopping of floors and the checking of equipment that has undergone minor maintenance, due to their simple nature and the many variations involved, have not been explicitly detailed in procedures. Instead, over the fourteen years of operation, general rules have been formulated and the task of seeing that routine applications conform to these criteria has been assigned to the process foreman."

"As reassembled "safe" tanks were prone to leak at the tank ends when placed back in service after the monthly inventory cleanup, leak testing of reassembled tanks by filling with water, checking the draining prior to their return to operation, was practiced. Leak testing with water was among the previously mentioned routine duties that were not formalized and were carried out under the discretion and supervision of the process foremen."

"Although this leak testing had considerable utility, as practiced it deviated from the intent of two mandatory area procedural rules by the incorporation of a 55-gallon drum to collect water drained from "safe" tanks after the leak testing. These rules are:

- a. Process liquids are never to be transferred from a geometrically "safe" container to a geometrically "unsafe" container.
- b. "Unsafe" containers used to collect dilute liquids (such as mop water) must contain a charge of cadmium nitrate (a nuclear poison).

An unfortunate interpretation of the above rules was that they did not apply to the leak testing of the 5" diameter "safe" tanks, since the tanks were clean and only water was used in the operation.

The significance of the foregoing, with regard to the accident, is that it furnished the mechanism whereby an "unsafe" geometry container (i.e., the 55-gallon drum) was separated from concentrated uranyl nitrate solutions by only a single valve.

"At 7:00 a.m., June 16, Foreman "X" relieved Foreman "Y". The accounts of whether Foreman "Y" notified Foreman "X" of the above mentioned uranyl nitrate leakage are conflicting. In any event, no mention was made of it in the operating log."

"The excursion took place after the concentrated solution in the drum had reached a height of 9 inches."

"Operator "A", an experienced man (one year of college training, six years in uranium processing operations), was adjacent to the 55-gallon drum observing the slow flow of liquid. The previously mentioned hydraulic experiments, performed after the accident, established that approximately a quarter of an hour was required for the liquid in the drum to reach the level at which it became critical. In addition, the yellow color of concentrated uranyl nitrate is distinctive and was well known to Operator "A". It would thus appear that Operator "A" had an opportunity to shut off the flow of solution prior to the accident."

"It was determined that a period of 3 to 5 seconds was required, after actuation of the radiation monitors, for the alarm sirens to reach audible speed. The first several seconds are the period of greatest danger in a criticality accident."

"The decision of Employees "C" and "E" to evacuate to the east rather than the west was unfortunate, in that this route actually led them closer to the 55-gallon drum."

"That all of these employees heeded the alarm and instantly evacuated the building must be emphasized. It can be stated unequivocally that fatalities in this incident were prevented by the rapid and orderly exit of employees. Their action in this manner, to which at least one (Employee "A") owes his life, is evidence of an effective indoctrination in safety practices."

"Nuclear Safety Education Program - The most recent nuclear safety training, prior to the accident, consisted of a program prepared by the Y-12 Radiation Control Department which was presented in a series of sessions in February and March, 1958. Nearly all supervisors in the plant, as well as all personnel in the plant who handle uranium, attended at least one session of one and one-half hours duration. About 550 supervisors and approximately 500 employees, including all chemical operators and foremen referred to in this report, attended."

This training included the following topics:

1. Nuclear safety; the nuclear chain reaction, its prevention and results.
2. Nuclear safety in Y-12.
3. The responsibility for nuclear safety.
4. Methods of nuclear safety.

This session included detailed information on the recognition and consequences of a nuclear accident quite similar to the actual concurrence of June 16, 1958.

Plant personnel involved in uranium processing were given a lecture on the same material approximately one year earlier.

In all of the above discussions, the primary emphasis was on the prevention of nuclear accidents.

"In addition, the complete exchange of significant information among personnel was not assured, nor was the potential significance of several observations, now recognized as highly pertinent to the occurrence, adequately appreciated."

"The committee also concludes that, although the environment in which this event took place and the performance of some individuals might have been improved, a nuclear accident will always be within the realm of possibility whenever potentially critical quantities of fissionable material are being handled."

RECOMMENDATIONS

"Within the bounds of economic practicability, nuclear safety should be incorporated in the design of the equipment, taking full advantage of the characteristics of the material and process."

"Transfers from a processing train which relies for nuclear safety on equipment construction to one which relies on administrative control should be avoided unless no practical alternative is available."

"An investigation of the use of fixed neutron absorbers in process equipment to implement nuclear safety should be actively pursued."

"The use of portable unsafe containers in operating areas incorporating "safe" processing equipment should be held to an absolute minimum."

"The means of communication between shifts, between operating and maintenance groups, and between production and staff groups should be more highly formalized than is customary in the chemical industry."

"It is recommended that the importance of nuclear safety in fissionable materials processing plants be restated and re-emphasized periodically to all personnel working in the processing areas. Although primary dependence for nuclear safety lies in equipment or procedural restrictions, it is clear that only by creating a constant awareness of nuclear safety can unusual and unexpected circumstances be viewed in terms of their possible nuclear hazard."

"Likewise, management and all plant personnel should be reinstructed periodically in the health physics aspects of potential nuclear emergencies."

"A competent, well-informed health physics group, vested with a reasonable degree of authority, is vital in properly coping with the aftermath of a nuclear accident."

"The following recommendation is made governing the approach of a near critical solution of U-235 by personnel. The recommendation is based on the analysis of the effect, on the solution reactivity, of the neutron reflection by a simulated human body which is presented in Appendix L. A vessel containing solution in which a nuclear accident has recently occurred should be approached not nearer than five feet, and the number of persons at this distance should be limited to one."

LOS ALAMOS CRITICALITY ACCIDENT

(Excerpts)

Editors' Note: "A sudden criticality in a processing vessel at the Los Alamos plutonium-processing plant occurred on December 30. As a result a technician died 36 hours later(NU, February 1959, p. 21). Nucleonics presents here a report of the official investigation of the accident. The report tells that the accident occurred during an inventory in which normal plant flow was interrupted. An unusual amount of plutonium had collected in a processing tank. When a stirrer was actuated an aqueous solution at the bottom of the tank flowed up around the plutonium-rich organic phase above it, producing criticality."

"A chemical operator started the motor driving the stirrer in the solvent-treating tank. There was a "blue flash" and a muffled report. The operator, who was looking into a sight glass at the top of the tank, was knocked off the two-step ladder on which he stood. The operator apparently turned the stirrer motor off and then on again (this time noticing a rumbling sound), ran out a nearby exterior door and called that he was "burning up". Though the shock displaced the tank about 3/8 inches at its supports, the tank was not ruptured and no plutonium escaped."

"The tank in which the accident occurred was not bolted to the floor. Tangential shift of one of the supporting legs was apparent because the initial position was outlined by the latest coat of floor paint. Apparently the tank pivoted about the opposite foot."

"We cannot be certain that there was no following low-order burst when the stirrer was turned on the second time, but it seems unlikely. No accompanying blue flash was reported, and it is doubtful that the few seconds presumed to have elapsed while the stirrer was off would have been sufficient to re-establish a potentially critical situation. Radiation-detector traces are consistent with a single-burst hypothesis, but do not exclude the possibility of two closely spaced pulses. The stirrer rumbles when turned on under normal conditions; it appears that degree of rumble could easily have been misjudged. We will never know for sure."

"At the time of the burst a second operator some 40 feet away in an adjoining room saw a reflection of the light on the walls (like a photoflash), heard the report, went to help, and was joined by a third operator. They joined the first operator who had by this time run out of a nearby door. All three men returned past the accident tank to lead the injured operator to a shower. By this time he suspected that he was suffering from an acid burn. As the three passed the tank in which the accident occurred, the second operator turned off the stirrer motor."

"The burst activated a radiation alarm located 175 feet away in a nearby building. (This unit was connected to an indicating instrument and set to sound at 10 mr/hr.) After a report of the alarm, the entire plant was evacuated. The time was 4:35 p.m., December 30, 1958."

"The fatally injured man received a radiation dose estimated at 12,000 rem $\pm$ 50%. The next highest doses received by any of the operating personnel are estimated at 134 and 53 rem. Other exposures from the supercritical burst were less than 4 rem."

"The chemical operator at the solvent-treating tank went into deep shock within 15 minutes of exposure. He regained consciousness about 6 hours later and remained rational and comfortable until nearly the time of his death at 3:15 a.m., January 1, 1959."

"Ironically, a nuclear-criticality review of the entire plutonium plant had been completed about a month before the accident. Changes in equipment associated with a hopefully improved solvent-extraction process were planned so as to reduce dependence on procedural control of batch sizes for nuclear-safety purposes. This type of control had been successfully used during the 7 1/2 years that the plant was in operation. Installation of the new equipment was scheduled for next June and July. Depending on efficiency of the new extraction process, the possibility of eliminating the succeeding raffinate solvent extraction and concentration stages was to be explored."

"The committee concluded that the accident was directly attributable to errors on the part of the operator who was killed. There has been some disagreement about how strongly the blame should be fixed. It has been established that the operator did not follow precisely the directions of his supervisor, who had outlined the procedure before the day's operations began."

"The operator was an experienced man who knew the processes he was carrying out and the reasons for them. He had always followed directions and had a reputation for reliability. The manner in which he departed from the prescribed procedure led him to handle several batches of material together instead of one at a time. The altered procedure made for easier inventory and a neater process. The investigators feel that this may have been his motivation in making the alteration."

"The committee found that closer supervision might have prevented the accident and commended Los Alamos personnel on measures they have taken to prevent a recurrence."

NUCLEAR INCIDENT AT THE IDAHO CHEMICAL PROCESSING PLANT

(Excerpts)

"A nuclear excursion of the order of 10^{19} fissions occurred in a process equipment waste tank of the ICPP about 0250 on October 16. It resulted from the accidental transfer of about 200 liters of uranyl nitrate solution containing about 34 kg enriched uranium (91 percent U-235) from critically safe process storage banks to a geometrically unsafe tank through a line normally used for waste transfers. It appears that siphon action from the storage bank to the waste collection tank was initiated by introduction of excessive sparge air to the storage banks."

"Upon achieving transient conditions of fissionable mass, moderation and geometry, the system went through criticality and returned to a subcritical state under conditions unknown to and unsuspected by operating personnel."

"The circumstance of a recent Rala run presenting the likelihood of air contamination and the absence of any apparent indication of a nuclear reaction prior to qualitative analysis of fission products confused the identification of a criticality incident."

"There are probably few other industrial or laboratory operations where it is so axiomatic that the price of safety is intensive, eternal vigilance. The coincidence of three major nuclear incidents in the Atomic Energy Commission in a 16-month period after many years of incident-free experience in this type of operation should represent the greatest possible argument for additional efforts in this area. While in this instance it was reassuring that no major personnel exposures resulted from a relatively large excursion, the security of shielding and protective devices is no substitute for prevention."

"A general lack of serious concern on the part of operating personnel over initial alarms was noted. This seemed to stem partly from the acknowledged regularity of alarms that did not reflect a general radiation hazard in the plant and to some degree from a confusion over the interpretation of alarm signals of various kinds. This confusion in turn resulted from the use of similar, or in some cases identical, sounds for radiation detectors and process controls."

"Intensification of the education program to combat the possibility of 'familiarity breeding contempt' for radioactivity in a plant such as the ICPP."

APPENDIX C
HISTORICAL BACKGROUND OF NUCLEAR PHYSICS

Many of us who are engaged in nuclear technology in one way or another are inclined to take the business for granted. In the confusion which accompanies a program of such large latitude, and as a result of the continuing pressures to accomplish our immediate objectives, it is excusable that the story of the beginning of the nuclear era may have been slighted. Without some effort, it is difficult to compile a coherent story of the work of the founders of the nuclear age. By condensing the material from many sources, a short history of the beginning of nuclear reactor technology is presented here.

The work we do and the terms we use are accepted among those of our profession and are in more or less common use, even among laymen. It is not surprising that this large industry, still moving rapidly as a result of the impetus given it by an all-out war effort, has been widely publicized. Its benefits will be accepted by this generation and those following. As nuclear technology grows older, its early history will become more obscure. This chapter will cover only the important developments and some of the people responsible for them.

In the 1890's, several European physicists were investigating the phenomenon of fluorescence. There were many tools employed in this research, among which were the Crooks (gas-electrical discharge) tubes and ordinary sunlight. It was noticed that many materials would fluoresce when exposed to cathode rays. William Roentgen (a German physicist) noticed that the glass walls of his cathode-ray tube fluoresced while the machine was operating. In one of his experiments, this tube had been covered with black paper so that the fluorescence experiments could be carried on in a darkened room. During one of these experiments, there was a brilliant luminescence exhibited by a sheet of paper near the enclosed discharge tube. The paper had been coated with barium platino-cyanide, presumably for another experiment. He subsequently proved that whatever made the paper fluoresce originated from within the tube, and he also concluded that it was the result of some form of penetrating rays, to which he gave the name of X-rays. Others were also on the track to the discovery of X-rays. For example, it was noticed that something frequently fogged any photographic plates which were left near these tubes. Some of such experiments were performed in 1890 and 1894, whereas Roentgen's experiment was performed in 1895. To observe is one thing; to identify and prove is quite another.

Shortly after the announcement of the discovery of X-rays, a French physicist, Henri Becquerel, became interested in them. When Becquerel inquired as to where in the discharge tube the rays may originate, he was told that apparently they originate at the luminescent spot produced where the cathode rays impinge on the discharge tube. In his possession he had a pure specimen of potassium uranyl sulfate salt which his father (who also was a physicist) had used in his earlier work on fluorescence.

In an attempt to determine whether there was any connection between fluorescence and X-rays, Becquerel devised an experiment in which the salts were placed on top of enclosed photographic plates and the assembly then was exposed to direct sunlight. The object was to determine whether the fluorescent salts would generate X-rays. Obviously, if this should take place, the photographic plates would become exposed. When two plates, prepared for such an experiment, had been placed in a dark desk drawer, there was not enough sun on those particular days to perform the experiment. They had lain there for the greater part of a week. Becquerel had actually irradiated the specimens in sunlight for a very short time before storage and proceeded to develop the plates for what he thought would be very faint exposures. To his surprise, the exposed images of the salt crystals were quite dark. This ultimately led to his conclusion that these rays were similar to those from the X-ray apparatus, and that the uranium salts emitted a penetrating radiation which apparently bore no direct relation to previous irradiation by sunlight. Two years later, in 1898, Marie Curie gave it the appropriate name of "radioactivity". A further similarity was methodically proved by Becquerel. He found that, like X-rays, these uranium-derived rays would also discharge a gold-leaf electroscope, and hence were ionizing in nature.

The radioactivity exhibited by the uranium salts was the subject of intense interest to the husband and wife scientific team, Marie and Pierre Curie. In their investigation, they worked with both relatively pure uranium salts and with a primary uranium ore, pitchblende. Pitchblende is largely uranium oxide with some radium and its daughter products. The Curies found that in the chemical treatment of the ore, the residue left after most of the uranium had been extracted was more radioactive than the uranium. By refining their chemical treatment, they were able to obtain material with about 400 times the specific activity of uranium. All the evidence indicated that there was an unknown element present. This element was named "radium", and the fact that it was newly discovered was confirmed by spectroscopy. The specimen was exceedingly small. By special arrangement, Marie and Pierre Curie obtained one ton of ore residues which had been depleted of uranium. This they ran through the chemistry they employed with the earlier ore, but on a larger scale. They obtained 1/10g of radium chloride of sufficient purity to enable them to determine the atomic weight of radium.

This was no ordinary element. It was "enormously more radioactive than uranium". It glowed visibly in the dark and gave off enough energy to remain perpetually warm. Of course, the heat generation was a by-product of the radioactivity. One can imagine the amazement of the scientists who observed this phenomenon. It was soon determined that the heat production was not a result of chemical reaction, and must, therefore, result from the radioactivity of radium itself.

In 1905, there came a possible explanation of the heat phenomenon. Albert Einstein published a paper in which he described his special theory of relativity. This paper covered a wide latitude and involved many new ideas, each with rigorous mathematical proof. One premise of this theory is that there is an equivalence between mass and energy.

The relationship was written " $E=mc^2$ " in which a mass, in grams, when multiplied by the square of the velocity of light in cm/sec would enable one to compute the energy yield in ergs if the entire mass were to be converted to energy. Einstein had, at the time this was published, suggested that physical proof might be obtained by applying his theorem to radioactive decay.

Even at that early date, the discovery of radium and the works of Albert Einstein gave rise to thoughts of the significance of energy from the atom. Of course, the very size of the mass equivalent conversion constant lends itself to speculation, and during the early part of the twentieth century it was publicized not only in technical journals, but in common advertisements in mass-published periodicals as well.

The important postulation and proof that an atom had a nucleus came in 1911. The astounding work of Sir Ernest Rutherford cannot be overemphasized. He proposed that the nucleus, much smaller than the atom itself, contains most of the mass. He also hypothesized that the nucleus is the origin of natural radioactivity. Henry Norris Russell, astronomer at Princeton University at that time, stated that surely the energy from the sun was not chemical. Science of the time simply was not capable of explaining the phenomenon or of even coming close to it until the time of Rutherford.

It must be noted that although radioactivity had been observed for a number of years, no one had succeeded in disturbing a stable nucleus or had produced artificial radioactivity. Here again, we owe the first of such experiments to Rutherford. In 1919, he succeeded in transmuting the nucleus of an ordinary element. He bombarded nitrogen with alpha particles (which we know now as helium nuclei) and transmuted the element to oxygen with the resultant emission of a proton. The process involved may be written as " $He^4+N^{14} \rightarrow O^{17}+H^1+E$ ", meaning that a helium nucleus of mass 4 striking a nitrogen nucleus of mass 14 produces an oxygen nucleus of mass 17 and a hydrogen nucleus mass 1 plus an energy yield. This is not artificial radioactivity, as such, but it represents the first time man had disturbed the stable nucleus of any atom. (Remember that the concept of the nucleus was then only eight years old.) Alpha experiments were carried on by many people and some very important discoveries were yet to be made as a result of these experiments. To keep the chronology correct, these will be discussed at their proper relative time. Another Englishman, Sir Arthur Eddington, observed that apparently the nuclear transformation energies in the center of the stars were approximately one order of magnitude higher than the energies available in the laboratories. He suggested that apparatus be built which could bombard nuclei with particles possessing about ten times the energy available from existing equipment. This took place about 1927.

The validity of his arguments was immediately recognized. Cockroft and Walton of England built an accelerator using rather conventional power methods which opened up new possibilities, and

Ernest O. Lawrence proposed, in 1929, a radically new accelerator which he called a cyclotron. The first machine started operating at the University of California in 1931. These types of machines and many new types of higher energy capabilities, which, in addition, have been adapted to bombard with particles other than electrons and particles (for example, deuterons) remain in use and still others are being built. These machines are necessary adjuncts. They will perform tasks that reactor experimentalists find difficult or impossible to do. For example, a heavy element may be produced by one bombardment with projectiles of mass 12, whereas this would require a minimum of 12 successive neutron absorptions if done in a reactor. While the latter can occur, it is an extremely time-consuming task even in reactors of the highest neutron flux.

In the decade of 1920-1930, however, not many accelerators were in use and the standard method of transmutation was accomplished with a natural source. In 1930-1931, reports from Germany and France indicated that the application of particles to certain elements, particularly to beryllium, produced very penetrating radiation. This radiation could not be stopped by massive lead shields, but could be shielded effectively by insignificant amounts of paraffin, wood or water. This, if it were electromagnetic in nature, as are γ - and X-ray photons, was certainly behaving strangely. If, on the other hand, these emanations were particulate, they did not obey known modes of behavior for particles either. Furthermore, they ejected high energy protons from the hydrogenous material which was used as "absorber". As more experiments were performed, the problem of identifying the radiation was no nearer to a solution. One thing was certainly obvious. It was neither completely X-ray nor particle in behavior, judging from past experiments. In 1932, J. Chadwick of England suggested that they were particles with no charge. This would seem reasonable. The common method of observing charged particles was with the use of the cloud chamber, a device in which a carefully controlled atmosphere is adjusted so that droplets of condensation are formed on the ions left in the path of a transitory charged particle, and these "rays" left no such trail. Chadwick then performed a classic series of experiments which not only proved the X-ray hypothesis untenable, but also demonstrated that these emanations were particles of approximately the same mass as protons and were without charge. Thus, the neutron was identified. This was another very important discovery on the road to nuclear (and reactor) technology.

It was soon learned that materials subjected to neutron bombardment become radioactive. Almost any material picked at random would continue to emit radiation of some sort after bombardment with neutrons. In particular, Enrico Fermi reasoned that large nuclei should be particularly susceptible to neutron penetration. With the α and proton energies then available such penetration was not possible because of the large coulomb forces present. (Both projectile and target were charged positively.) Fermi, then still in Italy, reasoned that the penetrated nucleus should, in all probability, become unstable and this instability should manifest itself by the resultant emission of

an electron. This, in turn, produces a nucleus of mass one unit higher and with an electronic charge of one more than that previously held by the nucleus. Since the charge on the nucleus has thus been increased by one, its atomic number is also increased by one, and it becomes a new element. Fermi's prediction was verified by both himself and others.

In general, Fermi was able to produce transurants. However, in subsequent analysis, others found elements which were lighter than the original target nuclei. No one at that time fully realized the significance of this, however, and the ability to transmute elements almost at will prompted many followup experiments.

It should be noted here that virtually all of the work of this period was done in universities, principally in Europe, with university funds. The fact that nearly every European university operated on government grants did not usually imply that there were any political strings attached to these funds, and up to the early 1930's there were few, if any, political overtones. The transition into the late 1930's, however, did bring pressure to bear on scientists connected with some universities to alter free scientific thought so as to promote some form of "patriotic" (nationalistic) thinking. Most of this was in Germany and Italy. In Germany, one manifestation was the anti-Semitism which prevailed practically everywhere and also reached into the universities. The anti-Semitism in Germany affected such people as Lise Meitner and Albert Einstein, who were of Jewish descent, and even some Germans, such as Werner Heisenberg.

Lise Meitner was one of a team of three which was investigating the production of trans-uranic elements. She, Otto Hahn and F. Strassmann had detected an element which was not of the expected mass range when heavy elements are transmuted by neutron bombardment. There was present an element of roughly half the mass of uranium which, for this particular experiment, was the target material. Friends informed her that the Nazis were about to make an arrest and she was forced to leave quickly, but not before she had concealed some of the chemicals in the lining of her clothing. It was with these samples that she walked across the border and eventually found her way to Stockholm. Shortly after her arrival, she heard that the light element had been identified as barium. Lise Meitner, in Stockholm, was the first to grasp the significance of the discovery. She reasoned that uranium must have split into two roughly equal parts, and submitted the hypothesis that the process of "nuclear fission" had occurred. She immediately set out for Copenhagen to visit Neils Bohr whom she knew was preparing his trip to the United States as the guest of the Institute for Advanced Study at Princeton University. If fission had occurred, the two parts of the nucleus should fly apart with tremendous energy. She calculated this by using the precise measurements of atomic masses made by F. W. Aston and the mass-energy equivalence equation of Einstein. She and another physicist, O. R. Frisch, both calculated the energy to be roughly 200 Mev. Frisch, incidentally, calculated the energy by using the coulomb repulsion of two particles, one with 56 protons and one with 36 protons, representing the nuclear charge of the two fission fragments.

Bohr was so interested in her discovery that he could only tear himself away from it with difficulty in order to catch the train. During Bohr's trip, Frisch confirmed the energies by experiment and cabled the news to Bohr at Princeton.

The news spread quickly. Enrico Fermi, now at Columbia University, realized his now-famous mistake. He had used uranium among the heavy nuclei in his slow-neutron transmutation experiments, and he had no doubt produced uranium fission much earlier. The new atoms were in an entirely different range from those for which he had been searching. At a conference on theoretical physics in Washington, D. C., Bohr and Fermi told of the discovery. It is told that their enthusiasm spread throughout the meeting and that before its conclusion, several confirmations had been produced of Frisch's work. Still, at this time, there seemed to be no evidence that real nuclear power could be obtained from the fission process.

The bulk of the theoretical and experimental work on the fission process was being done at Columbia and Princeton Universities. J. W. Wheeler and Niels Bohr at Princeton and Szilard, Zinn, Anderson, Fermi and Hanstein at Columbia worked on the theory that a fissioning uranium nucleus should release several additional neutrons when it divides. Before Wheeler and Bohr's theory could be published, the two groups at Columbia had confirmed this with the result that it was proved that two or three neutrons were emitted whenever a uranium atom undergoes fission.

For the first time, practical nuclear energy seemed possible. In the process of chain reaction, there must always be one neutron left over after leakage and parasitic absorption to produce the next fission. If the uranium atom releases two or three neutrons per fission, the chain reaction becomes, under the right conditions, a possibility.

In 1938, when all of this was at its peak, the attitude of Germany and Italy regarding expansion by military conquest put the development of nuclear power in a frightening aspect. It was known that Heisenberg and his colleagues were surely at work on such developments. Several of the principals, namely Szilard, Wigner and Einstein had first-hand experience and a healthy respect for German prowess in the scientific and industrial fields. For this reason, it was voluntarily decided among scientists in this country that any publication of possible military significance would be withheld. Since the state of art and science did not permit much more than conjecture about the controllability of nuclear reactions, the thoughts turned more or less to the uncontrolled type in which the energy yields could be quite impressive.

The agreement to hold back publication of this work, unfortunately, did not extend to Europe. The same work was published independently by H. von Halban, F. Joliot, and L. Kowarski in Paris. Further word had come from Germany that Hahn was continuing work in his laboratory before the early progress of World War II finally blocked all scientific news.

The probability that a chain reaction could be produced, coupled with the knowledge that about one percent of the neutrons emitted by the fission process are delayed, made nuclear power seem even nearer. The military dangers opened up by these facts greatly concerned Szilard and Wigner. They felt so strongly about it that they were determined to bring it to the attention of President Roosevelt. They decided that Albert Einstein was the best representative of science to write a letter to the President, and he agreed to do so. The prestige of Albert Einstein gave the letter he signed the proper dignity and importance necessary to impress fully on the President the gravity of the situation. Wigner and Szilard drafted the letter and supplied the necessary facts. It was delivered by a mutual friend of President Roosevelt and Albert Einstein who also acted as intermediary. The letter, now famous, said in part: (1) The studies of uranium fission foreshadowed both atomic power for driving ships and (though much less certain) extremely powerful atomic bombs; (2) German activities indicated alertness to these possibilities; and (3) A single bomb, exploded in port, could create enormous havoc.

President Roosevelt formed a committee to study the problem to determine whether the program should be supported. It is unfortunate that the committee's attitude was only lukewarm and although it suggested that the program was worthy of financial support, only \$6,000 was allotted to uranium research for one year.

It is noteworthy that the people who were working feverishly on the program were of two groups. They were the scientists who knew of the military significance of nuclear energy should it fall into the hands of the Axis powers, and the scientists in this country who recognized the possibilities from a purely scientific point of view. To match the \$6,000 the government allotted, Vannevar Bush allocated \$20,000 of the Carnegie Institution's funds, and this was matched several times over by a number of universities. They all realized, however, that the problem and its ultimate cost was simply beyond the typical budgets of privately endowed institutions and universities in general.

Vannevar Bush had accepted the presidency of the Carnegie Institution in Washington, largely to place himself where he could observe and advise the government as a person who had no obligation to any government office. Formerly, he was the Vice-President of MIT. He became cognizant, while in this position, of the inadequacies of the American research program for meeting our war needs. The voluntary placement of Vannevar Bush in such a strategic spot was of immense help in all fields of scientific effort, particularly to the nuclear program. The mounting concern of members of the National Academy of Sciences over our state of unpreparedness pointed out the need for something to be done effectively and quickly. It was agreed among the members that Bush should take up the matter with President Roosevelt. Such a meeting was arranged with the help of Harry Hopkins in June, 1940, one day after the fall of Paris.

During this meeting, Bush outlined a new committee to be liaison between the National Academy of Sciences and the military services, the function of which would be to correlate research in fields other than aeronautics. (Bush was already Chairman of the National Advisory Committee for Aeronautics.) This marks the beginning of the National Defense Research Committee. The members of this committee were: Karl T. Compton, James B. Conant, Richard C. Tolman, C. P. Coe, Brig. General G. V. Strong, Rear Admiral H. G. Bowen and Vannevar Bush as Chairman. This was a committee which could do some good. Among its responsibilities was the research on nuclear problems. A contract was signed with Columbia University for the amount of \$40,000 to support its continuing program. Before the year 1941 was ended, these uranium contracts had reached a total of \$300,000 in expenditures.

A. H. Compton began his active research program at the University of Chicago during this period. It was motivated primarily by the announcement of E. O. Lawrence that a new possibility had appeared. Experiments at Berkeley had indicated that element 94 (plutonium) is formed as a result of the capture of a neutron by U-238 followed by two successive emissions, and that the element undergoes fission with slow neutrons. This led to these conclusions: (1) Uranium-238 would be available for energy production and the energy production and the energy potential of uranium would be increased about one hundred-fold; (2) the use of element 94 should enable chain reaction units of 100 pounds, rather than 100 tons, as probably would be necessary for units built with natural uranium; and (3) if large amounts of element 94 were available, it is likely that a chain reaction with fast neutrons would be produced. In such a chain reaction the energy would be released at an explosive rate which might be described as a "super bomb".

The principals on the project had been saddled with the alternatives outlined by Wigner, et al., that there must be pure U-235 or moderated natural uranium before a chain reaction could be possible. The former represented a staggering task, that of the physical separation of U-235 from U-238. This job looked so difficult as to be almost impossible. The latter, while looking very good regarding the liberation of power, did not hint that it was any good at all for the military goal of producing a bomb. Needless to say, the plutonium possibilities looked promising. It gave a much-needed shot-in-the-arm to the whole project. The plutonium, it developed, could be produced in the natural uranium chain reaction. Thus, the building of the uranium graphite "pile" was now more imperative than ever. It was A. H. Compton's responsibility, as it developed, to demonstrate the practicability of the graphite moderated reactor. This was the first important job to accomplish. From it, if it were possible, would come the data so necessary for the production of plutonium. The related work had been carried on at other locations than Chicago. Fermi was still working at Columbia. There were others at Princeton, Berkeley, Pittsburgh and Cleveland. Compton had concluded that Chicago should be the place for the initial critical experiment. He took the initiative when it was obvious that the group could not come to a decision by itself. The meeting was held in Compton's

bedroom in which he was confined with influenza. Present were L. Szilard, E. O. Lawrence, Luis Alvarez, Norman Hilberry and R. L. Doan. Doan was on loan from the Research Department of Phillips Petroleum Company and had been working at Princeton. Of all those in attendance, only Doan agreed to support Compton voluntarily from the time the proposal for Chicago was presented. It was natural that those who had labored so hard and so long should like to see the initial critical experiment conducted at their own laboratories. The central location of the University of Chicago, the available manpower there, and the fact that it was less vulnerable to attack, however, made it the most logical location. Compton informed those present that, with the help of R. L. Doan, he would see the job through. Some were pessimistic, but Compton was adamant. The job would be performed at Chicago. When questioned by telephone, Fermi and Wigner agreed immediately to the move.

This was the beginning of the plutonium project code-named the "Metallurgical Project". The facilities became the "Metallurgical Laboratory" with R. L. Doan as the Director. His was a job of extreme complexity in that the laboratory was bound to grow rapidly, and he had to provide for the research program, the necessary personnel and equipment in the face of this growth. Three groups, headed by Fermi, Samuel Allison and M. D. Whitaker, were working on the chain reaction. In the chemistry division were Glenn Seaborg, Frank Spedding, and later James Franck. L. Szilard was responsible for the procurement of "pure" materials but actually was concerned with all of the enterprise. Volney Wilson was in charge of the rather special instrumentation job. Wilson was, incidentally, the first in the United States to perform a critical calculation a few years earlier. All endeavored to get the graphite reactor completed.

The procurement of both graphite and uranium of sufficient purity was difficult. To complicate this even further, the required amounts of each of these materials was in the order of tens of tons. Graphite was eventually obtained of sufficient purity for the project. It had been manufactured for years in the United States, but its impurities prohibited its use in the metallurgical project until methods were developed to remove them. This was worked out between members of the laboratory and the manufacturers. The uranium procurement was a different problem. Uranium had been produced only in gram quantities. Of the manufacturers that could produce it, one would supply uranium oxide and another would supply metal in powdered form. As uranium is pyrophoric, the finely divided metal particles (presumably resulting from chemical reduction) gave no end of trouble during the phase of making briquettes. These briquettes were pressed by hand, and often the metal would spontaneously ignite, thus requiring a cleanup job. It was only through the exhaustive efforts of several people, and the extraordinary ability and understanding of Edward Mallinkrodt, Jr., that the necessary amount of metal was obtained. He had the knowledge of how to handle volatile organic chemicals which aided immensely, since the one method which looked promising was an ether-extraction process.

A site outside of Chicago was selected as the site for constructing the first reactor. It had been scheduled to be completed by October 20, 1942, but had been delayed by labor difficulties so long it would not be finished in time for the critical experiment. Early in November, Fermi informed Compton that it was his opinion that the pile could be built to work safely on the campus. After listening to his story and discussing the problem with him, Compton was also convinced. He gave his approval to construct the graphite pile in a building under the west stands of the Stagg Athletic Field. It was a difficult decision to make when one considers all the possible consequences. But it was made, with A. H. Compton assuming all responsibility.

There was still an immense amount of work to be completed. The oxide had to be pressed, the graphite had to be machined and the whole structure had to be assembled. R. L. Doan recruited volunteers from among the scientists to work during the evening hours. The work was practically continuous from the time the materials arrived until the pile was ready for the first multiplication experiment. Uranium had been delivered in two forms, oxide and reduced metal. The reduced metal amounted to only a few tons and was reserved for the center of the pile.

In the course of building up the critical assembly, it was found that the infinite multiplication constant had been underestimated and that the reactor would go critical at a smaller size than had been anticipated.

On the afternoon of December 2, 1942, the first continuous chain reaction was initiated, controlled and shutdown. It was an historic moment and everyone present knew it. Fermi was aware of the inadvisability of continuing the experiment, and ordered the reactor shut down until the next day. The excitement involved was not very well portrayed in the coded message A. H. Compton gave J. B. Conant over the telephone:¹

"Is that so, : was Conant's excited reply. "Were the natives friendly?"

"Everyone landed safely and happy."

¹ A. H. Compton, Atomic Quest, (Oxford University Press, 1956), p. 144

APPENDIX D

RADIATION STANDARDS

1.0 References

- 1.1 AEC Manual, Chapter 0524
- 1.2 Pan Am SPI 14-017
- 1.3 NTO-A-0022

2.0 Radiation Safety Guides

2.1 Radiation from sources external to the body

<u>Type Exposure</u>	<u>Time</u>	<u>Dose (rem)</u>
Whole body, head, trunk	Accumulated	5 (N^*-18)
Active blood forming organs; gonads, or lens of eye	+Calendar Quarter	3
Skin of whole body and thyroid	Year = whole body	30
	Calendar Quarter - Thyroid	10
Hands, forearms, feet, and ankles	Year	75
	Calendar Quarter	25

* N equals the age in years at last birthday.

+ A calendar quarter may be taken as any predetermined period of 13 consecutive weeks or any predetermined quarter year, based on the calendar.

2.1.1 For individuals in uncontrolled areas and for off-site exposures, the exposure guides are generally limited to 1/10 of the applicable guide for personnel in controlled areas.

2.2 Radiation from sources internal to the body.

2.2.1 The Radioactivity Concentration Guides for concentrations in air and water above natural background specified in AEC Manual, Chapter 0524 shall be followed.

2.2.2 Off-site numerical values are based upon continuous exposure to the concentration specified for 168 hours per week. Radiation Protection Guides established in AEC Manual, Chapter 0524 shall be followed.

2.2.3 For purposes of applying the guides in 2.2.1 above radioactive concentrations may be averaged over periods up to 13 consecutive weeks provided work areas are appropriately monitored and exposure histories are maintained for each individual working in such areas.

2.2.4 If it is not feasible to govern exposures to internal emitters by applying airborne radioactive concentration standards, the following Radiation Protection Guides (RPG) shall apply:

<u>Type Exposure</u>	<u>Rem/Year</u>	<u>Rem/Quarter</u>
Whole body, active blood forming organs, gonads	5	3
Thyroid	30	10
Bone (other standard)	Body burden of 0.1 microgram of ^{226}Ra or its biological equivalent	
Other organs	15	5

2.2.5 If an individual receives simultaneous exposure from radiation sources external and internal to the body then the total exposure shall be limited such that the total dose to the critical organ does not exceed the applicable Radiation Protection Guide.

2.2.6 Respiratory protective devices shall be employed for personnel protection where airborne contamination exists in excess of the applicable RPG in AEC Manual, Chapter 0524. These devices may be employed when air concentrations are below the applicable RPG where practical to reduce internal exposures.

3.0 Internal Radiation Emitters

3.1 Methods of intake: Inhalation, Ingestion, Absorption through skin and via wounds

3.2 Protective Measures, depends on routes of intake but primarily are:

3.2.1 Adequate ventilations; use of absolute filters; use of respiratory/air supplied equipment; not eating, smoking, drinking in zones and use of protective clothing, decontamination technique, etc.

3.2.2 Dosimetry Methods:

Nasal swipes; analyses of body fluids, tissues and wastes; scanning with radiation detectors including whole body counters.