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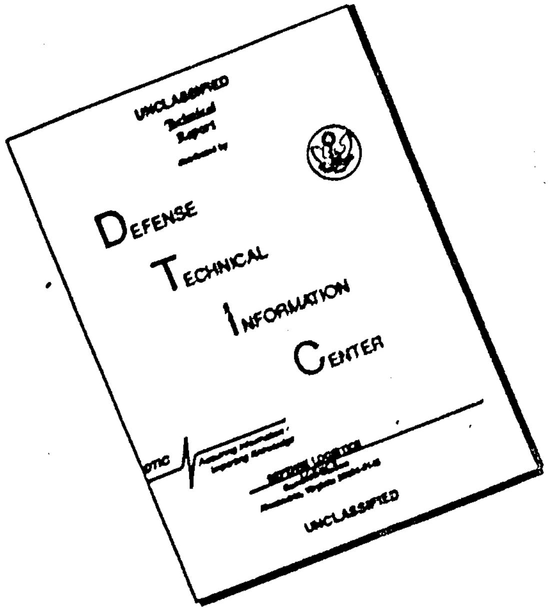

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THE EFFECTS OF NUCLEAR RADIATION ON AIRCRAFT MATERIALS

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THE EFFECTS OF NUCLEAR RADIATION ON AIRCRAFT MATERIALS

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I. INTRODUCTION

Eighteen years ago a small group of scientists and engineers, working at the University of Chicago, put into operation the first atomic reactor, and in so doing formed the nucleus of what is now a major branch of science and industry. Outside of this select group few people were well versed on the subject of nuclear engineering or were even aware of its existence.

Today the scene is entirely different. Nuclear scientists and engineers have made tremendous progress in providing the world with many new and wonderful devices. Nuclear powered submarines are in service, nuclear powered aircraft may be flying in a few years, and nuclear power stations are beginning to supply electric power for public consumption. It would be difficult to point out a branch of science or industry that has not been aided in some way by this technological revolution. New methods of research and analysis have been made available to botanists, chemists, geologists, geophysicists, astronomers, and a host of others. Yet amid all this progress there are many educated people, including engineers, who know very little about the subject aside from what information they garner from newspaper and magazine articles. Unfortunately, much of the data published for public consumption is very vague and misleading, and at best is quite inadequate.

This paper was prepared in an effort to provide some basic and useful information concerning the effects of radiation on materials, both structural and nonstructural, for use by aircraft engineers, particularly those design and structures engineers working on nuclear projects.

Often these design and structures engineers have neither the time nor the inclination to study the more technical aspects of nuclear engineering, but they do need to have a "talking knowledge" of the subject. The designer who knows which materials and components will perform the best in a radiation field, and who knows why other materials must be avoided or kept to a minimum, is usually able to produce a workable and reliable design which is acceptable to all concerned.

This report contains a short description of the various types of radiation, a discussion of the important changes in physical, electrical, and chemical properties found in various classes of materials, and an introduction to the nuclear reactions which cause induced radioactivity. Included are the definitions of some terms used in the field of radiation effects.

Although the subject of Health Physics is not of direct concern to the average design engineer, some data on this subject are covered to show the reader what effect radiation has on human beings and to outline the measure of protection given by present Health Physics regulations and methods.

Most of the material contained in this report is non-mathematical in nature to allow a broad, quantitative discussion of the field of radiation effects. No attempt will be made to give detailed numerical information for later use in design work. Instead, it is hoped that the reader will become acquainted with the material problems inherent in the design of nuclear aircraft systems and components.

II. DEFINITIONS

Activation - Producing radioactivity in a substance by exposure to neutrons or high energy charged particles.

Activity - The number of atoms decaying per unit of time. The unit of activity is the Curie, 3.7×10^{10} disintegrations per second.

Angstrom Unit (Å) - 10^{-8} centimeters.

Atomic Number (Z) - The ordinal number of each element in the periodic table, equal to the number of positive charges on the nucleus.

Atomic Weight (A) - The weight of one atom of an element relative to the weight of one atom of oxygen, which is assumed to be exactly 16.

Avogadros Number - 6.023×10^{23} molecules per gram molecular weight, where a gram molecular weight is that quantity of a substance which has a weight in grams equal to its molecular weight. Example: 2.016 grams of hydrogen, 32.00 grams of oxygen.

Barn	-	A unit of area used in expressing a nuclear cross section. 1 barn = $10^{-24}cm^2$.
Deuterium	-	An isotope of hydrogen with an atomic weight approximately twice that of hydrogen. The symbol D is used for this "heavy hydrogen."
Deuteron	-	The nucleus of the deuterium atom.
Dose	-	The total quantity of radiation absorbed by tissue during a single irradiation.
Dose Rate	-	The quantity of radiation absorbed by tissue per unit time, expressed in R/hour, rem/hour, or rep/hour. (See chapter on Health Physics.)
Electronvolt (ev)	-	A unit of energy equal to the work done in moving one electron against a potential of one volt. Equals 1.6 x 10^{-12}erg, where an erg is the work done when a force of one dyne acts through a distance of one centimeter.

Halflife	-	The time required for the radioactivity of a given amount of an element to decay to half of its initial value.
Half-thickness	-	The thickness of an absorber necessary to reduce the gamma-ray intensity to half its initial value. This term is often used in shielding work.
Isobar	-	One of a group of nuclides having the same weight but different atomic numbers.
Isotope	-	One of a group of two or more nuclides having the same number of protons, i.e., having the same atomic number, but with different atomic weights.
Lattice Vacancy	-	A point on the space lattice of a crystal which is not occupied by the appropriate atom or ion.
Negatron	-	Another term for electron.
Neutrino	-	An electrically neutral particle, small in size as compared to an electron, postulated by W. Pauli to account for otherwise unexplainable losses of energy in beta decay.

Nucleon - A general name given to both protons and neutrons.

Nuclide - A species of atom characterized by the constituents of its nucleus, i.e., by the number of protons and neutrons it contains. Radioactive elements are sometimes referred to as radionuclides.

Photon - The quantity of electromagnetic radiation associated with a single quantum of energy, a "particle" of radiation.

Positron - A positive electron.

Proton - The nucleus of the hydrogen atom. A particle of unit mass with a positive charge.

Semiconductor - An electronic conductor, usually of poor conductance compared to a metal, which conducts electricity either by means of electrons donated by impurities or by thermally excited electrons or positive holes.

Thermal Neutron - A neutron which has the same average kinetic energy as the atoms or molecules of the medium in which the neutron is being scattered. This usually amounts to about 0.025 electron volt.

Tritium - An isotope of hydrogen with mass number 3, symbol T or $_1H^3$.

Triton - The name given to the nucleus of tritium.

III. TYPES OF RADIATION

Introduction

The major types of radiation encountered in this study are alpha radiation, beta radiation, gamma radiation, and neutrons. There are several other radiations or high velocity particles which are of importance in other branches of nuclear science, but are of only passing interest when considering radiation damage. One of these, X-rays, is discussed briefly because most people have some knowledge of X-rays and their medical aspects, and a comparison may make the introduction to gamma radiation more easily understood.

The original source of most of this damaging radiation is, of course, the reactor. Some radiation comes directly through the shielding, the rest may find a way through openings provided for the control and cooling systems and for instrumentation. In ground installations, where weight is of little consequence, enough shielding is normally provided around the reactor to cut the radiation to a safe level. In aircraft installations, on the other hand, weight is of the utmost importance, and the minimum overall weight is achieved by placing some shielding around the crew compartment and the rest around the reactor. Unfortunately, this "divided shield" arrangement causes the aircraft and its contents to be bathed in a radiation field whenever the reactor is operating; as a result radiation damage occurs.

X-Rays

X-rays are a form of electromagnetic radiation, produced in a cathode ray tube by allowing a beam of high velocity electrons to fall upon a metal plate, called the anticathode. Deceleration of a moving electric charge is accompanied by emission of radiation, and this radiation is the familiar X-ray. It is often called "Bremsstrahlung" or slowing down radiation. X-rays are also produced when enough energy is imparted to an orbital electron to raise its energy sufficiently to eject it from the atom. Then other electrons fall into the vacated positions and in doing so emit radiation. X-rays produced by the latter process form the X-ray spectra used in studying atomic structure.

Examination of a typical wave length spectrum chart for electromagnetic radiations shows that X-rays have a shorter wave length than ultraviolet light, which in turn has a shorter wave length than visible light.

Gamma Radiation

Gamma radiation is also a form of electromagnetic radiation, having wave lengths shorter than X-rays. Since the energy level of any electromagnetic radiation is inversely proportional to its wave length, gamma rays contain more energy than X-rays or other kinds of electromagnetic radiation, and are therefore more penetrating and more dangerous.

We have seen that X-rays are emitted when the electrons of an atom give up their excess energy and return to a more stable state. In a similar fashion, gamma rays are emitted when the particles which make up the nucleus of an atom give up some or all of their excess energy. Gamma rays can occur either alone or in conjunction with other types of radiation, depending upon the size and energy level of the nucleus.

During the operation of a nuclear reactor, gamma rays are produced directly during the fission of the uranium fuel, by neutron capture in a nucleus, not necessarily fuel, by neutron inelastic scattering in heavy nuclei, and by decay of the fission fragments. Inelastic scattering refers to the capture and re-emission of a neutron with subsequent gamma production. Gamma ray emission is also associated with naturally radioactive elements.

In general, gamma rays are hard to stop; but best results are obtained with heavy materials such as lead, mercury, uranium, and tantalum. There are three atomic processes by which gamma photons are degraded in energy or stopped altogether; these are entitled the photoelectric effect, the Compton effect, and pair production. For low energy gammas and for absorbers of high atomic number, absorption is by the photoelectric effect. In this process electrons are ejected from the metallic absorber and carry away energy equal to the original gamma photon energy less the electron binding energy. In the Compton effect, which is important for medium energy gammas and absorbers of low atomic weight, a gamma photon may collide with a loosely bound electron and change direction by recoil, losing energy in the process. Pair production, actually the formation of an electron-positron pair, is caused when a high energy gamma photon passes near a nucleus of high atomic weight. This is the major process by which high energy gammas are stopped. The electron and positron thus formed each represent, by virtue of their mass, energy equal to 0.51 million electron volts (Mev). When a positron meets another electron both disappear and two 0.51 Mev gammas are formed. It is of interest to note that the process of pair production is an excellent example of the equivalence of mass and energy.

Beta Radiation

Beta radiation consists of high velocity electrons. Any stream of electrons is considered to be beta radiation, but we are concerned mainly with beta radiation produced by radioactive decay. Electrons do not exist in the nucleus of an atom as such, but under certain conditions they are ejected from the nucleus. For example, a nucleus with an excess of neutrons may reach equilibrium by changing one neutron into a proton plus an electron; this electron is immediately emitted from the nucleus. To preserve the mass-energy balance a neutrino is also emitted.

The emitted electrons have a continuous distribution of velocities from 25% to 99% of the speed of light (0.025 to 3.15 Mev). The range of beta particles in air is several meters and they are quite penetrating, but have only moderate ionizing power. Beta radiation loses energy by excitation of valence electrons in materials, by formation of ion-pairs, or by scattering.

Alpha Radiation

Alpha particles are helium ions with a +2 charge, and consist of two neutrons and two protons. Because of their relatively high mass and high velocity they produce a large amount of ionization when passing through gases. These same properties, however, limit the range to a few centimeters in air and to almost nothing in solid matter. A few sheets of paper will effectively stop alpha radiation.

Alpha particles are produced as a result of radio-active decay in elements with high atomic weight. The stopping mechanism for alpha particles is primarily loss of energy by the production of ion-pairs (32.5 ev per ion-pair). Alpha particles are scattered by heavy nuclei but this is relatively unimportant.

Neutrons

The neutron is one of the basic building blocks of the atom, having a mass almost equal to that of a proton but with zero charge. Because of this lack of electric charge, the neutron is not repulsed by the nuclei of atoms, therefore, it can react with most elements. This same lack of charge is also responsible for the fact that neutrons are difficult to detect.

Neutrons are produced mainly by fission in the reactor; there are also many nuclear reactions which produce neutrons of various energies. For example, bombarding some elements with alpha particles, dueterons, or gamma rays will produce a stream of neutrons. Regardless of how they are produced, neutrons usually start out at quite high energies.

When a neutron enters solid matter, several things may happen. It may hit a nucleus and change direction, causing the struck nucleus to leave its original position.

This process is called elastic scattering because the total kinetic energy of the system is unchanged. The energy lost by the neutron is inversely proportional to the mass of the struck nucleus. Therefore light atoms such as hydrogen and carbon are excellent for slowing down neutrons by elastic scattering, and such elements are used in reactors for shielding and moderators. The result of an elastic scattering is loss of neutron energy and lengthening of the neutron's path.

A second neutron-nucleus interaction is inelastic scattering, where the neutron enters the nucleus momentarily, forming a compound nucleus, and is then ejected at a much lower energy. In this process some kinetic energy is transferred to potential energy in the struck nucleus, this energy is then emitted as a gamma ray photon. Inelastic scattering is more probable in heavy nuclei.

Finally, a neutron may enter a nucleus and stay there; as a result, a hard gamma (approximately 6 Mev) is usually emitted. This is undesirable in most cases and so materials are chosen, if possible, that emit charged particles instead of gammas. Two examples are B^{10} and Li^{6}; both make excellent shields because of their high capture cross sections.

When considering the removal of neutrons from the scene it should be noted that the first collision is the most important, since, the lower the energy, the more probable becomes the next collision. In other words, the cross section of the absorber becomes higher as the neutron energy decreases.

A definition of "cross section" might clarify some of the above statements. Consider a plate of aluminum, dx thick, placed in a beam of neutrons. The fraction of the total number of neutrons in the beam, which interact with the metal by process "a", is $\Sigma_a dx$. Σ_a, called the macroscopic cross section, is the probability of occurrence, per unit length of travel, of any particular nuclear process. When considering all possible processes, the total macroscopic cross section is $\Sigma_T = \Sigma_a + \Sigma_b + \Sigma_c + \text{-----}$. A related term, the microscopic cross section, is defined as $\sigma = \Sigma/N$, where "N" is the number of atoms per unit volume in the target material. The microscopic cross section is usually thought of as the effective target area of the bombarded nucleus for a particle, such as a neutron. Note that Σ has the dimension 1/cm, and σ is measured in cm^2. There is a different cross section for each possible process, i.e., the absorption cross section is not the same as the scattering cross section.

Another term of interest is neutron flux ϕ, which is the product of neutron density in neutrons per cubic centimeter and velocity in centimeters per second. The units of flux are then $\frac{1}{cm^2sec}$. We can now multiply cross section by flux and get the expected number of collisions per unit volume per second. It follows that the product of flux and time of irradiation gives the total number of neutrons incident upon a unit area; this product is written "nvt" and is called the integrated flux.

TABLE I

SUMMARY OF RADIATION CHARACTERISTICS

	Range In Air	Range In Solid	Origin	Mass	Stopping Mechanism	Damage	Importance Induced Activity	Health Physics
X-Rays	Very high	High	Electron Interaction	--	Electronic collisions			X
Gamma Rays	Very high	High	Fission, decay, neutron interaction	--	Electronic collisions	XX		XX
Beta Rays	Several meters	Small	Decay	0.00055	Electronic collisions			X
Alpha Rays	3-8 cm	Very small	Decay	4	Nuclear & Electronic Interactions			X
Neutrons	High	High	Fission	1	Nuclear Collision or Reaction	XX	XX	XX

IV. RADIATION DAMAGE

General Data

The fact that radiation will change the physical properties of materials has been known for a good many years. For example, glass left in strong sunlight for several months will change color, and certain inorganic crystals will also change color when subjected to X-rays. Since many of the changes in physical properties are detrimental to the use of the material, these changes have been called "radiation damage." The magnitude of the radiation damage effect depends upon the property being studied, the type and intensity of radiation, the type and condition of irradiated material, the temperature, pressure, surrounding atmosphere, and many other variables.

Table II illustrates the broad field covered by the term "radiation damage." As engineers we are interested in only a portion of the items listed but a brief consideration of the rest is worthwhile.

Radiation damage is caused by the energy transferred from the radiation to the stopping material. Since the properties of a substance depend ultimately upon the configuration of nuclei and electrons, only that portion of

TABLE II

RADIATION DAMAGE TOPICS

Radiation Type	Property of Interest	Material Type	Experimental Conditions
Combined reactor radiations	Mechanical	Metal	Temperature
	strength	pure	room
	elasticity	alloy	low
	ductility	solid	high
Fission fragments	dimensional	liquid	
	creep rate		
	density	Ionic crystal	Pressure
Neutrons			
fast		Fused salt	
thermal	Thermal and electrical		Surrounding atmosphere
	conductivity	Molecular	
	specific heat	organic	inert
Gamma rays	dielectric strength	inorganic	reactive
	Hall coefficient	solid	static
		liquid	
Beta rays			
	Chemical	Semi-conductor	Shape and size of sample
	composition		
Alpha particles	corrosion rate		
	solubility	Polymeric	
		elastomers	
Accelerated particles		plastics	
protons			
deuterons		Amorphous	
helium ions		glasses	
electrons			

the energy transferred which results in a change in one of these configurations (a defect) can influence material properties. Different types of defects influence properties qualitatively and quantitatively in different ways. Furthermore, certain property changes are of more practical significance than others.

As was shown in previous discussions, there are three principal mechanisms of energy loss: nuclear collisions, electronic collisions, and nuclear reactions. The first of these mechanisms usually results in atoms being knocked out of position whenever the energy transferred from a neutron to the struck atom is greater than the bond energy between atoms. These "knock-ons" may then hit other atoms and knock them out of position, until finally all are brought to rest. During this process, electrons will be disturbed causing ionization, and other atoms will be hit only hard enough to cause excitation. Most of this transferred energy is finally dissipated as heat, the rest will appear as an increase in the potential energy of the stopping material. The latter is called "stored energy," and is the result of lattice vacancies and interstitial atoms. In some materials part of the damage can be removed by heating; this will be discussed later.

Electronic collisions result in excitation and ionization but there is little transfer of momentum to the nucleus of the struck atom. This type of interaction is important for gamma radiation and beta radiation, but the range of the latter is so small that little damage is done by beta radiation.

Nuclear reactions result in production of foreign atoms in the bombarded material. However, in metals, this transformation is negligible in influencing most mechanical or physical properties. Gold, with a very high cross section of 100 barns, will contain only 0.1% of mercury after three years irradiation in a flux of 10^{11} neutrons/cm^2/sec. In nonmetals the effect may be somewhat more pronounced especially when considering certain electrical properties.

It should be noted that damage done by nuclear reactions is irreversible, i.e., it is permanent and will not disappear with time or temperature. Some of the damage done by nuclear and electronic collisions is also irreversible but fortunately a fair part of the defects can be removed by heating (annealing) or may disappear without heating over a period of time. Therefore it is to be expected that the amount of radiation damage produced is highly sensitive to temperature. In general, metals and some inorganic solids will respond to annealing, but organic solids will not.

A survey of material property changes caused by radiation will often uncover test data that tend to be contradictory when compared to other test data, making the overall picture quite confusing. Perhaps the best explanation for this situation is the fact that test conditions, such as temperature, geometry of the samples, grain size, and instrument accuracy, often have more effect upon the test results than does the presence of radiation.

In the discussions which follow, the term "radiation" is meant to include both neutrons and gamma photons unless otherwise specified. Alpha and beta radiation normally is not penetrating enough to cause detectable damage in structural materials.

Aluminum

Aluminum has long been a favorite structural material for use in nuclear reactors and associated equipment, by virtue of its physical and nuclear properties. The first Oak Ridge reactor employed aluminum tubes to contain the uranium fuel slugs, and when these tubes were examined after more than a year of operation, little or no radiation damage was evident. Subsequent tests of irradiated aluminum have shown that hardness, tensile strength, yield strength, and electrical resistivity are increased, ductility is decreased, and the impact properties are reduced. In general, irradiation appears to have no appreciable effect on fatigue in aluminum. However, limited data indicate that in a few cases the fatigue life of some structural alloys may be considerably shortened.

It has been found that, for both aluminum alloys and other metals, the greater the initial hardness, the smaller the effect of radiation. Furthermore, as hardness increases due to irradiation, the rate of increase of hardness decreases. Strength and hardness have the same relationship after irradiation as after cold working, which fact has been used as the basis for the so-called "cold work analogy" by scientists in their studies of the basic mechanisms of radiation damage.

Since the aluminum alloys of primary interest to the aircraft designer are the heat treated or work hardened alloys, it is safe to say that an aluminum airframe for a nuclear powered aircraft will not be appreciably damaged by radiation. Of course, there may be isolated cases where some critical structural elements are subjected to very high flux levels for long periods of time; these elements should be designed with the latest radiation damage data in mind.

Copper

The effects of radiation on the major copper alloys are much the same as noted for aluminum, namely an increase in hardness, tensile strength, and electrical resistance.

Percentage-wise, changes in hardness are fairly large for annealed samples and small for cold worked samples. The changes in electrical resistance are small even for pure annealed copper, being about 1.7%.

Iron and Steel

Iron and steel are among the few materials which exhibit an accelerated corrosion attack while being irradiated. Aside from this, the effects of radiation on ferrous alloys are identical with those found for the other major structural metals. The increase in hardness and strength caused by irradiation is again a function of the initial hardness of the samples. The carbon content of the various alloys seems to have little effect upon the property changes.

Tests have shown that certain of the softer alloys, including plain carbon steel and some stainless steels, will double or triple their yield strengths when subjected to very large amounts of radiation. This fact might lead one to think that radiation could be used to improve the strength of steel for commercial purposes, but such is not the case. The time and expense involved make such a nuclear hardening process quite uneconomical.

To sum up the case for the structural metals, it can be said that, because of their tightly bound crystalline structure, they suffer very little radiation damage, even when considering rather large doses of the order of 10^{20} nvt.

Semiconductors

The demand for small, lightweight electronic components for aircraft has made the use of semiconductors widespread in the past few years. These semiconductors are normally affected by temperature and impurity content, and when in a radiation field exhibit marked changes in electrical behavior. It would seem, therefore, that these materials would be a poor choice when designing components for a nuclear powered aircraft. Nevertheless, the weight saving cannot be overlooked, and many investigations have been made in an attempt to determine precisely the radiation damage done to germanium, silicon, selenium, tellurium, and various oxides and sulfides.

High speed neutrons do the most damage to semiconductors, with high speed electrons second in importance. Damage to the material may consist of heating, transmutation of elements to form impurities, lattice displacements, ionization, and breaking of covalent bonds. The most significant property change in these semiconductors is the change in electrical resistivity; the manner in which this property changes with irradiation is a function of the type of crystal used.

Not only does each of the elementary semiconductors differ from the others in electrical characteristics both before and after irradiation, but different crystals of one given element may also vary in behavior. For example, N-type germanium crystals exhibit an increase in resistivity up to a maximum, followed by a decrease with further irradiation. P-type germanium crystals, on the other hand, exhibit a steady decrease in resistivity until a minimum is reached. In even a low neutron flux these changes may come about in a very short time.

At this point a short discussion of P-type and N-type conductors is included to help clarify the above statements.

When considering the electrical properties of materials it is often convenient to think of matter as consisting of a "sea" of electrons. Some of these electrons may be loosely bound and free to migrate when influenced by an electrical potential. Other electrons may be more tightly bound and less free to migrate unless higher potentials are used; still other electrons may be so closely bound that they will not migrate under any normal potential or voltage drop. Metals have what might be termed an excess of loosely bound electrons and are therefore excellent conductors of electricity. Glass has no "free" electrons and is an excellent insulator. Between the two extremes there is a class of materials called semiconductors.

The question of whether any given electron is free or bound can be answered only by a study of electronic energy levels, which is far beyond the scope of this discussion. Suffice it to say that some electrons normally are held in a chemical bond and are not free to move; others do not form part of the bond and are free to move. The addition of energy to the system, either thermal or radiative, may excite electrons from the valence bonds into the conduction states where they are able to move or migrate. However, an electron missing from the chemical bonds leaves a hole in the normal electronic distribution (the sea of electrons) and this hole can also migrate through the material as if it were a particle of positive charge.

An N-type semiconductor is one in which the carrier of electricity is negative in sign (the electron). A P-type semiconductor is one in which the carrier is positive in sign (the positive hole). It should be noted that the kind of impurities present in the crystal determine to a large extent which type we have.

It has been found that irradiation of a semiconductor will increase the number of positive holes. This explains why a P-type crystal undergoes a monotonic decrease in resistivity upon irradiation whereas an N-type crystal will first increase in resistivity as electrons are neutralized by the new positive holes, and will then decrease in resistivity as more positive holes are formed.

As the electrons and positive holes, often called P-type centers, migrate through the crystal they may be trapped by interstitial atoms, lattice vacancies, or other defects. These traps have an important effect upon the ability of holes and electrons to recombine.

Most of the damage done to semiconductors by radiation will anneal out at room temperature, particularly the damage done by fast electrons. Neutron damage may require higher annealing temperatures.

Optical Materials

While glass is not a primary structural material it has enough aircraft applications to make a short review worthwhile.

Most glasses become colored during irradiation, and this coloration can be very troublesome in lenses, prisms, and windows. Intense irradiation may also make some glasses brittle. A portion of the color can be annealed out of glass, but the temperatures required are such that self annealing is slow or nonexistent. Therefore, work is now being done to develop noncoloring glass suitable for use in high flux regions.

The damage mechanism in glass consists of the trapping of electrons in metastable states at lattice vacancies or defects. These trapped electrons absorb light of various frequencies, causing coloration.

It is interesting to note that the addition of lead oxide gives a glass which is not only fairly resistant to radiation but makes a good gamma shield, being equivalent in shielding properties to steel.

Elastomers

The term elastomer refers to both natural and synthetic polymers with rubber-like characteristics. Several major types of elastomers are listed below:

1. Butadiene Type Rubbers (Buna-S, Buna-N)
2. Acrylic Type Rubbers (Hycar PA)
3. Isoprene Rubbers (Natural)
4. Haloprene Rubbers (Neoprene)
5. Elastolenes (Butyl)
6. Elastothiomers (Thiokol)

Most rubber compounds seem to have a radiation damage threshold of approximately 10^{15} nvt. Above this dose they begin to suffer damage, and this damage rapidly builds up to the point where the compounds are essentially useless.

Radiation will cause butyl and Thiokol to soften, most of the other compounds tend to harden and lose both tensile strength and resilience. Other properties such as compression set, specific gravity, and dielectric strength also change. In general, rubber compounds do not seem suitable for applications in regions of high flux. It is possible that mixtures of various elastomers may be developed with improved characteristics, but there is little chance that radiation resistant rubber will be available in the near future.

Since tires and tubes represent the biggest application in aircraft, some definite experiments have been done on these items. At the present time, it appears that tires and tubes will suffer about 25% damage after 50 to 200 hours of operation in a nuclear aircraft.

Experiments have shown that Buna-N and neoprene O-rings can stand appreciable damage without leaking. However, work remains to be done on combining effects of irradiation and hydraulic fluids in service. In general, rings get harder and weaker by about 30% of the original values after several days irradiation.

Plastics

There are about 30 distinct types or families of plastics; all of which can be classified as either thermosetting or thermoplastic.

Radiation damage in plastics is mainly the result of ionization caused by fast neutrons and gamma rays. Since plastics are long chain polymers or cross-linked networks of complex molecules, ionization will cause permanent changes in the molecular structure and in the chemical bonds between the molecules.

With very few exceptions plastics are considered to be nonradiation resistant. Some plastics swell and become soft or gummy, others become brittle and eventually crack or crumble. Gases may be given off during irradiation; most of this gas is hydrogen.

Experiments have shown that most plastics have a threshold dosage below which the physical properties remain fairly constant and above which these properties rapidly change. The threshold dose for most plastics is roughly 10^{15} to 10^{16} nvt, with the best ones going as high as 1.7×10^{18} nvt. It is also convenient to establish a 25% damage level based on the dosage at which one of the major properties, such as tensile strength, will be 25% below normal.

The plastics which have shown the most radiation resistance are listed below. The order of listing is no indication of resistance.

1. Furan with asbestos and carbon filler
2. Bakelite with asbestos filler
3. Plaskon Alkyd
4. Polystyrene (Amphenol or Syron)

It should be noted that almost all plastics change color rapidly during irradiation; therefore, in applications where this is important the damage threshold may be quite low.

Organic Fluids

The basic types of organic fluids of interest are oils, greases, hydraulic fluids, and fuels. Several inorganic lubricants are also worth consideration, including graphite and molybdenum disulphide.

There are many kinds of lubricating oils even if we confine our attention to mineral base oils. Most of these oils are aromatic or naphthenic hydrocarbons, and most of them react roughly the same when subjected to radiation. There is also a large class of synthetic lubricants which must be considered.

In general, it can be said that oils will exhibit an increase in viscosity during irradiation, accompanied by evolution of gas and formation of sludge. Aromatic (benzene derivative) oils are less susceptible to radiation than are aliphatic (fatty base) oils. Alkyl aromatics with special additives show considerable promise and work is now in progress on these oils. The above statements can also be applied to hydraulic fluids and some greases, since these are made from the same basic crude petroleum.

While it appears that satisfactory oils, greases, and hydraulic fluids can be produced by the use of additives such as selenium or iodine compounds, or by the compounding of various oils, the design of aircraft systems is still complicated by the fact that sludge and gas must be continually removed. This may mean that hydraulic systems, for example, will include sludge filters, gas traps, and provisions for constant circulation of all fluid in the system.

Aircraft fuels have been tested in several reactors, and the results show that gasoline and jet fuels are not sufficiently damaged by radiation to warrant any special attention. A small viscosity increase was noted, and both gas and sludge were formed in small quantities, but burnability and volatility were not impaired. At high dose rates, however, damage may be considerable.

There are several "by-products" of radiation damage in lubricants which should be mentioned briefly. One is "coking," or deposition of carbon on hot surfaces, another is accelerated corrosion caused by acids formed in the lubricant. Both of these side effects should be considered when choosing lubricants.

Electrical Insulation

Materials used for electrical insulation include ceramics, glass fiber, mica, plastics, elastomers, fabric, and asbestos. These materials can be used alone or in combinations such as mica-asbestos, asbestos-filled plastic, and phenolic-glass laminate.

The most significant property of insulating materials is electrical resistivity, with tensile strength and hardness important only as they affect resistivity.

As might be expected, inorganic insulation is much more resistant to radiation than is organic insulation. Mica tapes will withstand intense gamma radiation with no apparent damage, but cellulose acetate and Teflon tapes become damaged to the extent that their usefulness is very limited. Some bakelite type insulating materials have withstood about ten months irradiation in the Oak Ridge pile without appreciable damage. Both polystyrene and polyethylene have proven to be good insulating materials in radiation fields, with polyethylene rated as the better of the two because of its flexibility, even though polystyrene shows less actual damage for a given total dose.

Quartz and glass show a decrease in resistivity under intensely ionizing radiation and also tend to become brittle and crack. Nevertheless, these materials are still the best insulators for prolonged irradiation in strong fields when compared to all other available materials.

Porcelain (as used in spark plugs), silicone impregnated glass fiber, and inorganic Ceroc all have good resistance to irradiation.

The final choice of an insulator for any particular application will depend to a large extent upon the environmental conditions. Temperature, dielectric stress, mechanical stress, heat cycling, vibration, and humidity must all be taken into account. Many insulators which have a high resistance to radiation make excellent solid insulators but cannot be used as wire insulation because of inherent brittleness. Examples of this type are polystyrene, the ceramics, bakelite, and porcelain. Tests have shown that quite often insulation failure resulted from a decrease in physical strength, with resultant cracking and electrical breakdown.

Electrical Equipment

Included in the following discussion are a few remarks concerning the radiation damage to be found in many common electrical components. Since these components are constructed of basic materials with predictable radiation resistance, it is not too difficult to estimate the approximate useful life of a given part, knowing its constituents.

Carbon and wire wound resistors, when subjected to a moderate flux for one hundred hours, exhibited less than 2% change in resistance. Copper oxide and boro-carbon resistors also show little or no change in resistance, but the so-called metalized or metal film resistors proved to be unreliable when irradiated, some types showing almost a 100% change in resistance.

Paper and mica condensers, bakelite encased mica condensers, and ceramic condensers show little or no damage after several days irradiation at moderate flux levels. Electrolytic and oil impregnated condensers show considerable evidence of damage; this damage ranges from a simple drop in capacitance of about 10% to actual rupture of the condenser casing.

Most types of vacuum tubes are not permanently damaged by moderate amounts of radiation, but there is evidence that transient effects may impair their usefulness. These transient effects depend upon the rate of irradiation and tend to make the tube operating characteristics become erratic. When permanent tube damage is noted, it usually is found that either the seal or the glass has become porous, allowing gas to leak in and destroy the vacuum.

Several makes of dry cell batteries have been irradiated for approximately 100 hours, and, as might be expected, some deterioration was measured. This amounted to a drop in circuit voltage and an increase in internal resistance. It appears that dry cell batteries can be used but will have a fairly short service life. Lead storage cells show no appreciable damage, but bias cells behave in an erratic manner and their reliability as a source of grid voltage is questionable.

Magnetic coils and electric motors operate satisfactorily in radiation fields if built with radiation resistant insulation. Most motors now available tend to short out in the windings after a few hours operation. The same remarks can be applied to the various types of transformers in use.

Electronic Equipment

Since electronic assemblies utilize the same basic components discussed in previous sections of this report, not much can be added except to note that complex assemblies are no more resistant to radiation than their weakest component. This "weak link" concept is often used to help predict the operational life or functional threshold of an assembly. Once the detail design stage is reached, however, it is necessary to rely upon experimental results involving the assemblies to be used.

It is interesting to note that of the many electronic sets that have been radiation tested, quite a few became radioactive and remained so for many days after removal from the reactor in which they were tested.

Miscellaneous Materials

There are many materials that, while they may be of secondary importance, must be considered in aircraft design and construction. A short list might include sealants, radomes, potting compounds, paints, photographic materials, fabrics, explosives, and insulations. Most, if not all, of these items contain organic compounds and therefore are suspect, making it necessary to evaluate them on an individual basis. In general, the experimental approach is the only method presently available by which the designer can hope to find the best material for any given application.

V. INDUCED RADIOACTIVITY

When an element is bombarded with either electromagnetic radiation or accelerated particles of sufficient energy the result is often a radioactive element which will decay at a constant rate with the emission of one or more types of radiation. The product element may be an isotope of the original element or it may be an entirely different element, depending upon the projectile used, the energy of this projectile, and the target element.

There are a great many possible combinations of nuclear reactions, a few of which will be listed later, but we are mainly interested in the so-called neutron-gamma reactions. These neutron-gamma reactions account for most of the radioactivity induced in aircraft materials.

It should be noted that once an element has been made radioactive by artificial means it is identical in all respects to the natural radioactive elements. In other words, the manner in which a given radioactive substance is formed has no influence upon its subsequent decay.

The study of induced radioactivity is complicated by the fact that not all nuclear reactions result in radioactive isotopes. This is best illustrated by consideration of a few of these interactions. Boron 10, when struck by a slow neutron, will give up an alpha particle and become lithium 7. The latter is a stable element. Aluminum 27, when struck by a neutron, will emit an alpha particle and become sodium 24, which in turn will emit both beta and gamma radiation with a 14.8-hour halflife. Sodium 24 is therefore a radioactive element.

For convenience a shorthand type of notation is normally used when discussing nuclear reactions. This notation consists of writing down, in order, the target element, the incident particle (projectile), the product particle or radiation, and the resulting element. The two cases mentioned above would be written:

$$B^{10}\ (n,\ \alpha)\ Li^{7} \text{ and } Al^{27}\ (n,\ \alpha)\ Na^{24}.$$

Note that the above notation gives no indication of whether or not the final element is radioactive. This must be ascertained by examination of a nuclide chart such as the Segre Chart found in Volume I of "Introduction to Pile Theory" by Clark Goodman.

The following is a short list illustrating a few of the possible types of reactions, with the radioactive products noted.

1. N^{14} (n, p) C^{14} radioactive
2. Cd^{113} (n, γ) Cd^{114} stable
3. N^{14} (α, p) O^{17} stable
4. C^{12} (p, γ) N^{13} radioactive

5. Cu^{63}(d, p) Cu^{64} radioactive

6. Al^{27} (α, n) P^{30} radioactive

where

p = proton, nucleus of hydrogen

d = deuteron, nucleus of deuterium.

Some mention should be made of the fact that the incident particle and the target nucleus first form a compound nucleus which has an exteremely short life, (10^{-12} sec) because it is an unstable system. Therefore the product particles are given off essentially at the instant of collision of the target and incident particle. The product isotope is considered to be radioactive only if it continues to decay after the source of incident particles has been shut off.

In item 2 above we have a neutron-gamma reaction which results in a stable element; however, most other neutron-gamma reactions give radioactive elements. The neutron-gamma reaction is often called radiative capture, and is the most common nuclear process, since it takes place with nearly all elements if the neutrons are moving slowly (thermal neutrons). The product of a neutron-gamma reaction is usually a beta emitter or a beta and gamma emitter.

So far no mention has been made of the physical changes going on in the nucleus during these transformations. Assuming that the target nucleus was originally in its normal or ground energy state, the addition of an incident particle to the nucleus will result in a compound nucleus containing an excess of energy plus an excess of protons or neutrons, depending upon the type of incident particle used. This compound nucleus may then eject a proton, neutron, alpha particle, or deuteron, or, if the energy of the compound nucleus is not sufficient to permit expulsion of a nucleon, some or all of the excess energy may appear as gamma radiation. As was mentioned previously, the product nucleus may or may not be a radioactive isotope. If the product nucleus contains a stable neutron-proton ratio, and contains no excess energy, it will be a stable isotope. If, on the other hand, too many protons or neutrons are present, the isotope may reach its ground state over a period of time by the emission of an electron or a positron, perhaps accompanied by gamma radiation. If the neutron-proton ratio is stable but excess energy is present in the nucleus, only gamma radiation is emitted. Nuclei which contain an excess of energy are usually described as being in an "excited state."

Let us now consider what happens to a given volume of pure metal when it is placed in a thermal neutron flux, assuming that the neutron-gamma reaction (radiative capture) is predominant. The activation per second is equal to the flux times the activation cross section times the number of atoms in the sample, or

$$a = \emptyset \sigma a \, N_x \tag{1}$$

As soon as some radioactive atoms are formed they begin to decay, and this decay can be expressed as

$$\frac{dN}{dT} = - \lambda N \tag{2}$$

where N is the total number of active atoms and λ is the decay constant. Therefore, at any time after the start of irradiation the net increase in activated atoms is

$$\frac{dN}{dT} = \emptyset \quad \sigma_a N_x - \lambda N \tag{3}$$

Solving for N, we get

$$N = \emptyset \frac{\sigma_a N_x}{\lambda} (1-e^{-\lambda T}) \tag{4}$$

The induced activity A is therefore

$$A = N\lambda = \emptyset \sigma_a N_x \; (1-e^{-\lambda T}) \tag{5}$$

at any time during the irradiation. After the sample has been removed from the neutron flux the activation is

$$A = \emptyset \sigma_a N_x \; (1-e^{-\lambda T}) e^{-\lambda t} \tag{6}$$

where T is irradiation time and t is time elapsed since the sample was removed from the flux. Although the above formula was derived for a sample containing only atoms of one element, it can be used for alloys by doing the calculation separately for each element, using the proper cross section, decay constant, and number of atoms for each, and adding the results. These calculations may be further complicated by the fact that more than one isotope of each element is present, or by the fact that several modes of decay are possible for some isotopes.

After all necessary factors have been considered, the total activity of the sample is calculated and then converted from gamma flux to roentgens per hour. The dose rate D, in R/hr, can be expressed as

$$D = \frac{W\phi}{r^2}X \qquad (7)$$

where W equals mass in pounds, r is the distance between the observer and the sample in feet, and ϕ is the thermal neutron flux in neutrons per cm^2-sec. The roentgen is a unit defining a certain quantity of gamma radiation; the formal definition will be given later. The last symbol, X, is the unit dose, or the dose at a distance of one foot from a one-pound sample that has been irradiated in a flux of one neutron per cm^2-sec. Values of X can be calculated for any given alloy for the desired combinations of irradiation time and decay time. Such data are usually prepared by the use of IBM calculators and compiled in tabular form.

In the event that the sample being considered is large in size and cannot be considered a point source, equation (7) must be integrated over the volume and some absorption coefficient must be used. If our sample happens to be an airplane containing a nuclear power plant, and if we need to know, for example, the dose rate at the left wing tip 10 hours after a 20-hour flight, we must consider the airplane to be made up of many small pieces, each one containing various elements, each one in a different neutron flux, and each one a different distance from the point of observation. It is easy to see that the determination of the dose rate in such a case becomes a problem of tremendous proportions, and must be solved by high speed electronic calculators.

Going back, for the moment, to equation (5), note that the exponential term approaches zero at the time T gets large. Therefore, the activity will not increase appreciably beyond a given period of irradiation; this peak activity is called the "saturated activity."

Table III presents twenty common structural alloys arranged in order of increasing induced activity, with the least active alloys at the top and the most active alloys at the bottom. Activations were calculated assuming an irradiation time of 20 hours and cooling, or decay, times of 10, 20, and 40 hours. Note that, as the decay time increases, some alloys change their relative positions in the table. This change is caused by variations in both cross sections and decay constants between the various alloying elements.

TABLE III

Common alloys arranged in order of increasing induced activity after an irradiation time of 20 hours and a decay time as indicated.

Decay Time: 10 hr	20 hr	40 hr
Republic RS140X	Republic RS140X	Alum 1100
Alum 1100	Alum 1100	Alum 356
Alum 356	Alum 356	Republic RS140X
AZ51	AZ51	Az51
Alum 7075	Alum 7075	Alum 2024
19-9 DL	1020 Steel	1020 Steel
Inconel-X	Inconel-X	8630 Steel
1020 Steel	4130 Steel	4130 Steel
4130 Steel	19-9 DL	4340 Steel
AMS6470 Nitroloy	AMS6470 Nitroloy	Alum 7075
4340 Steel	4340 Steel	AMS6470 Nitroloy
8630 Steel	8630 Steel	Nimonic 75
Alum 2024	Alum 2024	410 Stainless
410 Stainless	410 Stainless	17-7 PH
17-7 PH	17-7 PH	Inconel-X
Nimonic 75	Nimonic 75	347 Stainless
S-816	347 Stainless	302 Stainless
302 Stainless	302 Stainless	AMS5735 (A-286)
347 Stainless	AMS5735 (A-286)	19-9 DL
AMS5735 (A286)	S-816	S-816

VI. HEALTH PHYSICS

Introduction

Prior to the last war, little was known about the effects of radiation on humans, although X-ray and radium therapy had been in use for many years. When the first reactor was built in 1942, it was realized that some means must be found to protect personnel from the harmful reactor radiation, and at this time a radiation-protection service was begun.

At first this protection service, now called health physics, was mainly concerned with ascertaining the maximum daily or weekly tolerance dose for humans. Back in 1934 the International Committee for X-ray and Radium Protection set the tolerance dose at 0.2 R/day or 1 R/wk, and this was revised to 0.1 R/day or 0.5 R/wk in 1936. The latter value was adopted in 1942 by the U. S. Atomic Energy Program, and was used throughout the war years. In 1950 the radiation tolerance dose rate was again reduced to 0.06 R/day or 0.3 R/wk; this value was in use until 1958. In 1958, the National Committee on Radiation Protection and Measurement recommended that the maximum permissible radiation exposure limit be reduced to 0.1 R/wk or 0.02 R/day, which is one third of the previous maximum. The new values are being used at some laboratories but have not, as yet, been universally accepted.

The work of health physics personnel has been expanded during the past few years to include the following major functions:

1. Aid in selection of site for reactor or other nuclear installations.
2. Aid in design of reactor shielding.
3. Personnel monitoring and records of exposure.
4. Radiation surveys of area and equipment.
5. Furnishing and calibrating radiation - detection instruments.
6. Setting maximum permissible exposures.
7. Waste disposal.
8. Development of methods of bioanalysis.

Radiation Units

Before starting the discussion of health physics and its many aspects, it would be wise to define the important radiation units.

1. Roentgen (R) - That quantity of X-rays or gamma rays which will produce, by ionization, one electrostatic unit of electricity of either sign, in one cubic centimeter of dry air at 0°C and standard pressure. One roentgen expends about

83 ergs per gram of air, where an erg is roughly equivalent to 0.95×10^{-10} BTU. Note that the roentgen is a measure of only X-rays and gamma radiation, and is therefore not adequate for all reactor radiations.

2. Roentgen Equivalent Physical (rep) - That quantity of ionizing radiation which, upon absorption in body tissue, causes a gain of 93 ergs of energy per gram of wet tissue. In tissue, one rep is roughly equivalent to one roentgen. Since physical effect and biological effect are not necessarily the same, a third unit is now being widely used.
3. Roentgen Equivalent Man (rem) - That quantity of ionizing radiation which produces the same biological damage in man as one roentgen of X-rays or gamma radiation.

The above three units can be compared in a table which also shows the relative biological effectiveness (RBE) of the various radiations.

Since the radiation field surrounding a reactor consists of many types of radiation the table of RBE equivalents is used to find a total dose rate for the mixed field. The maximum allowable weekly dose might consist of 0.3 rep of X, gamma, or beta rays, 0.03 rep of fast neutrons, 0.06 rep of slow neutrons, 0.015 rep of alphas (internal), or any combination of the above that would be equivalent to 0.3 R/week of gammas.

TABLE IV

RELATIVE BIOLOGICAL EFFECTIVENESS

Radiation	R	rep	rem
X & Gamma	1	1	1
Beta	-	1	1
Fast Neutrons	-	1	10
Thermal Neutrons	-	1	5
Alpha Particles	-	1	20*
Protons	-	1	10*

* True only if radioactive source is within body.

To avoid the use of small decimals the term milliroentgen (mr) is commonly used, where 1R = 10^3 mr.

Standards have also been set up to cover the amounts of radioactive substances which may safely be taken into the body, either by inhalation, ingestion, or through cuts in the skin. These standards are usually expressed in microcuries (μc), where a curie is 3.7×10^{10} disintegrations per second. For example, the maximum safe intake of radium is set at 0.1 microcurie. In connection with internal dosages, the term biological halflife is often used. This is defined as the time required for half of the original quantity of the element to be excreted by the body. Taken together with the radioactive halflife of the element, the damage done by any given amount in the body can be estimated.

As a matter of general interest, the following table has been included to show common X-ray exposures given in hospitals and doctors' offices.

Average X-ray	120 mr
Chest X-ray	100 - 1000 mr
Gastro-intestinal series	1-8R
Dental X-ray	1.5 - 15 R
Fluoroscope exam	5 - 15 R
Tumor treatment	3000 - 7000 R
Skull X-ray	4 R

Radiation Hazards

In a nuclear reactor installation such as Oak Ridge there are many sources of radiation and all of them constitute hazards. A few of these are listed below:

1. Radiation escaping from a reactor.
2. Any material removed from a reactor, including fuel elements, control rods, coolants, instruments, dust, and materials inserted for irradiation.
3. Wastes from process plants, including air, other gases, coolants, dust, liquids, etc.

These radiation hazards can be divided into two types, internal and external. External exposure can be controlled by shielding, by limiting exposure time, and by maintaining enough distance between the source and the personnel. Internal hazards can be controlled by strict personal hygiene, dust control, air and area surveys, personnel monitoring, waste control, and good housekeeping. The internal hazards are particularly serious because the effects are usually long-lived and because the ingested material is in most cases impossible to remove.

The various types of radiation differ in their effects on humans. Gammas, X-rays, and neutrons are the most important because of their penetrating power. Alpha and beta particles are not too important as an external hazard even though high energy betas can penetrate the skin and do some damage. When considering internal hazards, alpha particles are by far the most important because of their ionization power. Most alpha emitters are bone-seekers and, if enough alpha emitting material is collected in the body, the blood producing cells in the bone marrow are destroyed, resulting in bone cancer and anemia. Barium, calcium, radium, uranium, and plutonium are all bone seekers.

Dosages

It is interesting to compare the maximum permissible exposure (formerly called tolerance dose) of 0.3 R/wk with doses that are known to cause damage in the human body. The following table gives the effects of various exposure levels.

Total-Body Exposure to Cammas in Roentgens	Results
0 - 25	Safe
25 - 50	No detectable damage
50 - 100	Detectable damage
200 -	Probably kill 10% of persons
*400	" " 50% of "
600	" " 75% of "
800	" " 90% of "
1000	" " 95% of "

* Called median lethal dose

The data in the table were compiled from investigations of Nagasaki and Hiroshima survivors plus information gained at AEC installations. Note that a total dose of 50 R, absorbed over a short period of time, results in no detectable damage, while we are restricted to 0.1 R/wk, or 5 R per year. Since much of the damage to the human body is not accumulative, the present maximum permissible exposure gives a "factor of safety" of well over ten.

Even if a worker were to receive 0.3 R/wk for a period of many years, he still would experience less bodily damage than would be done by a quick 50 R dose. AEC records show that during the past few years the ten workers who received the highest total dosages got only 4.2 R/year.

Radiation Damage to Tissue

We have already discussed the processes by which the various types of radiation are stopped in aircraft materials. Damage to human tissue is caused mainly by ionization, either directly by gammas and X-rays or indirectly by neutrons (neutron-gamma reactions). Slow neutrons may also interact with nitrogen to give carbon 14 and a proton. Carbon 14 is radioactive, emitting beta particles, and the proton produces ionization; therefore, interactions of this type are quite dangerous. Fast neutrons may do some damage by causing recoil protons in hydrogenous compounds.

The amount of radiation damage done to tissue is a function of the type of radiation, the depth of penetration, the extent of the body exposed, the amount of radiation absorbed, and the time element. As was mentioned before, one large dose will cause more detectable damage than will several smaller doses, even though the total dose is the same in both cases. It should be noted that throughout this discussion the term "dose" or "dose rate" refers to total body irradiation. Certain parts of the body are far more resistant than others, particularly those parts not containing vital organs. As an example, 5000 R on the hand will not cause permanent damage, but 500 R over the whole body is usually fatal.

Damage to tissue may be classified as reversible or irreversible. Damage done to skin and blood is reversible, damage done to organs such as the brain and kidneys is partly irreversible and will not heal with time. There is, however, a threshold of damage for most of these effects, and it is possible to prevent permanent damage to the body by careful observance of health physics regulations.

Symptoms and Effects of Radiation Damage

A person exposed to a fairly high (but not lethal) dose for an extended period of time will usually exhibit one or more of the following symptoms:

1. Reddening of skin, loss of hair, possibly followed by cancerous growths.
2. Decrease in number of white blood corpuscles, later decrease in red cells.
3. Ridging in fingernails when hands are affected.
4. Temporary sterility is possible.

Exposure to a high dose, say 300 R, over a short period of time is termed an acute exposure, and will result in a series of symptoms as outlined below. These symptoms are usually divided into four steps, and these stages, taken together, constitute what is popularly known as "radiation sickness."

1. Nausea very soon after exposure, followed by nervousness and extreme weariness.
2. Feeling of comparative well-being for a period of perhaps several days.
3. Prostration, loss of appetite and weight, fever, bleeding of gums, loss of hair, and internal bleeding.
4. If the patient survives, convalescence of about six months.

There are many possible aftereffects to an acute exposure, including cataracts, permanent sterility, cancer, and kidney diseases. Little definite information has been published concerning genetic effects and possible mutations. It is certain that such effects exist, but just how serious this matter is remains to be seen.

Concerning the question of which types of tissue are the most sensitive to radiation, it is generally agreed that lymph glands, reproductive organs, lining of the stomach and intestines, eyes, and bone marrow are the most sensitive, and muscle tissue, nerves, and fully grown bone are the least sensitive.

Dosimeters and Film Badges

Two types of radiation detectors are normally issued by health physics to personnel working in radiation fields. These detectors serve to keep a check on the radiation exposure of each person and are checked periodically by health physics personnel.

The film badge is a small metal film packet containing three types of film and a cadmium shield. The shield covers only half of the badge and serves to filter out slow neutrons, soft gammas, and betas. One film is beta and gamma sensitive in the range 25 mr to 5 R. The second film is beta and gamma sensitive in the range 500 mr to 2 R, and the third film is neutron sensitive. These films are checked by comparing the degree of darkening of each film to a series of standards for both the shielded and unshielded portions. The resulting readings are recorded and kept on file by health physics, and constitute a part of the file kept on each worker.

Whenever personnel are working in an area where high radiation fields are common, they are issued a pair of pocket ionization chambers along with the film badge. These chambers, shaped like a fountain pen, are normally checked each day. One type of pocket chamber is simply a condenser which is charged up to about 150 volts before being issued. Ionizing radiation will discharge the device and the remaining potential can be read on a galvanometer. The second type contains a fiber electroscope, and is called a pocket gamma dosimeter. When the device is fully charged, the fiber will indicate zero on a scale. Gamma radiation will cause discharge at a rate proportional to the ionization caused, and the fiber will move across the scale accordingly. The dosimeter is read by holding it up to the light and looking through an eyepiece on one end. The dosimeter can be lined with a boron compound and used for the detection of slow neutrons.

Summary

We have discussed briefly only a few of the aspects of health physics. There are many more duties carried out continuously by health physics personnel in an effort to safeguard everyone working in the area. For instance, at the Hanford installation in the state of Washington, every building is equipped with automatic alarm systems which will indicate, by horn or siren, any rise in radiation level or any malfunction in the reactors or equipment. Air in the buildings is drawn through filters, and these filters are checked daily for activity. Detection instruments are placed around the surrounding countryside including all the streams and lakes, and these too are checked periodically for activity level. Protective or disposable clothing is issued to all workers in the labs and shops. This clothing is collected after use and is either thrown away or laundered by special methods.

Health physics is also responsible for all waste disposal, which is a very important and troublesome function. Liquid wastes are often stored in underground tanks or, if not too active, may be diluted with water and stored in reservoirs until the activity falls below a safe level. Active gaseous wastes are filtered and then discharged from tall stacks into the atmosphere. Solid wastes are usually buried after being encased in concrete.

All in all, it may be said that health physics performs a vital function which will become more important as the use of radioactive materials and reactors increases.

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