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ELECTRON

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Special RADIAC Issue

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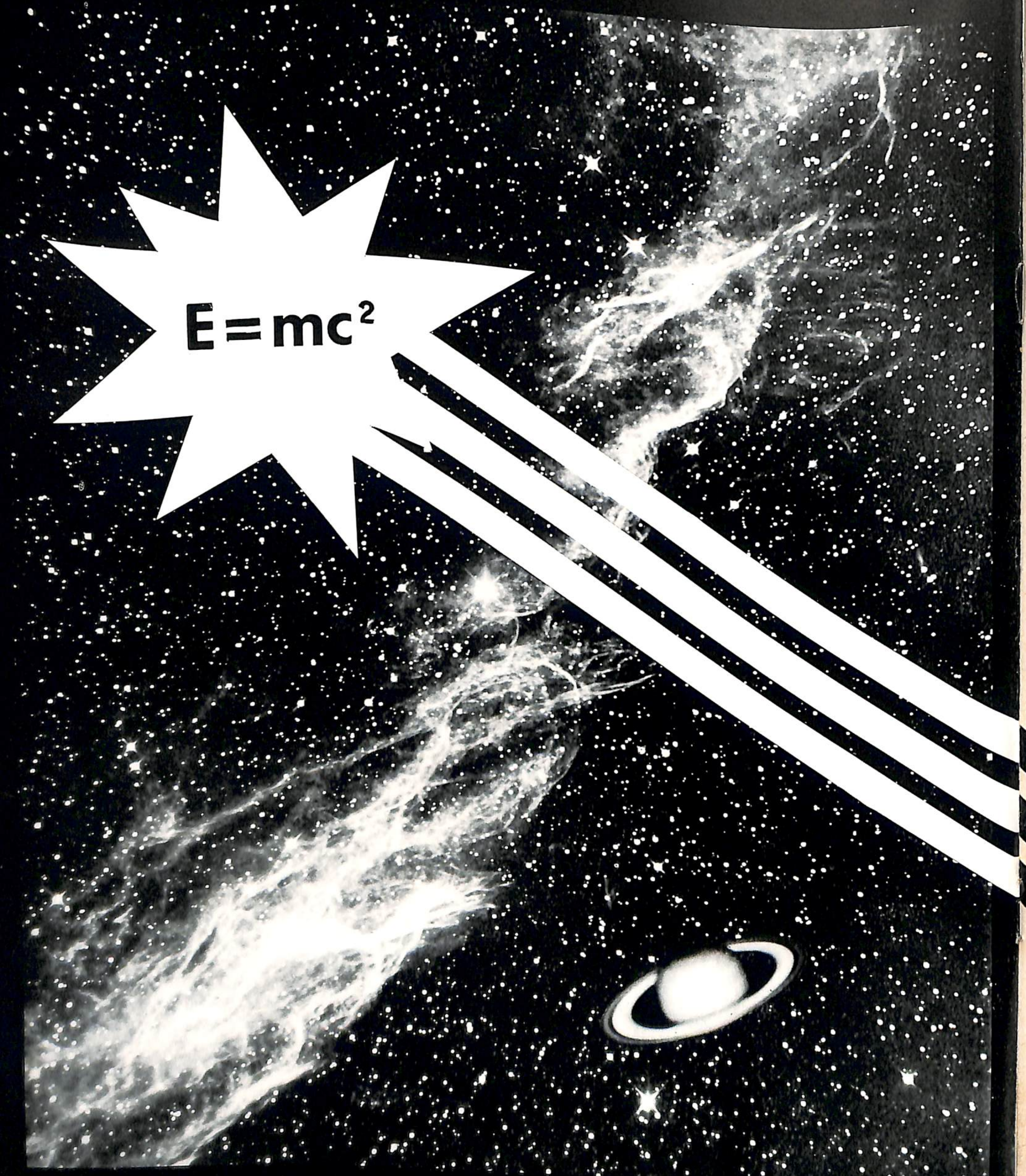
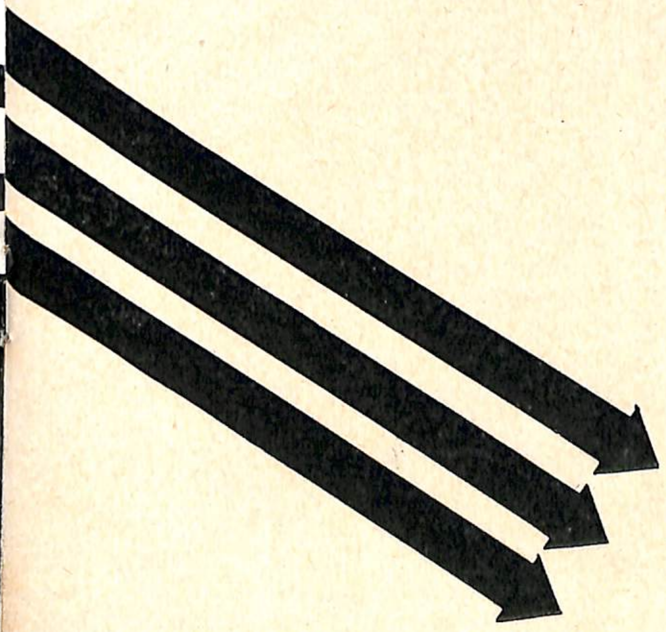


The Electronics Technician looks at Radiac

Prologue

Never in the history of the World has a new discovery, a new effort of man, been heralded as dramatically as was the atom bomb. With this special issue, BuShips ELECTRON welcomes and embraces a new field of Naval science and instrumentation initiated by the bomb, a field of equal importance and scope in every way to radio, radar, and sonar. This is the field of radiac. As atomic energy makes its imprint on the Naval Service, the readers of ELECTRON will encounter increasing need to know more about this field and its background. Anticipating this need, ELECTRON submits this article in the sincere hope that it may be of real value to the field.

It is time to take a look at radiac.



Introduction

To the man on the street, atomic energy, if the subject ever came to his attention at all, always seemed a pretty remote sort of thing. Oh yes, he may perhaps have read a few imaginative stories in the pulp science-fiction magazines, or glanced at an occasional reference to atomic power in the Sunday newspaper supplements, but such reference always seemed to lie in the realm of fantasy. "Maybe some day, but we'd never live to see it." All this has changed. We all remember staring unbelievingly at the screaming headlines of our newspapers or listening to our radios on the morning of August 7, 1945, reading or hearing how, the day before, a single bomb, *atomic* in nature, had blasted the city of Hiroshima. With the rocket and the guided missile, the bomb gave us the Buck Rogers age as our immediate way of life.

As befits a wide-awake military organization, the Navy has taken swift action to adjust and adapt itself to this change. The Navy has come a long way from the picturesque old days of its infancy. The era has passed of the tall, proud ships, with their lofty spars, gleaming red in the sunlight, with their hemp rigging, smelling of Stockholm tar, with their spreading stu'n-sails, like so many saucy petticoats. No longer do the cutlasses flash, nor the "Long Toms" buck against the gun-tackles as they belch shot and puffy clouds of white smoke at the silhouettes of enemy frigates. The electronic equipment of to-day, the "eyes and ears of the Fleet," is a far cry from the gear of those days, and now, with the advent of atomic energy and radioactivity, nuclear weapons are changing the art and science of warfare still further.

Accordingly, the electronics technician should know more about the atomic bomb, about radioactivity, and about the new field of nucleonics and its sub-division the radiac which have grown up in association with the bomb, and which will become of widespread importance in the Navy. Nucleonics, in essence is the subject of the practical application of processes made to take place inside the nucleaus of the atom and of the release of energy resulting from these processes. "Radiac"—like "radar," "sonar," etc.—is a coined word, and means "Radio-Activity Detection, Identification And Computation." (Actually what is detected are radiations, indicating the presence of radioactive substances.) Radiac equipments are electronic in nature—an added reason why the electronics technician should take a look at radiac.

Since radiac is such a new subject, it was felt that it would be inadequate just to talk only about specific equipments. Right now when nuclear warfare is relatively new, the electronics technician should know something about the "overall picture." Then later on, in subsequent articles, when new radiac equipments are discovered as they make their debut, he will be able to approach them with a better perspective. An attempt has been made to make this article comprehensive in scope so as to portray this overall picture, rather than to analyze specific radiac equipments. Such material has been included as was felt would be helpful to the technician in enabling him to better understand his radiac equipments and the circumstances under which they would be useful, and to enable him to co-operate more closely and effectively with other branches of the Naval service.

The article is divided into the following sections:

1—Fundamentals. The atom and radioactivity.

2—The development of the atomic bomb, and the nuclear chain-reaction.

3—Phenomena of an atomic bomb explosion. Aerial and underwater explosions.

4—Damage resulting from an atomic bomb explosion (including medical aspects).

5—Radiac equipments for detecting nuclear radiations. The types and how they operate.

6—Nuclear units.

7—Representative Navy radiac equipments now in use.

Radiac and the atomic bomb are such involved subjects that only a specialized expert thoroughly cognizant of the latest developments in a particular field is fitted to discuss individual details authoritatively. Moreover, much of the information on these subjects is "under wraps" from a security standpoint. However, in furtherance of the fundamental policy of ELECTRON, a conscientious effort has been made to make the article as accurate as such limitations would permit. Many reputable publications and books outside the services and many official Navy publications were scanned. Naval experts in many of the specialized fields touched upon were kind enough to offer constructive criticism on the sections concerned with their specialties. It is felt that without their aid it would have been impossible to achieve the fundamental aim of this article. In addition, several outstanding scientists, both within and outside the Navy, graciously granted permission to publish illustrative material which is particularly appropriate to our subject—radiac.

Fundamentals

The "trons": Electrons, Protons, Neutrons, Positrons, and Mesotrons

From an extensive series of laborious experiments by a small group of zealots, at times neglected and scorned by the majority of mankind, we know that matter is composed of small "building-blocks" called atoms. An atom is the smallest unit of matter which can enter into a chemical change. By intricate arrangement of these atoms in an ever-surprising variety of patterns, nature has built up the material world. It is typical of her economy that she needs less than a hundred types of atoms to construct all the infinitely-varied species of matter which we encounter. Quietly working in his laboratory, the scientist has furthermore found that these fundamental building blocks are themselves composed of other constituents. Some of these turn out to be particles of "pure electricity." According to our present concepts, these particles are three: the electron, the proton, and the neutron.

The electron carries a negative electric charge while the proton has an equal charge of opposite or positive polarity. As one can see from its name, the neutron is neutral in charge. In general, much is known about the behavior of these particles, but little is known about the nature of the particles themselves. It is known, however, that the proton and the neutron are each about 1850 times heavier than the electron.

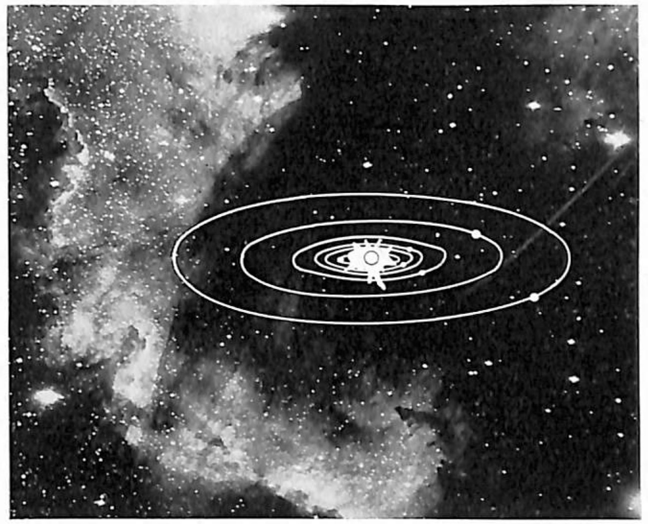
It should be emphasized that these particles are extremely small. One solitary electron weighs only 0.000,000,000,000,000,000,000,000,000,91 gram! It would be hard to imagine anyone doing it, but if one did, it would be found that many billions of electrons would have to be placed side by side to cover the width of a single dot in the letter "i" on this page! That such "super-tiny" entities can be so important stems from the fact that there are so very many of them—in one gram of hydrogen there are no less than 600,000,000,000,000,000,000,000, (six hundred sextillion) electrons! Such minute and such large figures are truly staggering—"They're either too big or too small." But one gets accustomed to this in the study of the atom.

In recent years a few more fundamental particles have taken their place beside the electron, the proton, and the neutron. These are the positron and the mesotron. The positron is a positively-charged electron, and the mesotron is a heavy electron, which may apparently be either positive, negative, or neutral. Both are produced in the earth's atmosphere by cosmic ray showers. Cosmic rays are radiations (probably high-speed protons) which have their origin in the dark reaches of interstellar space, and which are continually bombarding the earth. Some evidence is beginning to show that the mesotron may be involved in the nucleus. There is theoretical indication, too, that a third additional particle, the neutrino may exist. These, then, are the "building-blocks" of atoms.

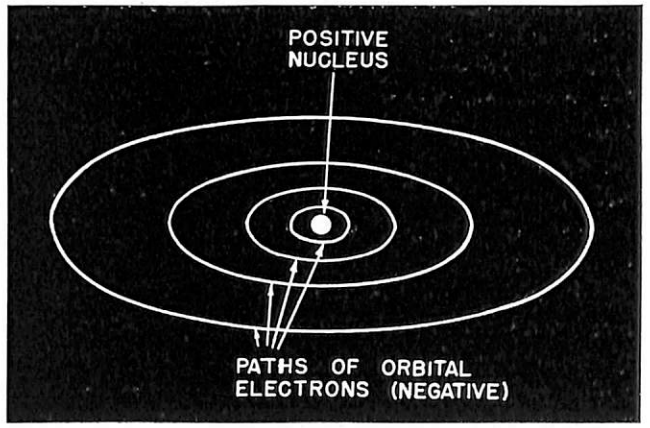
The Nature of the Atom

For all practical purposes, the stable atom may be considered as a miniature solar system. The neutrons and protons are concentrated in a kernel or nucleus, and the electrons whirl around this nucleus just like the planets rotate around the sun in the solar system. Of course, all this is on a very small scale, for the nucleus is only about 0.000,000,000,000,1 inches in diameter. Because of its protons, the nucleus is positively charged, and holds the electrons in their orbits by the attraction of charges of unlike polarity. This solar-system model is admittedly crude and old-fashioned, but it is a good one, and is used by everyone for ordinary purposes.

The chemical properties of an element—the way it



Solar system model of the atom. TOP—The solar system on a celestial background, with the planets (including the earth) rotating about the sun. BOTTOM—The solar system model of the atom (after Rutherford and Bohr) shows the negatively-charged electrons revolving about the positively-charged nucleus. When completely filled with electrons, the innermost orbit holds two electrons, the next outer orbit holds eight, the next eighteen, the next also eighteen, the next thirty-two, etc. (Star background, *Mt. Wilson Observatory*.)



behaves in chemical reactions—are determined by the number and arrangement of the planetary electrons. It is found that we may often have several kinds of atoms, all having the *same* number and arrangement of planetary electrons, yet having *different* nuclei and atomic weights. Since the number and arrangement of the external electrons are the same, the chemical properties are the same, and hence they are all varieties of the same chemical element. The differences are in the nuclei, which contain the same number of neutrons. Such varieties of a chemical element, chemically-identical but with differing atomic weights and nuclei, are known as *isotopes* of the element. The difference in the nuclei of several isotopes of an element may appear to be subtle and unimportant, but this is not so. As we shall see, it was necessary physically to separate the uranium isotope of atomic weight 235 from the uranium isotope of atomic weight 238 in order to prepare the bomb material for the first atomic bomb, for the difference between the nuclei of these two isotopes is such that the 238-isotope is absolutely useless as a bomb material in itself, while the 235-isotope works very well.

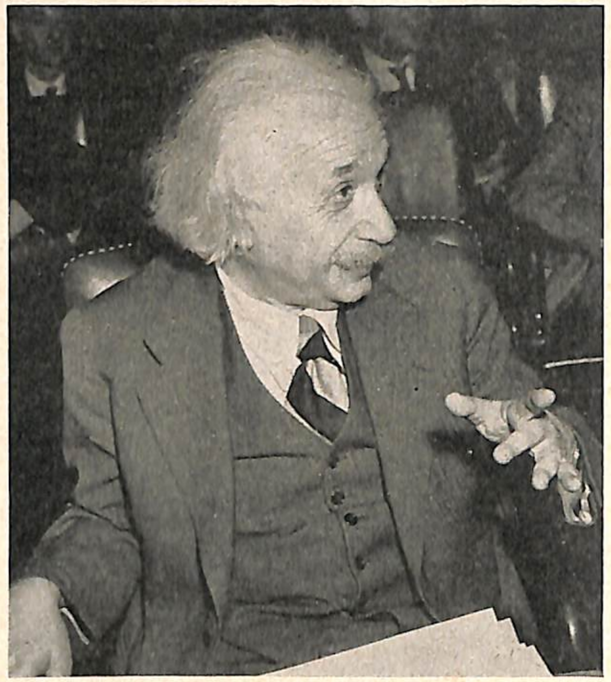
Although two of its three constituents are charged, the atom as a whole is electrically-neutral since the number of protons is equal to the number of electrons. It is relatively easy, however, to strip off one or more of the outermost electrons, leaving a positively-charged residue. This residue or "almost-atom" is called an ion, and the process is described as ionization. Ionization is important in chemistry and in electrical discharge in gases. It is particularly important for us, since it is the vital mechanism in several types of radiac equipment, and is the process underlying physiological effects on the human body when neuclear radiations penetrate living tissues.

The details of the electron paths of the atom (or "shells of energy") are very complicated—in fact, a new branch of mathematics had to be invented to explain them. In spite of this complication, it is believed that they are fairly-well established. Only now, however, is the nucleus beginning to yield its secrets to the eternal probings of the scientist.

There is a very real reason for this. The way to study a nucleus is the same as the way a watchmaker would study a new watch: take it apart, note its construction, and "see what makes it tick." Unfortunately, the components of the nucleus cluster together so tightly that they resist with the utmost vigor any attempt to pry them apart. Nuclear binding forces are so enormous that they not only counteract the natural tendency of the nuclear protons to fly apart (like charges repel, remember) but manage to go beyond and hold them and the neutrons together in an exceedingly tight embrace. Moreover, the electric fields of the electrons and the nucleus are strong enough to discourage all but the most highly-energetic charged particles and keep them from penetrating. Only with modern techniques, such as the huge and expensive "atom-smashing" machines, can the nucleus be penetrated and studied.

The Energy Inside the Atom

One reads many references to the energy locked inside the atom. Where is this energy? The answer to this question was supplied by the twentieth-century scientific virtuoso, Albert Einstein. As a surprising consequence of his theories of relativity, a consequence which has since been amply verified by experiment, he proposed that matter and energy are equivalent. "Equivalent? What does that mean?" Well, Einstein predicted that if by some process pure energy could be changed into matter, a definite weight of matter would make its appearance for each quantity of energy put in; similarly, if by some process matter could be changed into pure energy, a definite quantity of energy would make its appearance for each unit of matter consumed. In mathematical terms $E = mc^2$, where E is energy, m is mass, and c is the velocity of light.



Albert E. Einstein, whose famous expression for the equivalence of mass and energy ($E = mc^2$) has reached practical significance in the atomic bomb and the nuclear chain-reacting pile, where energy is obtained by direct conversion from matter. *(Wide World Photos, Inc.)*

At this point a nineteenth-century physicist would have thrown up his hands in disgust, crying "Visionary! Abstract conjecture! Impossible! Bah!" In fact, two of the most firmly unshakable tenets of classical physics were that energy could neither be created nor destroyed, and that matter could neither be created nor destroyed. But here is Einstein coming along to predict that mass might be changed into energy, if a process—the answer to an alchemist's prayer—could only be found to do so. In the atomic bomb just such a process has been achieved on a grand scale. Matter is changed directly into energy. A small portion of each atom of the bomb material entering into the explosion literally disappears, releasing energy which did not previously exist except in the form of matter. In the above little formula, elegant in its simplicity, lies the secret of extracting energy from the atom.

The amount of energy obtained by mass-to-energy conversion is astronomical in relation to the amount of matter consumed. Let us manipulate a few figures. Suppose one gram of matter were totally converted[1]. The energy obtained would be

$$\begin{aligned} E &= mc^2 = 1(3 \times 10^{10})^2 = 9 \times 10^{20} \text{ ergs} \\ &= 9 \times 10^{13} \text{ joules} = 25{,}000{,}000 \text{kwh!} \end{aligned}$$

Twenty-five million kilowatt-hours! This is enough to supply the electric power needs of a hundred thousand people for a full year! A teaspoonful of coal, if all its mass were converted into energy would drive the *Queen Mary* across the Atlantic and back! Is it any wonder that publication of Einstein's formula stimulated the imagination of serious workers as well as popular science writers, and set their thoughts a-dancing?

Before we can understand the fascinating process of obtaining atomic power, we must examine the phenomenon which unlocked the first door to Nature's storeroom of atomic energy, natural radioactivity.

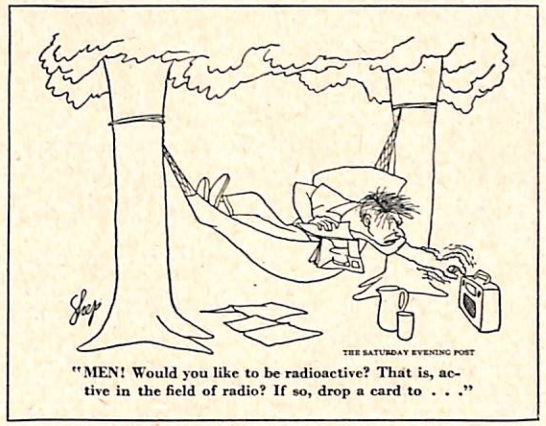
Natural Radioactivity

We must not lose sight of ordinary chemistry. Chemical changes are taking place about us all the time as the atoms of the elements are being constantly rearranged: spring greens of the leaves merge into the pictorial yellows and browns of autumn; wood burns cheerfully in a campfire and slowly curls up as bluish smoke; crisp, fragrant bacon is eaten and digested and becomes part of a nerve fiber or perhaps a strong muscle; sticky, useless-looking coal tar is transformed into colorful dyestuffs and exotic perfumes. In spite of these chemical changes, the individual atoms are very stable. A given atom of sodium, say, has probably been an atom of sodium for as long as the earth has endured—for billions of years. No matter how she shuffles her atoms, Nature prefers stability in her nuclei.

There are a few places, however, where she has made exceptions. A few rare types of atoms are unstable, with their nuclei spontaneously breaking up and decaying. Various sub-atomic radiations are emitted in the process, and new and different atoms are left as a residue. This spontaneous disintegration is the phenomenon of natural radioactivity. Its discovery initiated a revolution in physics, and gave prophetic hint of the forces leashed within the atom.

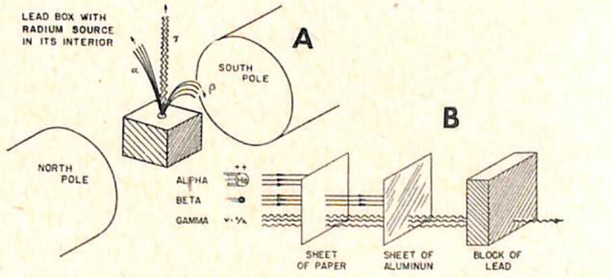
Most naturally-radioactive materials lie among the heavier elements. In these elements there are so many protons packed into the nucleus, so much mutual repulsion of the positive charges they carry, that the forces holding the nucleus together can barely keep it intact. Indeed, there is a certain probability that the cohesive forces will not win out, and an instantaneous re-shuffling of the nuclear constituents will take place to bring about a new arrangement in which the cohesive forces will have more command of the situation. The rearrangement involves the ejection of some form of nuclear radiation as a by-product. The well-known radioactive substance radium, for example, decays into the element radon, emitting an energetic helium nucleus as the radiation by-product.

$${}_{88}\mathrm{Ra}^{226} = ({}_{2}\mathrm{He}^{4})^{++} + {}_{86}\mathrm{En}^{222} + \text{kinetic energy.}$$



"MEN! Would you like to be radioactive? That is, active in the field of radio? If so, drop a card to . . ."

Radioactivity in the public eye. This cartoon from a popular weekly magazine emphasizes the fact that the word "radioactivity" does not refer to radio, in spite of the inclusion of the term "radio," but refers to a nuclear, sub-atomic process. (Reprinted by special permission of *The Saturday Evening Post* and the cartoonist, Mr. Don "Shep" Sheppard. Copyright 1948 by the Curtis Publishing Company.)



Alpha, β, and γ-rays from radium. (A) The α- and β-rays consist of charged particles and can be bent by a magnet. The γ-rays are electromagnetic radiations and are not bent. (B) Comparison of the penetrating powers of α, β, and γ-rays.

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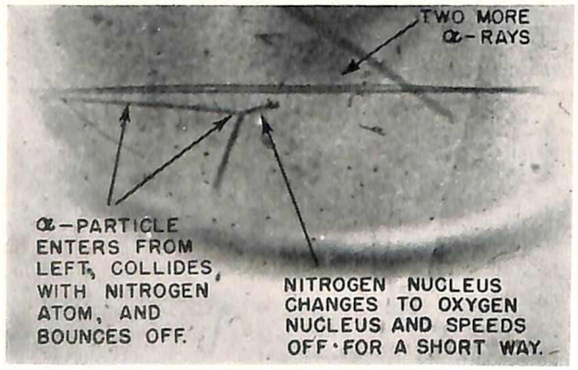
[1] *This is a hypothetical example for illustrative purposes only. No process is known for producing such total conversion of matter into energy. Even in the explosion of an atom bomb only a small percentage of matter is converted into energy.*

The newly-formed atom of radium is itself unstable, and sooner or later will in its turn undergo a somewhat similar radioactive disintegration. Indeed, radium and radon are but two steps in a whole series of such radioactive transformations. The series starts at uranium (${}_{92}U^{238}$), proceeds through such elements as thorium (${}_{90}Th^{234}$), protoactinium (${}_{91}Pa^{234}$), radium, radon, polonium (${}_{84}Po^{218}$), and thallium (${}_{81}Tl^{210}$), and stops with prosaic, stable lead (${}_{82}Pb^{206}$). Except for a few isolated cases among the lighter elements, all naturally-radioactive substances belong to one of three such radioactive series, all ending in lead. It is interesting to note that geologists make use of a "radium clock" for ascertaining the geological age of the earth. If one assumes that all the lead now in existence was originally uranium and was formed by radioactive disintegration, then the age of the earth may be calculated from the known rates of decay and from the amounts of uranium and lead now present in the earth's crust.

All radioactive substances decay at definite rates—some fast, some slow. Each disintegrating atom breaks up almost instantaneously when it does disintegrate, but in slow decayers the number of atoms actually dying in one second is so small that it takes many years for one-half of the original material to be transformed. Radioactive *half-lives,* as they are called, cover a very wide range, from one-millionth of a second for polonium (${}_{84}Po^{214}$, also called RaC^{1}), to 4,400,000,000 years for uranium (${}_{92}U^{238}$).

Of great interest to us are the radiations of the type produced in this natural radioactivity. So prominent a position do they occupy in nucleonics—for they are emitted by or associated with the atom bomb—that their outstanding characteristics should be memorized by the technician. They draw on the Greek alphabet for their names: alpha particles, beta particles, and gamma rays (sometimes written "α-particles," "β-particles," and "γ-rays").



The micro-mechanics of artificial radioactivity and transmutation. The Wilson cloud-chamber shows the paths of three α-particles. One collides with a nitrogen atom, and bounces off at an angle. The nitrogen nucleus is transmuted into an oxygen nucleus, which proceeds until it looses its ionizing power after a short distance. *(U.S. Bureau of Standards.)*

Throughout the text, we will be making frequent references to rays and particles in what may seem to be a somewhat loose manner. It might be well at this point to clarify the situation.

Alpha, beta and neutron radiations appear to have mass, and finite velocity less than the speed of light. Gamma-radiation, on the other hand, appears to be electromagnetic in nature, just like radio, infra-red, visible light, ultraviolet, and X-rays. Like all these, γ-rays travel with one and only one velocity, that of light (3 x 10^{10} cm per sec). But—there would have to be a "but," of course—research in recent years has shown that electromagnetic radiation may, surprisingly enough, exhibit some of the characteristics of particles as well as of waves. The effect is there in radio waves, to be sure; but it never shows up experimentally, and need never be mentioned outside of advanced physics courses. For radio, the simple wave treatment suffices. With γ-rays, however, the emphasis is on the particle nature. We can't really call the units of electromagnetic radiation "particles," for they are not true particles with a velocity which can vary; therefore, because of this distinction, a special name has been invented for them: *photons.* A beam of γ-rays, then, is to be considered from our standpoint as a burst of numerous minute bullets called photons.

Thus, α, β, neutron and γ-rays are to be visualized as streams of submicroscopic bullets, consisting of particles of mass in the case of the first three, and of particle-like photons in the case of the fourth. When we refer to the aggregate or bulk characteristics of these streams, treating them as if they were a beam from a searchlight, we call them collectively "rays": α-rays, β-rays γ-rays, and neutron-rays. When our concern is with the individual, corpuscular characteristics, we make reference to α-particles, β-particles, γ-ray photons and neutrons. Occasionally, either term is used: we might say "one β-ray," meaning "one β-particle." In general, however, the distinction is clear, and is to be adhered to, although it is not critical as long as no ambiguity arises.

Alpha-particles are particles which have proved to be helium nuclei, doubly-charged helium ions in which both planetary electrons of the neutral atom are missing. They are positively-charged and may be deflected by a magnetic field. Alpha-particles are met with in common life, for the light of the luminous figures on our radium wrist-watch dials is produced by bombardment of a fluorescent material by alpha particles from radium mixed in the dial paint.

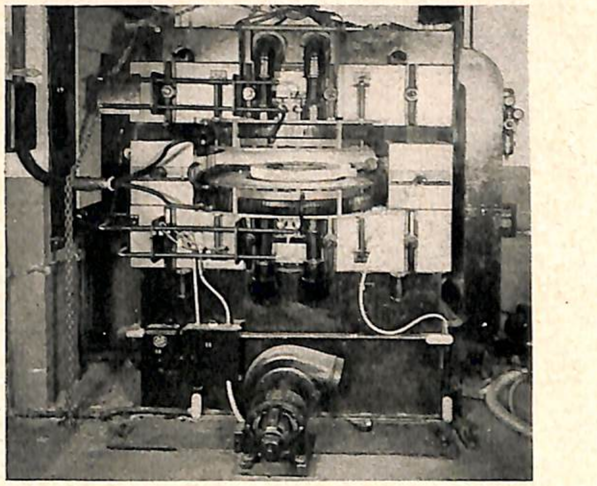
In general, the number of radioactive substances emitting alpha particles is relatively small. Alpha-emitters lie among only a few of the heavier elements. It is important to note that alpha-particles do not penetrate matter to any great depth, being stopped by an ordinary sheet of paper. Carrying high energies, they nonetheless produce heavy ionization in the small range before they are stopped. Beta-particles are common, garden-variety electrons originating in the nucleus, shot out at high-speeds. They are negatively-charged, and are deflected by a magnetic field, but in the opposite direction to α-particles. They have both medium penetrating power and medium energies (see Table I). They pass right through paper which would stop the α-particles, but can be stopped by putting a sheet of aluminum a few millimeters thick in their path. Their ionizing capabilities are not so great as those of α-rays, but, penetrating further, they can ionize atoms which the latter could not reach.

Gamma-rays are beams of electromagnetic radiation like radio waves, infra-red rays, visible light rays, ultraviolet rays, and X-rays. They have the shortest wavelengths of all electromagnetic rays. Their behavior is similar to that of X-rays. They produce little direct ionization per centimeter of path, but their range is so great that the total number of ions produced is large. Their penetrating power is very impressive; a lead shielding of several inches thickness or several feet of concrete is needed to effectively diminish their intensity.

We see thus that α-particles produce a very intense local ionization effect, while β-particles and γ-rays produce a strong effect in depth. The deep penetration of γ-rays is particularly important.

By bombardment with high-speed particles as in cyclotrons or in nuclear reactors, it is possible to induce radioactivity in elements which are normally stable. This phenomenon is called artificial radioactivity and is important. We do not have space to discuss this subject in the manner it deserves.

Experience has shown that all radioactive materials must be handled carefully. Before this was known, much serious physiological damage occurred. It is related, for example, that one physicist who was an early worker in a radium-refining plant knew that beyond doubt he was doomed when his breath, exhaled onto a fluorescent screen produced scintillations or flashes of light from α-particle bombardment too numerous to count! Modern workers treat radioactive substances with all the care and respect they deserve.



Atom-smashing machines. TOP—The betatron at the Naval Research Laboratory is shown. BOTTOM—A beam of protons is shown proceeding from the Harvard cyclotron. The power of the beam is emphasized by the luminescence it causes by ionization of the air. (U.S. Naval Research Laboratory) and (From "Why Smash Atoms?" by A. K. Soloman. Copyright 1940, 1946 by the President and Fellows of Harvard College; published by Harvard University Press.)

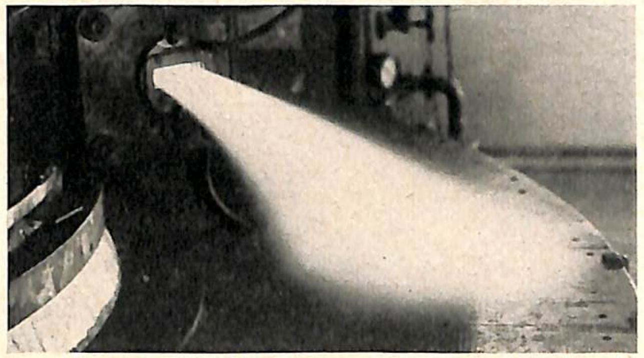


TABLE I—Characteristics of nuclear radiations from naturally-radioactive substances

Radiation	*Nature of Radiation*	*Energy*	*Ionizing Power*[2]	*Penetrating Power*
Alpha	Heavy positively-charged particle. Helium nucleus = doubly-charged helium ion = He^{++}.	High energies (4-9 Mev[1]).	High.	Weak. Stopped by a sheet of paper. Cut-off sharp[3].
Beta	Light negatively-charged particle. An electron with high speeds (1/20 velocity of light).	Up to medium-high energies (0-3 Mev[1]).	Medium.	Medium. Stopped by a few mm of aluminum. Cut-off sharp[3].
Gamma	Electromagnetic radiation (wave-length from 5 x 10^{-10} to 4 x 10^{-8} cm).	Low to medium-high energies (0.03-2.6 Mev[1]).	Weak (perhaps 1/10,000 that of α-rays).	High. Requires several inches of lead to effectively diminish intensity. Cut-off gradual[3].

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[1] One Mev or mega-electron-volt is the energy acquired by one electron when it is accelerated through a potential difference of one million volts. It is not a unit of voltage, but of energy. See section on nuclear units for elaboration.

[2] Depends on many factors. It is necessary to differentiate between the number of ions formed per centimeter of path (which is what we have tabulated) and the relative shock or disturbance created when an α-particle, a β-particle or a γ-ray finally does collide with an atom. Further consideration would lead us too far afield.

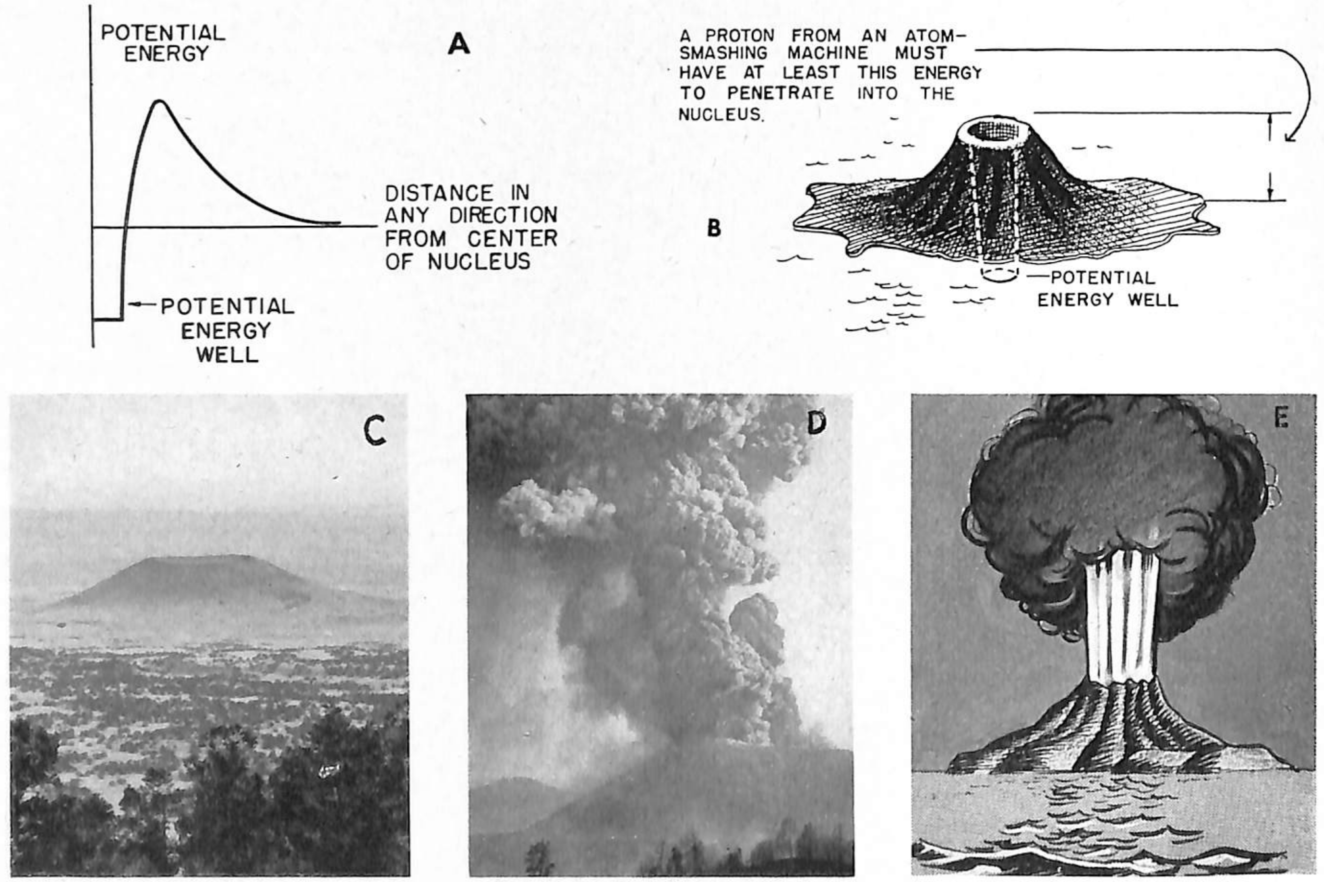
[3] As the thickness of a slab of absorbing material placed in a beam of the radiation is increased, the α- and β-particles are diminished in intensity sharply, but the γ-rays only gradually.

The Development of the Atomic Bomb and the Nuclear Chain Reaction

Nuclear Fission

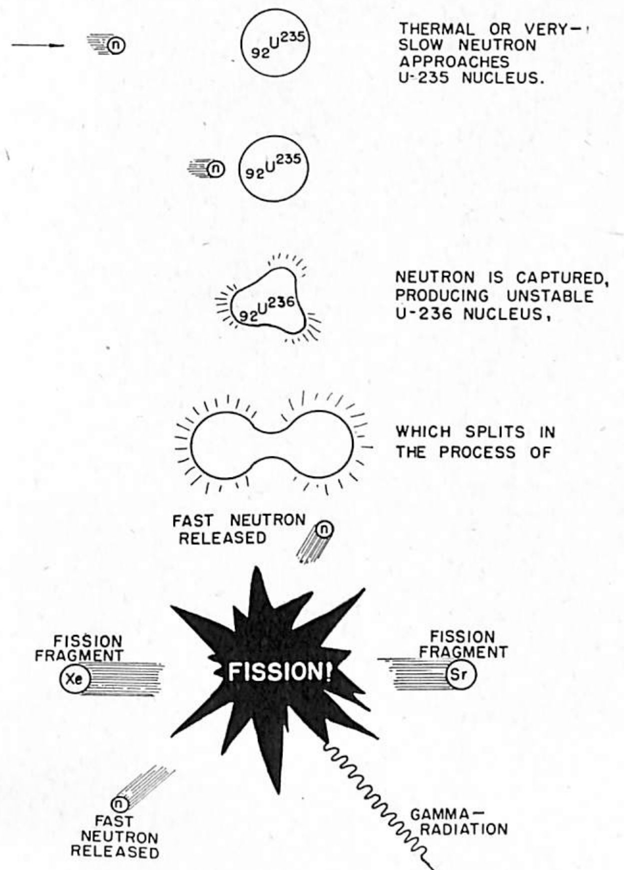
Nuclear fission is a peculiar type of nuclear reaction which we shall discuss in detail. Its unparalleled importance lies in two facts: 1—energy is liberated in the process of fission in unprecedented quantities and 2—once it is started, the process may be self-sustaining and continue. If the process continues slowly, we have a "nuclear fire" or controlled nuclear reaction in the atomic pile or reactor; if it proceeds rapidly, we have an uncontrolled nuclear reaction or nuclear explosion in the so-called atomic bomb. This self-sustaining characteristic means that the process can start on a sub-microscopic scale, but develops until it is operating on a scale involving pounds of material. All other nuclear reactions, such as artificial radioactivity, if they are on a microscopic or sub-microscopic scale, will remain on that scale.

The meaning of nuclear fission is simple. Nuclear fission means splitting of the nucleus. In ordinary radioactivity, an unstable nucleus ejects some form of nuclear radiation, and is transformed into a nucleus of an atom differing only slightly in atomic weight and number from the parent atom. In nuclear fission, on the other hand, the unstable nucleus breaks up into two fragments, both of which are nuclei of daughter atoms. (The two daughter atoms are not of the same kind for every fission process, and many elements are represented among the fission-products). In the course of the fissioning process a significant portion of the original mass disappears, and an equivalent amount of energy appears in its place, chiefly as kinetic energy of the fission fragments, which fly apart with great vigor. Simultaneously, various nuclear radiations are emitted as subatomic "shrapnel." Fission occurs among a few of the heavier elements, such as thorium, protoactinium, and notably the 235-isotope of uranium, and plutonium, the new man-made element to be discussed later.



"Volcanic crater" analogy of the nucleus. A plot of the potential energy in the nucleus vs. distance in any direction from its center, (A) bears a remarkable resemblance to a volcanic crater, as shown by the three-dimensional graph or drawing of (B). Just as a man must work against gravity, climbing up the crater to reach the rim, so must a proton do work against the repulsive field of the nucleus to penetrate inside the nucleus (into the potential energy well). On the basis of this analogy, a stable nucleus is equivalent to a dead volcanic crater (C), a radioactive nucleus is equivalent to a volcano erupting spontaneously—(D) shows the recently-born volcano of Paricutin in Mexico, and (E), a nucleus undergoing fission is equivalent to the gigantic explosion of the volcano on the island of Krakatao in the East Indies in 1883. *(U. S. Geological Survey)* and (Dr. Forshag of the Smithsonian Institution).

Fission is triggered off by neutrons which enter the nuclei of the atoms of the target material. In general, neutrons are very prolific in inducing nuclear reactions. Carrying no electric charge, they are not discouraged by the electric field of the nucleus, as protons would be, and penetrate with relative ease. Once inside, a neutron may or may not produce fission, of course. Although fission is produced by neutrons of all energies, Nature likes to play an occasional prank, for it is not the most energetic neutrons which have a high probability of causing fission, but rather some of the weakest. Such feeble neutrons possess energies of only one-fortieth of an electron-volt[1], and are called "thermal" neutrons, because their kinetic energy is about the same as that of gas molecules at room temperatures.



Nuclear fission of U-235. A thermal neutron joins a U-235 nucleus, forming a compound U-236 nucleus. The latter fissions and splits into two fission fragments, plus an unspecified number of fast neutrons, plus γ-radiation, plus kinetic energy.

When an atom of U-235 fissions, the process is as follows: A neutron approaches the U-235 nucleus, enters it and joins it to form a compound nucleus (U-236). This compound nucleus is unstable, and almost immediately fissions. Two daughter nuclei are formed, gamma-radiation is emitted, and several neutrons are released, along with a quantity of energy. Every fission process does not result in the same kinds of daughter nuclei; indeed, among the fission-products, as they are called, are found a wide variety of elements, although those near the middle of the Periodic Table tend to predominate. Most, if not all, of the daughter nuclei are themselves radioactive. They emit beta-particles and gamma-rays, producing in many cases other elements which in turn are radioactive.

The most important thing, however, about the fission process is the energy which is released. In nuclear fission Nature has seen fit to hand us an unexpected dividend. In fact, the energy developed by conversion from matter is some fifteen or so times greater than the highest energies developed in either natural or artificial radioactivity. In fission of $_{92}U^{235}$, for example, the average energy developed per fission is no less than 200 million electron-volts. When it is considered that the highest α-particle energy from naturally-radioactive materials is 8 million electron-volts (see Table I), and the energy obtained per molecular reaction in chemical reactions (such as the combustion of gasoline or even the explosion of TNT) is of the order of only a few electron-volts (smaller by a factor of millions!), no clairvoyant is needed to interpret the reasons for the unparalleled violence of the explosion of an atom bomb!

The 200 Mev per fission from $_{92}U^{235}$ is distributed among the fission by-products in the manner tabulated in Table 2.

TABLE 2—Approximate distribution among fission products of energy liberated in fission of $_{92}U^{235}$

Fission Product	*Energy (Mev)*
Fission fragments	160
Prompt neutrons	5
Prompt γ-rays	5
Radioactive series	20
Absorbed neutrons	10
Total energy	200

It will be seen that most of the energy is supplied as kinetic energy to the fission fragments, and is the chief form in which the energy of an atom bomb or power plant is made available. A small portion appears as kinetic energy of the released neutrons, which develop an additional quantity of energy (10 Mev) when they are absorbed. Still more of the energy is diverted into the γ-rays which are emitted during fission. About one-tenth of the energy appears later when the fission fragments begin to decay in radioactive series, and is evidenced as β- and γ-radiation.

Not all of the neutrons are emitted instantaneously or "promptly" during fission. A small but significant percentage are produced at later times (1% delayed at least

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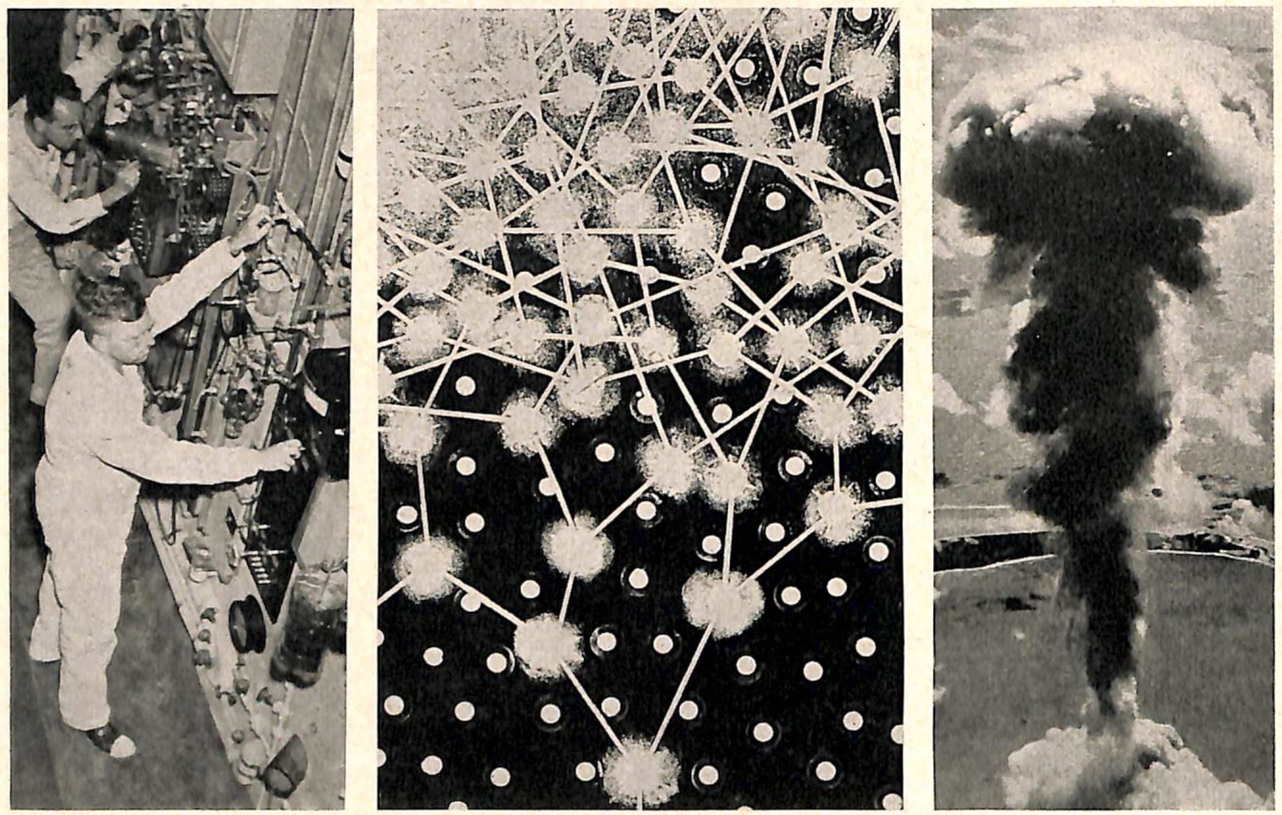
[1] *One million electron-volts equals one Mev. One electron-volt is 1.60 x 10^{-19} watt-sec of energy.*

0.01 sec., and 0.07% as long as one minute). These are called delayed neutrons, and permit control of atomic energy piles.

The Nuclear Chain-Reaction

Fission would clearly not be of much practical use unless it could be made to operate on a large scale involving pounds of material instead of a few atoms. The one point which enables atomic energy to be realized on a practical scale is that *nuclear fission develops the very means to reproduce and multiply itself.* Since neutrons produce fission, and since they are also produced (set free) as a by-product of fission, these secondary free neutrons can produce new fission in turn. Note that more neutrons are developed (set free) than were put in! Thus, suppose that in the fission of one atom three neutrons are released, of which two are available for new fissions, the remaining one being lost or absorbed in non-fission reactions. Then the first fission will lead to two secondary fissions, which will produce four fissions in turn, leading to eight fissions and then to sixteen, and so on. The process can build up from a single sub-microscopic fission until a very-sizable quantity of material has undergone fission! This self-sustaining—and not only self-sustaining, but self-multiplying—reaction is called a *nuclear chain-reaction,* and enables us to realize atomic energy on an industrial or military scale.

A similar chain-reaction underlies all burning or explosions. When a piece of wood is ignited, heat is evolved during the resultant chemical combustion, and is enough to instigate further combustion. The chemical chain-reaction continues until all the wood has been consumed. If conditions are such that the process is extremely rapid, as with dynamite, an explosion occurs. As we have previously indicated, nuclear chain-reactions can be made to occur slowly, as in atomic energy plants, or rapidly, as in atomic bombs.



The famous nuclear branching chain-reaction. The first fission of pure U-235 or plutonium produces two fissions, these produce four, which result in eight, and so on until the whole mass is involved. Certain liberties have been taken for illustrative purposes: the reaction is shown proceeding in one direction, non-fission neutron captures are not shown, and the number of neutrons produced per fission has arbitrarily been set at two. (Photo of men working in the atom bomb plants by U.S. Atomic Energy Commission, and bomb photo by Joint Army-Navy Task Force One).

This brings us to a further characteristic of the nuclear chain-reaction: it can be controlled. The control is achieved by varying the number of neutrons available to cause secondary fissions. Clearly, for the nuclear-fission to sustain itself, at least one secondary fission must be produced for each primary fission. If less than one fission occurs for each primary fission, the chain-reaction tails off and dies out. If more than one fission occurs, the chain-reaction builds up. If exactly one fission takes place for each primary fission, the reaction continues at a steady rate.

Among the factors which control the chain-reaction are the amounts, concentrations, and arrangement of fissionable material, and these factors are important. It is found that if the volume of a piece of pure fissionable material is below a certain, definite limiting volume called the *critical size,* the chain-reaction will not build up. Each fission process may produce, for example, three neutrons, but if the volume is too small, so many neutrons will escape from the surface that the number of neutrons available for fission is less than one, and the chain dies out. If the volume is above the critical size, the chain-reaction builds up. Another factor controlling the chain-reaction is the presence of impurities. Even a small trace of impurity may be enough to spoil or "poison" the reaction. This is one of the reasons why natural deposits of uranium had not long ago exploded off the face of the globe. We shall shortly describe nuclear reactors and the atomic bomb, and shall see how these principles of control are applied practically. All these principles depend on varying the number of secondary neutrons available for subsequent fissions.

When the discovery of nuclear fission was first announced, there was much uninformed speculation that a chain-reaction, once started, would build up until the entire world were consumed. Such a catastrophe cannot happen because a chain-reaction in ordinary matter will not sustain itself.

For emphasis, let us review the four characteristics of nuclear fission which make it of practical importance:

1—Unprecedented quantities of energy are released by conversion of matter into energy.
2—The process can be made self-sustaining in a chain-reaction so that, once started it will keep on going of its own accord.
3—The process can be made self-multiplying; it can be started on a sub-microscopic scale, and will soon involve very large amounts (pounds) of fissionable material.
4—The process can be controlled. It can be started. It can be made to proceed slowly, as in the "nuclear burning" going on in atomic power plants. It can be made to occur rapidly, as in an explosion of an atomic bomb. It can be shut off completely.

Prelude to the Atom Bomb

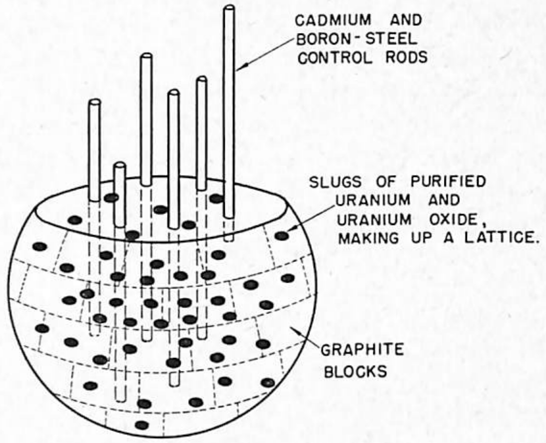
In the days immediately preceding World War II, nuclear fission had been discovered and studied, and its military and industrial potentialities envisioned. When the details of the process became clear, it appeared that a slow chain-reaction might be made to go in purified natural uranium if the fast neutrons from each primary fission could be slowed down to thermal speeds, when they would have a high probability of producing secondary fissions. Moreover, if the fissionable material U-235 isotope could be separated and obtained in pure isotopic (or at least enriched) form, a rapid chain-reaction might be set up without slowing down the fast neutrons. *The concentration of fissionable nuclei would be so great as to more than counteract the low probability of fission with the fast neutrons.* Thus, if pure U-235 could be obtained in quantity, an atomic bomb seemed feasible. An additional discovery of the greatest significance was made when it was found that a new element called plutonium could be manufactured from U-238, and was even more readily fissionable than U-235. Thus two bomb materials suggested themselves: 1—isotopically-pure U-235, and 2—pure plutonium, if it could be manufactured from U-238. It turns out that plutonium could be manufactured in a nuclear-reactor, and both U-235 and plutonium were both produced in quantity sufficient for atomic bombs.

Unfortunately, limitations of space do not allow us to review the exciting history of the events leading to the first bomb. The first suggestions of a small group of patriotic, far-seeing scientists, the first chain-reaction, under an old track stadium at the University of Chicago, the gigantic industrial plants at Oak Ridge and Hanford, the lab at Los Alamos, the dawn of a new age at Alamogordo, "bombs away" at Hiroshima and Nagasaki, and the tests at Bikini—these events, these names, are all well-known and well-documented. However, we should say more about the nuclear chain-reacting pile and about the atomic bomb, so "here we go."

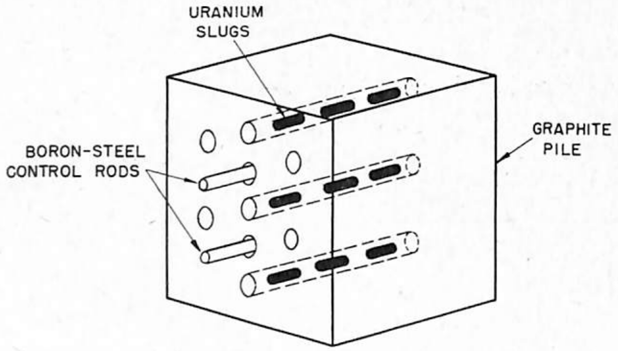
Plutonium and Nuclear Chain-Reacting Pile

Before fission was discovered, no element of atomic weight heavier than uranium was known. Research following the discovery showed that several new elements could be formed, elements which are not found in nature, elements which are radioactive and which possess a greater atomic weight than uranium. Of these, plutonium is the most important, and is formed by bombarding the 238-isotope of uranium with neutrons. The neutrons have to be rather slow neutrons (but not as slow as the thermal neutrons, the so-called "resonance" neutrons), with energies of about thirty-eight electron volts. A succession of transformations takes place, ending with plutonium. Now here is a strange coincidence: If we build a nuclear chain-reacting pile, in which a slow, controlled chain-reaction is made to occur in natural uranium (containing both U-235 and U-238), we find that plutonium is produced automatically. If we build a pile for the primary purpose of developing atomic energy (in the form of heat), then plutonium is a by-product. If we build a pile for the primary purpose of manufacturing plutonium, then we get heat as a by-product. "Bargain night" indeed, and a fortunate thing it is, too!

A typical nuclear chain-reacting pile or nuclear reactor consists of slugs of purified natural uranium arranged in a lattice and surrounded and separated by purified graphite. It has rods of cadmium- or boron-steel inserted in it for controlling the speed of the reaction.



Nuclear chain-reacting piles. TOP—Similar to the Chicago pile, the first ever operated. BOTTOM—A pile for the production of plutonium.



Remember that both fast and slow neutrons will produce fission, but that fission is most probable with very slow or thermal neutrons. Remember, too, that the secondary neutrons released during each fission process are fast neutrons. Now then, if we use natural uranium, in which the ratio of fissionable U-235 atoms to non-fissionable U-238 atoms is only about 1 to 140, it is hard to produce a nuclear chain-reaction. The fissionable atoms are too widely scattered. Indeed, in order to get a chain-reaction to go at all in natural uranium, we have to slow down the fast neutrons released in fission. In fact, they have to be slowed down to thermal speeds, where fission is most likely. A chain-reaction just will not go in a single block of natural uranium (1:140 ratio), no matter how large it is, or how pure. We have to have the pile larger than its associated critical size, and we have to have something to slow down the released neutrons if the chain-reaction is to go. A substance which slows down these neutrons in a pile (a kind of glorified "atomic brake") is called a *moderator,* and graphite is the most practical material for this use.

Boron and cadmium atoms absorb or "soak-up" neutrons readily. The pile is so constructed that the chain-reaction would build up uncontrollably with boron- or cadmium-steel rods not inserted. With the rods all the way in, so many secondary neutrons are absorbed that any chain-reaction which might be started would soon die out. (Remember that it was stated that control is achieved by varying the number of neutrons *available* for secondary fissions. If the neutrons are absorbed, they are certainly no longer "available.") As the control rods are drawn out of the pile, fewer neutrons are absorbed, and finally the chain-reaction starts. At this critical point the reaction is building up slowly; just slightly more than one fission-producing neutron is being released for each primary fission. This slight excess consists of the "delayed" neutrons mentioned when the process of fission was discussed. Because of the delayed release of these neutrons, fortunately, the build-up of the chain-reaction is slow, and can be controlled at the desired rate by pushing the control rods back in a bit to steady the chain-reaction at the chosen operating level.

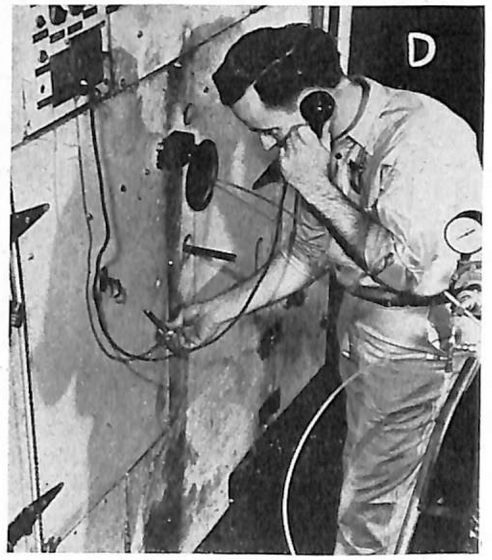
The Atomic Bomb

In an atomic bomb we have an extremely-rapid chain-reaction. This rapidity is achieved by using pure fissionable material instead of material such as natural uranium in which the fissionable substance is mixed and greatly diluted with non-fissionable material. Pure U-235 is obtained by separation from natural uranium, and plutonium, of course, is manufactured in nuclear reactors built for the purpose; both fissionable substances were prepared in quantity at Oak Ridge and Hanford. No moderator is desired in an atomic bomb to slow neutrons down to thermal speeds.

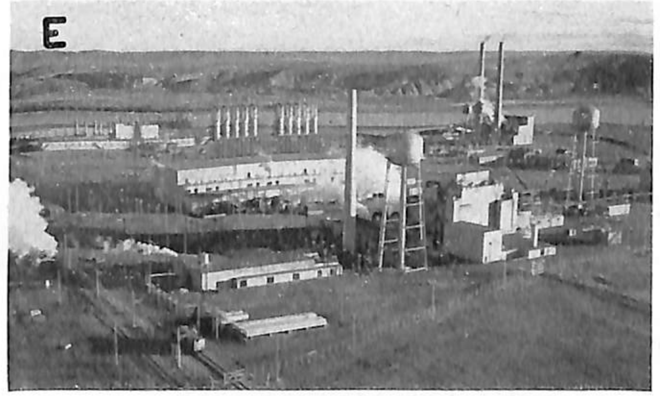
An atomic bomb is detonated by suddenly assembling together several pieces of pure fissionable material. Each piece alone is below the critical size in volume and hence will not explode by itself, but the assembled aggregate of pieces is above the critical size, and explodes. The assembling of the several pieces must be almost instantaneous (within a few millionths of a second), or the combination of pieces may be blown apart before the chain-reaction has had a chance to really build up to efficient proportions. To help prevent such an inefficient explosion, the bomb is surrounded by a heavy substance known as a *tamper,* which tends to prevent the escape of neutrons, and also keeps the pieces together because of its mechanical inertia.

Phenomena of an Atomic-Bomb Explosion

During detonation, the kinetic energy of the fission-fragments heats the exploding bomb to very high temperatures. Like all sufficiently-hot bodies, the exploding bomb emits infra-red radiation or radiant heat, ultra-violet radiation, and visible light. Trillions of watt seconds of thermal and optical energy are emitted. Intense beams of "prompt" γ-rays and neutrons are also radiated.



The atomic bomb plants. A portion of the Oak Ridge installation for the separation of U-235 is shown in (A). Two views of the Oak Ridge gas-diffusion towers appear in (B) and (C). In (D) an operator is shown at some of the controls of the electromagnetic separator. A portion of the Hanford plutonium works appears in (E). (U.S. Atomic Energy Commission).



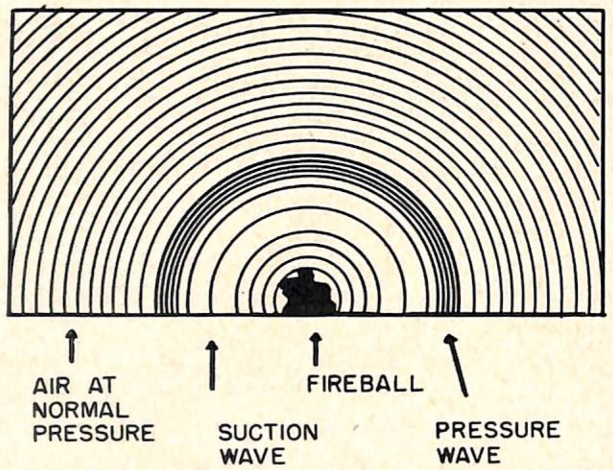
As would be expected, mechanical blast waves are experienced. The fission products are radioactive, emitting both β- and γ-rays right from the moment of the explosion, and continuing to do so for some time in the case of some long-lived fission products. Non-fissioned bomb material (plutonium or U-235, both of which are α-emitters) also adds to this delayed hazard. Note that γ-rays may be produced in two ways: 1—as primary or "prompt" γ-rays emitted during fission, and 2—as secondary γ-rays emitted later by radioactive substances.

The explosion of an atomic bomb contains many features already familiar to us now on a smaller scale. The mechanical damage and damage from thermal, ultra-violet, and visible radiation are qualitatively similar to that experienced in any large bomb explosion. Injury to personnel exposed to nuclear radiations, especially γ-rays from sources outside the body, are similar to those of medical workers over-exposed to beams from X-ray machines. Injury from bodily-absorbed radioactive substances (including α-emitters) is similar to that sometimes seen among workers in factories manufacturing radium dial paint for watches and clocks.

The phenomena observed when an atomic bomb explodes of course depend on many factors. The nature of the bomb, the location of the explosion (city, harbor, open ocean, etc.), the relative number of personnel involved, the elevation of the bomb when it explodes (in air, underwater, etc.), the characteristics of the buildings, ships, etc. exposed (wood, concrete-steel, etc.), the meteorological conditions of the atmosphere and the oceanographic conditions of the bodies of water involved, and finally the topography of the land areas affected—all these will influence the results. The discussion below is based on available data on the explosions at Alamogordo, Hiroshima, Nagasaki, and Bikini. Clearly, with atomic bombs of a different type, detonated under different circumstances, we may expect the effects to differ.

Characteristics of an Aerial Detonation (The "Mushroom")

In brief, the visual phenomena observed during an explosion in air of an atomic bomb are as follows: The detonation is heralded by a surpassingly-brilliant flash of light. At the same time, a mechanical air-blast shock-wave hammers out in all directions, followed by a suction wave. A spherical condensation cloud of moisture surrounds the site of the explosion, but speedily evaporates. Beginning its formation at the instant of the explosion, but obscured for a time by the condensation cloud, is the so-called fireball, or "ball of fire," one of the explosion's most characteristic features. An incandescent, globular mass of heated air gases, fission-products, etc., it grows and rapidly shoots sky-ward. Shortly, it loses its luminescence and transforms itself into the familiar mushroom-shaped cloud, the symbol of the atomic age. Continuing to rise, it sucks in air, smoke, etc., underneath to form its stem. As it reaches high altitudes, it may be surmounted by a small cloud-cap, composed, it is believed, of minute ice crystals. Finally, after some time, the mushrooming cloud loses its characteristic shape, and becomes visually indistinguishable from normal clouds. These phases—the flash, the shock wave and its condensation cloud, the hot fireball, and the mushroom cloud—may be traced in the accompanying photos. Let us look at them in more detail:



This diagram shows a cross-section of the spherical air blast wave of an aerial detonation. The pressure wave and the following suction wave are visible. Variation in air pressure is indicated by variation in the separation of the concentric circles.

1—*Bomb flash.* See "fireball."

2—*The air blast* is a sharp, mechanical shock impulse which speeds out from the point of detonation as a spherical or bubble-shaped shell of high pressure. Close to the center of the explosion, it presents a very sharp wave front, acting like a gigantic sledgehammer in the suddenness of its effects. Further out, however, its sharp front is rounded off, and it begins to resemble a violent gust of wind. When it reaches the surface of the ground or ocean, it is partially reflected; the reflected wave adds to the wave in the air and increases its violence in the region close to the earth's surface, just the region where exposed buildings or ships lie. If the explosion is over a body of water, the progress of the spherical blast wave may be clearly traced from the sharply-delineated circular pattern propagated on the surface of the water.

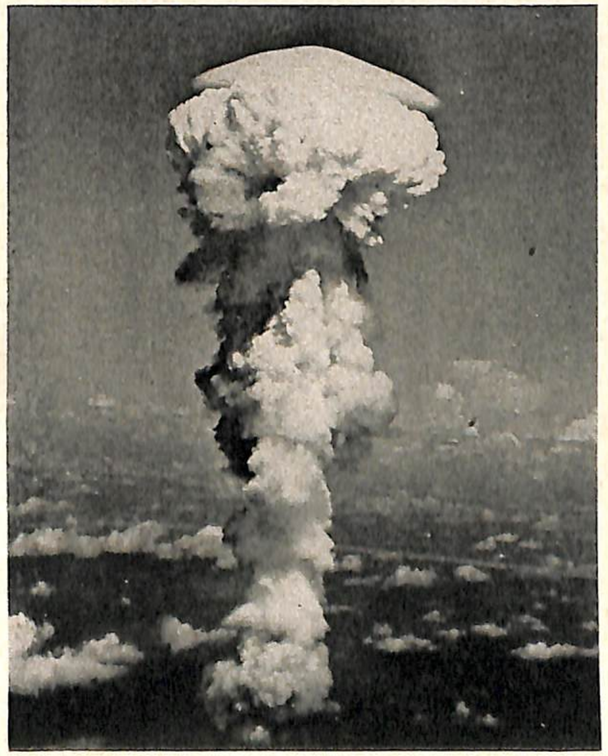
3—*The suction wave* is a spherical shell of low pressure concentric with the air-blast shell. A corresponding but weaker force is exerted in the other direction as the wave experienced by the object changes from pressure to suction. It is as if a strong hurricane with a wind velocity of several hundred miles an hour were suddenly turned on, then off after a second or so. Moreover, when closed compartments or other volumes are hit by the waves, the difference in pressure between the outside and the inside tends to buckle the structures.

4—*The condensation cloud* is a cloud of moisture precipitated out by the suction wave. The air within a given volume is first compressed when the pressure wave hits it, then expands when the suction wave, or wave of rarefaction hits it. The expansion cools the air, and condenses out the minute droplets which make up the cloud. At first the cloud has a globular shape in correspondence with the expanding form of the suction wave, and is brilliantly illuminated by the hot fireball within its interior. This lasts for only a few seconds. Within a period of about five seconds the globe has become a ring, with the fireball visible in its center. Five seconds later only slight patches of cloud are left to indicate that there ever was a condensation cloud.

5—*The fireball.* The exploding bomb smoothly but rapidly expands from almost pin-point size (relatively) to a large, globular mass of incandescent gases and fission products. The "pin-point" phase is at the instant of detonation; the accompanying blinding flash of light lasts only a few millionths of a second. A matter of seconds later, when the expanding mass of super-hot gases (what is left of the now-exploded bomb and the air immediately surrounding it) has clearly reached a globular shape, we have the fireball phase. Visible light rays, infra-red or radiant heat rays, and ultra-violet rays are emitted during and between both phases. Most of the ultra-violet, optical, and thermal radiation is radiated in the instant of the blinding flash. Practically all of it has been emitted after the first half-second, although the fireball continues to radiate until it becomes the mushroom cloud. The initial flash is brighter than the noonday sun, and is bluer. It has been estimated that the light output surpasses the total output of all the light bulbs ever manufactured—the flash would be clearly visible to an observer on the moon! Not only do we have a large part of the energy of the bomb radiated as optical and thermal radiation, but intense beams of "prompt" γ-rays and neutrons accompany the blinding flash, and the fireball strongly radiates β- and γ-rays from short-lived radioactive fission products.

The three figures above display typical successive phases in an aerial A-bomb explosion, as shown in the "Able" blast at Bikini. (A) was taken at or within a few thousandths of a second of the initial flash. Compare the intensity with that of (B) taken a few seconds later, which shows the spherical condensation cloud lit up by the fireball in its center. (C) This picture shows the condensation cloud after it has lost its spherical shape and changed into a ring as it evaporates. In the center, the red-hot fireball is rising rapidly, and will soon become the mushroom cloud. Below are the ships of the Bikini target fleet, and the circular pattern propagated on the water by the spherical air blast wave. (Joint Army-Navy Task Force One.)

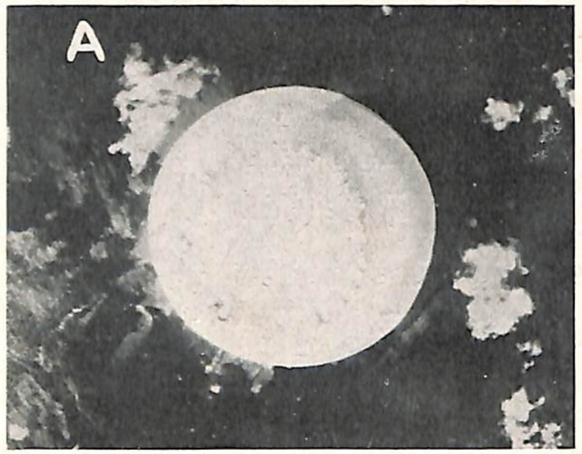
6—*The mushroom cloud* is the cooled-off and expanded remnant of the fireball. It may rise many thousands of feet. A tenuous, swirling, billowing mass of gases, vapor, smoke, and fission products, it varies in color from creamy white to a pheasant brown to a delicate peach tint. It contains radioactive fission products. It has been stated that their radioactivity is temporarily equivalent to that of a hundred tons of purified radium (the world's supply is only a few pounds!) At all times subsequent to the detonation these products are slowly settling out. The settled material is called *fall-out.* We must emphasize that fall-out contamination in an air burst is relatively minor; but is perhaps the most significant factor in an underwater detonation. In the accompanying photos can be seen the cloud-cap of ice crystals (it is believed) which sometimes forms at high altitudes. Such are the visual characteristics of an aerial detonation of an atomic bomb, at least as exemplified by the "Able" explosion at Bikini.

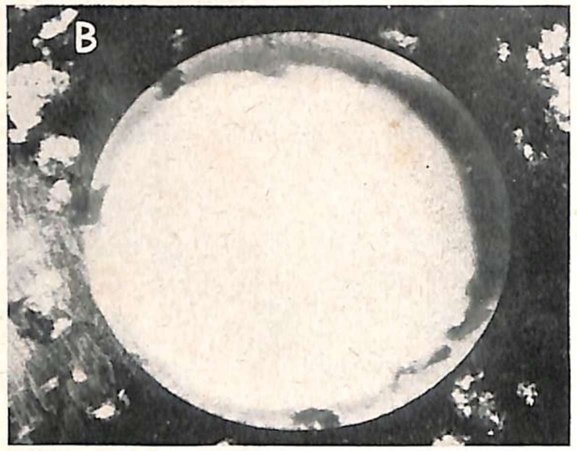


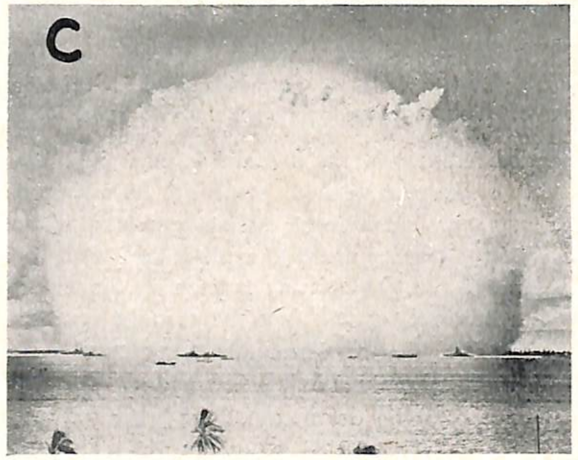
The Mushroom Cloud. (Joint Army-Navy Task Force One.)

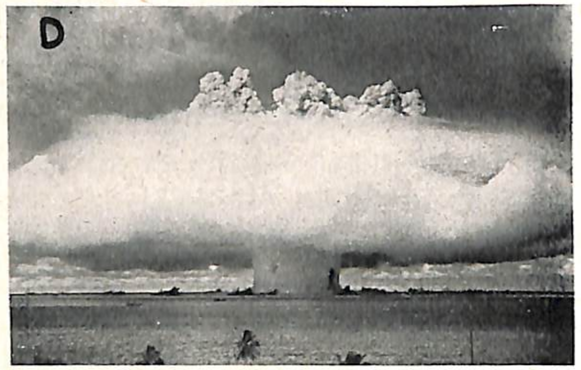
Characteristics of an Underwater Detonation (The "Cauliflower")

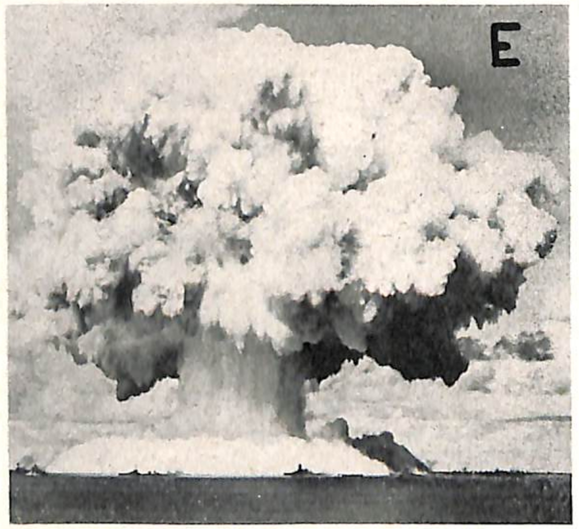
In brief, the characteristics of an underwater detonation are as follows: the exploding bomb forms a "gas bubble" or *underwater fireball* of incandescent gases, vapor, and fission products. Two shock waves hammer out, one in the air and one in the water, each setting up a separate circular pattern on the surface of the water. Within a few hundredths of a second, the underwater fireball heaves upward, bulging the surface of the ocean in a *dome.* The dome bursts and a cloud of gases, vapor and fission products is hurled skyward. At the same time hundreds of thousands of tons of water are flung upward. The water forms a vast cylindrical column, topped by the cloud. The cloud and column together remarkably resemble a cauliflower, and the cloud is called the *cauliflower cloud.* The upward surge of the water column is obscured at first by the more or less spherical condensa-

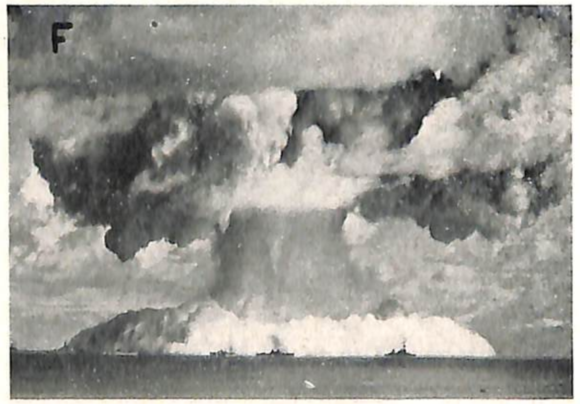












The six figures on this page display typical successive phases in an underwater A-bomb explosion, as shown in the "Baker" blast at Bikini. In this group, are two views showing the propagation of the air blast wave as traced by the circular pattern on the surface of the water. (B) was taken shortly after (A) in a plane flying directly above the bomb. The top of the cauliflower cloud is visible in (A), and the white mass in the circular patterns of (A) and (B) is the spherical condensation cloud.

(C) The spherical condensation cloud. The underwater fireball or "gas bubble" has burst. At the top are just visible a few tufts of the cauliflower cloud, but most of it is hidden by the spherical cloud of condensed moisture.

(D) In this dramatic shot, the spherical condensation cloud has become a ring, and more of the cauliflower cloud is visible. The column of water contained an estimated one-half million tons of water. The black area at the right of the column is not a target ship, but seemed to be a "hole" in the water.

(E) The full cauliflower is visible. At the top is the cauliflower cloud, and the water in the column has started to fall back into the ocean, setting up the base surge (the cloud of spray at the base of the column) as it pounds against the surface of the ocean.

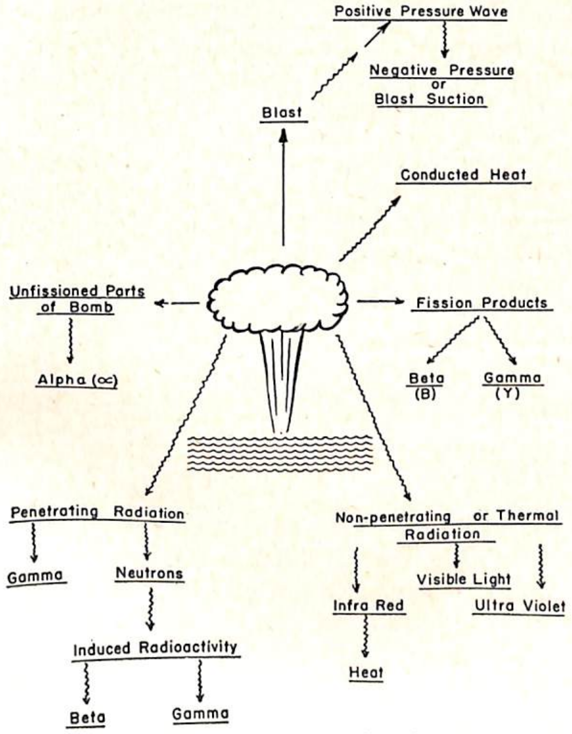
(F) a later stage. The cauliflower cloud has started to spread out, and the base surge has rolled out further. (Joint Army-Navy Task Force One.)

tion cloud formed as usual by the suction wave accompanying the air shock wave. This cloud flattens out, becomes a vast wafer-like ring, and rapidly evaporates. Water rushes in to fill up the cavity left by the water in the water column, thus creating high surface water waves on the ocean. After the skyward-flung water in the column reaches its greatest altitude, it begins to fall back again in the ocean. A heavy cloud of mist, spray, and vapor is set up as the falling water pounds against the surface of the sea. This is the *base surge.* It looks like a white ring or collar lying on the surface of the ocean close around the base of the column of falling water. The base surge grows rapidly outward from the column, surging out until it becomes a low cloud of fog covering many square miles. After the collapse of the water column, the cauliflower becomes the *aftercloud.* Finally rain may fall from the aftercloud.

Damage Resulting from an Atomic Bomb Explosion

The damage and injury which results from an atomic-bomb explosion is a complicated subject. It varies in character, extent, and emphasis. This becomes clear as we compare the effects of explosions which have occurred under different circumstances; for example, the damage and injury from an explosion over a city with that from an explosion underwater at sea.

In this study we shall first survey the types of injuries to personnel and look carefully at the effects of radioactivity, since that is the new element in warfare. In preparation, it is important to understand that an atomic bomb explosion produces damage and injury which basically is no different qualitatively from that produced by the detonation of any large charge of explosive, except injury to personnel from radioactivity which is essentially no different from that well-known to medical science in certain industries or resulting from X-ray. Quantitatively, however, the effects that are similar to an explosion of a charge of TNT exceed those of any charge ever detonated, and never before have nuclear radiations been used as military weapons.



The harmful agents in an aerial A-bomb explosion. Reprinted by permission from USF 85, *Manual of Radiological Safety* of the Office of the Chief of Naval Operations.

The injuries arising from an atomic-bomb explosion are difficult to classify because of their complex natures. A more-or-less satisfactory classification has been worked out, and is followed in our discussion.

Injuries from Mechanical Blast

The air shock wave is intense and violent, and injury may be sustained by personnel who are in the open and hence are directly exposed. As the air blast wave hits, an exposed individual experiences a pushing force, then an external overall pressure as the wave envelops the body. The resulting tearing and compressive action on the tissue constitutes primary air blast injury. Hemorrhages appear, especially at boundaries between tissues and gas volumes in the body, such as in the lungs, the ear-drum, the intestine, and the stomach. This type of injury is exactly similar to air blast injury from the detonation of large bombs or explosive shells filled with ordinary explosives. Many of the Londoners killed by V-2 bomb explosions, for example, died from this type of injury.

Fortunately, living tissue is much more resistant to air blast than ships or buildings are. In fact, the radius within which death occurs is amazingly small; one is either killed outright or is all right after a few minutes. Even for those within the fatal radius, primary air blast injury is of importance only if the person is in the open and is directly exposed. Air-raid shelters or even the walls of buildings may furnish adequate protection. Other deleterious agents of the explosion extend out to larger radii, so that a person untouched by the air blast may receive many times the lethal dose of gamma-radiation.

The water shock or blast wave from an underwater detonation may be expected to injure those in the water at the time of the explosion, if we may judge from wartime experiences with the detonation of depth charges.

Although primary air blast injury is a relatively minor cause of death, the secondary effects of the air and water blast waves are not. The blast waves topple over buildings, pound ships, distort or crush structural members, shake loose plaster, shatter glass, and recklessly hurl about objects not firmly secured. Falling timbers and debris may injure those in their path. In Japan many people received contusions, lacerations, broken bones, and other injuries from these causes. The blast waves furthermore may slam people against walls of buildings or ships' bulkheads and add to the mechanical injury, and the impact of the blast waves may send shock pulses through the structures to pound against personnel in contact with them at the time. The mechanical injuries from the secondary effects of the blast waves in Japan closely resembled those seen in hurricane disasters.

In Japan many fires were started from the radiant heat or hot gases from the fireball; others were produced as secondary results, as the air blast waves overturned stoves and hotplates, rupturing powerlines and gas mains. With the extremely inadequate fire-fighting facilities in Japan, many people were burned to death.

Hiroshima. The only aerial-ladder fire-truck in Hiroshima is visible. A modern city with fire-fighting apparatus designed for, and personnel trained for dealing with an A-bomb explosion would have had far fewer fire casualties. (U.S. Air Force, Wash., D.C.)

Such injury may be reduced in large measure by the use of air-raid shelters, by proper building construction, by securing loose objects, by avoiding cornices or other timbers which might be expected to fall, and by the use of modern fire-fighting apparatus properly disposed and operated by personnel trained to meet the requirements of nuclear warfare.

Injuries from Visible, Ultra-Violet, and Thermal Radiation

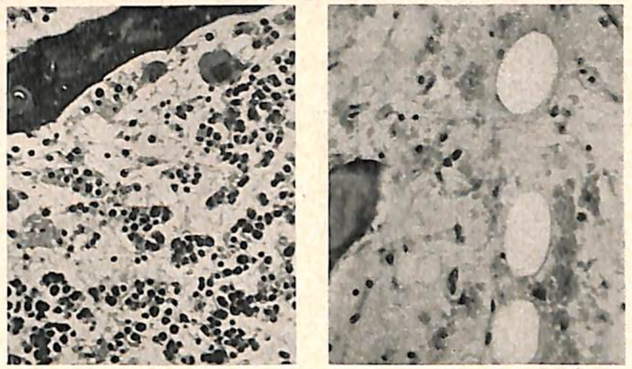
The only effect of the visible radiation is to cause temporary blindness. The chief effect of the ultra-violet is to produce burns much like sunburn.

The outstanding harmful agent among the optical and near-optical radiations (in the case of an aerial detonation) is the infra-red. When infra-red radiation is absorbed by matter, it rapidly heats the surface of the object exposed. Many people in Japan were injured from this cause, receiving burns ranging from slight reddening of the skin to major third-degree burns. Burns produced by the infra-red rays (and those caused by envelopment by the hot gases of the fireball) are known as flash burns, in contrast to those produced by fires, which are called flame burns. One rather curious phenomenon observed in Japan was due to the fact that dark material absorbs infra-red more readily than light-colored material. Often victims displayed burns which faithfully reproduced the artistic design patterns woven into or printed on their clothing; the burns were more severe on those portions of the skin directly under the dark-colored material. It is to be noted that in some cases the dark material charred and burned, adding flame burns of the skin to the flash burns. The effect of infra-red radiation probably extends to greater radius in an aerial detonation than any other agent. Fortunately, however, it is of importance only to those directly-exposed; relatively-thin clothing (such as Army summer khaki) especially if it is light colored or has a glossy surface, will furnish adequate protection.

The Effects of Ionizing Nuclear Radiations on Tissue

All the injuries so far discussed are encountered in association with the detonation of large charges of ordinary explosive, though never to as great a degree. The new element in warfare is the inclusion of ionizing or nuclear radiation as an agent of offense. Injury from such radiations are well-known in civilian life, but they have never before been used as a weapon.

The harmful effects of ionizing radiations (α-particles, β-particles, γ-rays, neutrons, etc.) all result from the ionization produced in the cells of the exposed tissues. Cells may either be killed outright by this ionization, injured to die later, or be injured without death to recover completely later. We don't know exactly what biochemical or bio-physical changes are involved in the injury or which parts of the cell structures are most affected, but we do know these changes are due to ionization, and



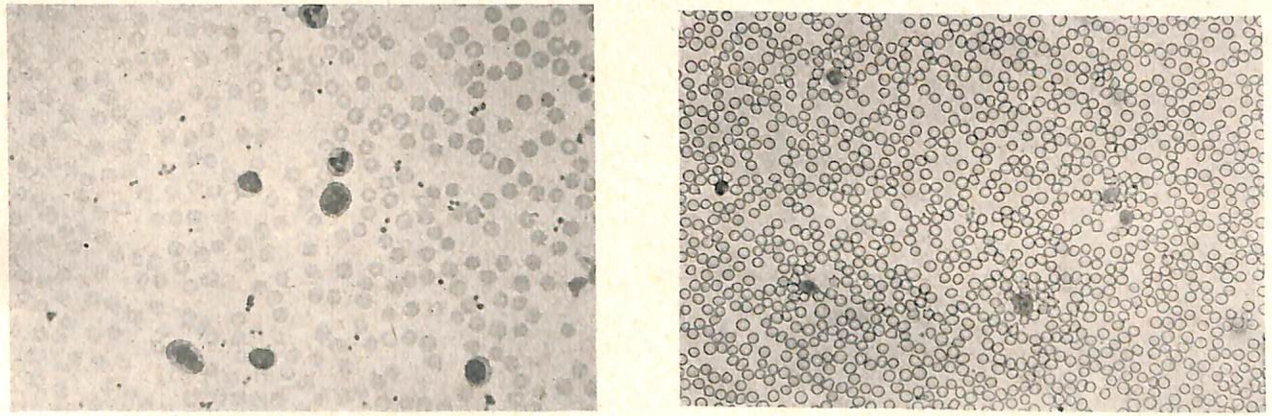
Impairment of the blood-forming processes in radiation sickness. On the left, a microscopic view of a section of normal bone-marrow of a pig. The numerous back spots are white blood-cells in various states of formation, selectively stained by dyes, and hence appearing black. On the right, a similar section from a pig with radiation sickness. Almost no white cells are being generated. (Photos made expressly for this article by the U.S. Naval Medical Research Institute.)

we do know that this ionization impairs cell functions.

The different ionizing radiations do not differ in the basic nature of the effect produced on a given cell, although there is some difference in the degree of this effect—neutrons have been estimated to be some fifty times, and X- or γ-rays some five times as effective as β-rays, although this is only a rough estimate. In informal terms, we might say a given cell can't tell whether it was hit by α-rays, β-rays, γ-rays, neutrons, or X-rays, or whether these rays were produced in an A-bomb explosion, an atom-smasher in a physicist's laboratory, or an X-ray machine in a doctor's office—it only knows it has been ionized.

The different sets of symptoms which result from exposure to different types of radiation are actually due to the fact that these radiations differ in their ability to reach different tissues. Weak β-rays do not penetrate deeply into matter, so that the effect of exposure to β-rays from outside the body is a slight reddening of the skin. The deeply-penetrating γ-rays, however, are able to reach the internal tissues, and produce systematic reactions such as anemia, with associated symptoms of quite another kind. At first glance, therefore, one might be lead to believe (at least from the standpoint of external exposure) that β-rays react differently on tissue from γ-rays, although we know they both react in the same way, by causing ionization in the cells. Another important factor in determining the type of symptoms exhibited is the variation in the sensitivity of different kinds of cells to ionizing radiations. The cells in the blood-forming tissues (and to some extent the mature cells in the blood) appear to be the most sensitive, followed by the sex cells in the genital organs. The cells of the hair and skin tissues are somewhat less sensitive. The muscle tissues are somewhat resistant and the brain cells particularly resistant to nuclear radiations. In general, too, the less mature a cell is, the more sensitive it is.

The point is, the *symptoms and physiological reactions observed depend on the type of radiations, the ionizing power of the radiations, the quantity of radiations which were able to reach the tissues, and the sensitivity of the tissues to radiation.* In the example of external exposure just presented, for example, the β-rays were only able to reach the skin cells, and the only symptoms observed resulted from injury to these cells. The γ-rays were able to reach the internal tissues. Injury to the sex cells and the



Microscopic views of stained blood smears. Normal human blood apears on the left, and blood from a pig with radiation sickness on the right. On the left, the red blood cells appear as numerous, light-gray disks, and seven white blood cells are visible. The latter are almost colorless in their natural state, but have been selectively stained by dyes to make them stand out, so as to appear dark-gray. The small "specks" are the blood platelets or thrombocytes. One of the most important ways of diagnosing radiation sickness is by making studies of the blood, and noting changes in the number and characteristics of the various blood cells (including the several varieties of white cells); the decrease in the number of white blood cells, the most characteristic feature, cannot be shown in a single microscopic field of view, and the count must be taken over the whole smear. (Photos made expressly for this article by the U.S. Naval Medical Research Institute).

blood-forming tissues of the bones caused by the γ-rays produced a reaction on the systems of the body; this reaction caused the symptoms noted.

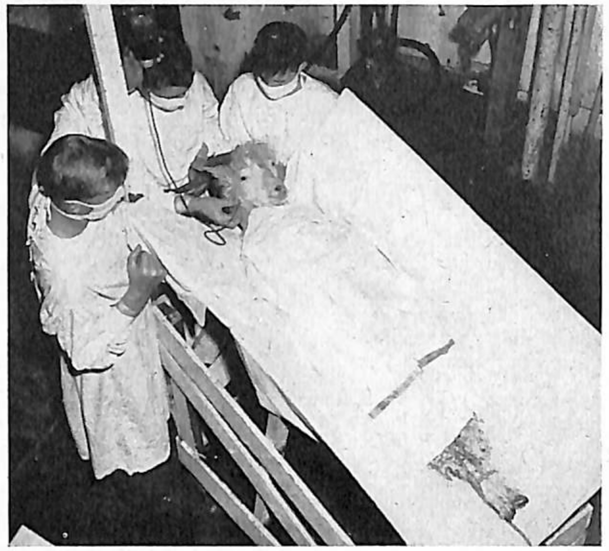
Other, less-sensitive tissues also reached by the same γ-radiation would clearly not be affected to the same extent, and symptoms associated with injury to them would be less-evident or absent entirely. On the other hand, if β-ray-emitting fission products which are bone-seekers are absorbed into the body, they may also reach the blood-forming tissues and injure them in much the same way as the γ-rays. Thus, we should approach the subject of injuries from nuclear radiation by thinking along the lines given in the above, italicized sentence.

Because the effects of nuclear radiations depend to such an extent on what tissues they are able to reach, the exposure hazards may be divided into two clear-cut categories of the greatest importance: external and internal. Knowledge of the nature and existence of both is essential to an understanding of the dangers of radioactivity, of how harm may be sustained from radioactivity, and of how to avoid or minimize the harm. The external hazard is the danger of radiations from sources outside the body. The danger of prompt γ-radiation from an exploding A-bomb in an aerial detonation, or the external β- and γ-rays from fission products in the region of the base surge, are examples. The internal hazard is the danger of radiations from radioactive substances absorbed into the body. The hazard of particles of α-emitting plutonium or U-235, or of particles of fission products, absorbed by breathing or swallowing, are examples.

With these facts about the effects of nuclear radiations on living tissue at our disposal, we are ready to review the types of injuries they produce in exposed personnel.

Radiation injury. Radiation injury consists of damage to local tissues of the body, such that general reactions on the whole system of the body do not result. It may be produced by α-, β-, γ-, or similar radiations, and the onset is usually slow. Prolonged and repeated exposure to X-rays over a period of years, doctors well know, will produce local skin cancer or changes in the fingernails and fingerprints, for example. There was little evidence of radiation injury in Japan, unless we view the loss of hair observed in the victims as radiation injury. What part radiation injury would play in an underwater detonation is not known.

Radiation sickness.[1] Radiation sickness, in its specialized medical sense, is illness produced by exposure to penetrating ionizing radiations generated by a source external to the body, in which the injury is such as to produce a reaction on the overall system of the body.



The Navy studies ways of improving treatment of radiation sickness. TOP—A goat exposed at Bikini, a little bewildered by all the attention it is getting, receives blood plasma. BOTTOM—A mother and her litter from a group of white rats exposed at Bikini. Genetic effects are beng studied, but most experts do not feel that the bomb would produce abnormal monsters in the descendents of those exposed. (Joint Army-Navy Task Force One.)

It may be produced by X-rays (especially "hard" X-rays of short wavelength), by γ-rays, and by fast neutrons. The role of β-rays, especially in cases of close proximity to radioactive contaminants, is not too certain. Radiation sickness is a characteristic result of an atomic-bomb explosion, especially in an aerial detonation, chiefly because of the γ-radiation, but was well known to medical men before Hiroshima. It is not a new disease produced by the bomb. It was first seen a generation or so ago among physicists and doctors who were working with the then-new X-ray machines and radium. Having no precedent to guide them, and not realizing the danger of inadequate shielding, these pioneers, unlike modern workers, blithely worked away with little or no protection, and showed the results. Occasionally radiation sickness is seen in certain industries using X-ray machines to discover flaws in metal castings, or may be encountered as a consequence of X-ray (also called roentgen-ray) therapy. Radiation sickness has been carefully studied; indeed, many diseases are not as easily diagnosed or so fully understood. The atomic bomb explosions in Japan added little to our knowledge of the basic facts of radiation sickness, but did extend our data.

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[1] The presence of other injuries, such as flash-burn or broken bones, considerably complicates the clinical picture of radiation sickness. For this reason, the discussion below is based on data from victims at Hiroshima and Nagasaki who were injured by nuclear radiation alone.

Radiation sickness caused a surprisingly-small percentage of deaths in Japan. It has been estimated that if γ-radiation had been absent from the Hiroshima and Nagasaki explosions, the total casualties would have been only five to seven percent less. Radiation sickness might be a larger factor in causing death, in other circumstances, of course.

In the Japanese who received the heaviest dosage, severe shock, severe weakness, and prostration were about the only symptoms evident. These victims died in a few hours. There seems to be an overall effect on the cells of the body, in contrast to injury to specific tissues. This type of radiation sickness, produced by an overwhelming dose of radiation, had been seen in human beings only in rare instances before Hiroshima.

In less-severe cases, the injury was selective. Certain tissues which were most radio-sensitive were the most impaired, and in general the reactions on the systems and the associated symptoms were the result of impairment of the functions of these tissues.

The majority of the bomb victims with this less severe form of radiation sickness experienced nausea immediately after the bombing, but this went away, and they felt no further ill effects until several days or weeks later, when they began to complain of general weakness and lassitude, and possibly loss of hair. In general, the more severe the exposure the sooner the delayed symptoms appeared, and the sooner death took place in those who did not survive.

One of the outstanding features of the less-severe type is disturbance of the digestive or gastro-intestinal system. Nausea and diarrhea are characteristic.

In all victims sufficiently-strongly exposed to produce systemic reactions, loss of hair was seen. This loss of hair chiefly occurred on the top of the head, but was temporary in most cases, a soft fuzzy down appearing after a month or so.

Injury to the sex-cells produced sterility in the Japanese, *believed to be temporary*. Sterility must be distinguished from sexual impotence (or frigidity, as it is called in women): Sexual impotence or frigidity is the constitutional or psychological inability to engage in sexual intercourse. It occurred in Japan only in those with pronounced weakness and lassitude. Sterility is the inability to conceive children, although intercourse be carried out, because of the absence or weakness of the active germ cells.

There is no specific, primary treatment for radiation sickness in the sense that quinine or atabrine are specific for malaria. Treatment consists in supporting the natural recuperative processes in the body, and aiding it in combating infection: whole-blood transfusions, penicillin, sulfa drugs, streptomycin, vitamines, rest, good food, and aseptic and antiseptic conditions. Evidence of the regeneration of the blood-forming tissues was evident in most of the Japanese who survived beyond six weeks or so. In general, the more severe the exposure, the longer the interval of recovery.

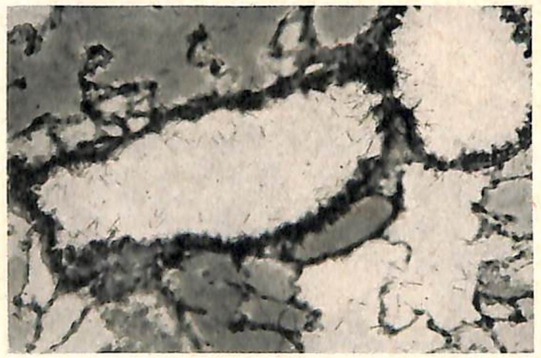
Radioactive poisoning. Radioactive poisoning is the harmful result of the absorption of radioactive substances into the body, where localized injuries, or general reaction on the system, or both, are produced. It is the internal hazard. The onset is usually slow and subtle in making its appearance—may, indeed, not appear until years after absorption of radioactive contaminants. Radioactive poisoning may be produced by α-, β-, or γ-emitters. Alpha-emitters are not a hazard from an external standpoint, since the weakly-penetrating (but not weakly-ionizing) α-rays are all stopped by the horny cells of the outer layer of the skin. If the α-emitters are carried into the body, however, the weak penetration no longer is a protective factor, since the rays have "penetrated" by the very act of absorption of the α-emitter. The great ionizing power of α-rays then produces dense ionization, so that radioactive poisoning has become chiefly associated with α-emitters. β-and γ-emitters must not be lost sight of, however.

Like radiation injuries and radiation sickness, radioactive poisoning has been known in civilian life for years. It was first seen about a generation ago, when an unusual and suspiciously-high number of deaths from anemia and bone cancer were observed among the workers who painted the luminous dials of wristwatches and clocks with paint containing radium. Investigation revealed that it was the habit of these factory workers to point their small paintbrushes by wetting them with the lips, thus affording the radium a portal of entry into the body. A high incidence of lung cancer was also reported among the workers in the radium mines of Schneeburg and Joachimstal and other places in the vicinity of southern Germany and Austria.

Radioactive contaminants may be absorbed into the body through an open wound, by swallowing, or breathing. When radium is swallowed, most of it is excreted, but some eventually reaches the bones. Since the blood-forming tissues in the bone marrow are very radio-sensitive, we can readily understand the resulting anemia. The intense tissue bombardment by α-rays is a constant irritant, and bone cancers and tumors are also a consequence. If particles of radium-bearing material are breathed into the lungs, little effect is noted on the blood-forming tissue, since that is located in the bone marrow and not the lungs; here, the chief result is lung cancer. If radioactive contaminants are present in a region, it is exceedingly easy to absorb dangerous radioactive substances which may fall on food or lodge on particles of tobacco or other smoke, unless care is taken.

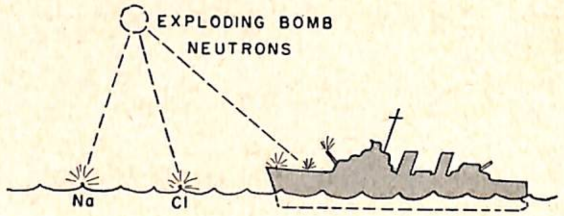
Radioactive contaminants may be swallowed or breathed in with ease unless proper care is taken. That is the reason for this sign prohibiting smoking on an exposed Bikini target ship. (Joint Army-Navy Task Force One.)

When an atom-bomb explodes, not all of the fissionable material undergoes fission, and particles of plutonium or U-235 may be scattered about in the vicinity. Both are long-life α-emitters and have, in experimental animals, produced radioactive poisoning similar to that of radium poisoning. We are fortunate to be able to reproduce a figure which shows the tracks of α-particles from plutonium in the lung tissue of an experimental animal. Here we see radioactive poisoning in the process of happening. Note the short but dense tracks. It behooves everyone to follow the instructions of the Medical and Radiological Officers implicitly, for there is no known treatment for poisoning by radium or radium-like material.

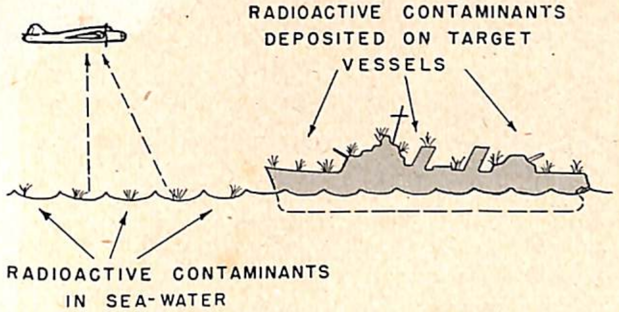


Radioactivity poisoning by plutonium in the process of happening. Plutonium emits α-rays, and particles of unfissioned plutonium may be present in a region where an A-bomb has been detonated. This photograph shows a microscopic view of a section of lung tissue from a white rat which had breathed in plutonium oxide. The numerous small tracks are the paths of the α-rays. (Courtesy of Dr. J. G. Hamilton and Miss D. J. Axelrod of the University of California, and the *U.S. Naval Medical Bulletin.*)

The reaction to β- and γ-ray emitters depends on many factors. Different radioactive fission products may wander into different organs, and will produce results depending on the range and ionizing power of the radiation, the organ or tissues reached, the radio-sensitivity of the cells of these tissues, and the length of time the tissues are exposed to the radiation from the absorbed contaminant. If the bone marrow is affected, anemia may result, as well as bone tumors. Cancers may appear in other organs. Such long-lived radioactive fission products as Sr^{90}, C^{14}, Cs^{135}, Cs^{137}, Sb^{125}, and Ce^{144} may be involved.



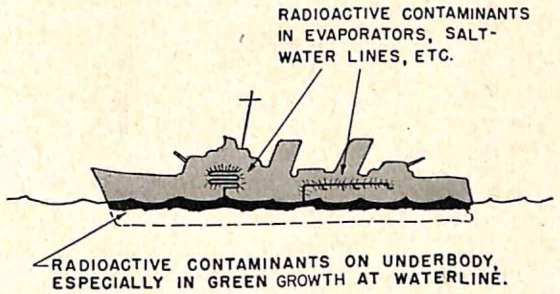
Induced radioactivity. In this and the following drawings, what looks like eelgrass growing on the ships and surface of the water is a diagrammatic representation of the presence of radiating radioactive substances. Neutrons emitted at the instant of detonation are able to induce artificial radioactivity in certain substances, just as in an atom-smashing laboratory. Among these substances are metals containing copper, bronze or manganese, certain soils and drugs, phosphorus, sodium, and even the gold of one's teeth. Sodium is particularly susceptible, and is present in sea-water, soap, table salt, and baking soda. In an underwater blast most of the neutrons are absorbed by sea-water, with radioactivity being induced in the sodium, etc. Radioactive sodium emits β- and γ-rays, but has a short half-life, and is relatively harmless after a few days. In general, induced radioactivity is not as important as radioactive contamination such as fall-out. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery.)



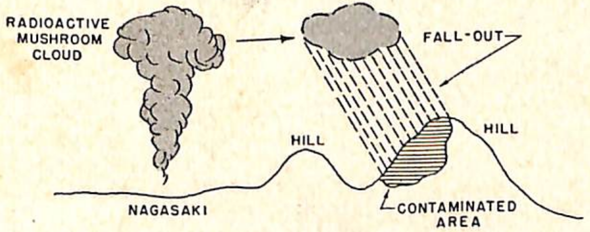
Radioactive contaminants (unfissioned bomb material and fission-products) in an underwater detonation. Residual radioactivity produces a combination of internal and external hazards. Gamma-rays may be measured early by planes at an altitude of several thousand feet, as shown, and dangerous areas detected. Another aspect of contamination is the necessity of making certain that contaminants are not picked up on one's feet, etc., and carried to a "clean" region, thus contaminating it. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery.)

Some Factors Concerning the Manner of Exposure to Nuclear Radiations

The majority of the nuclear radiations are emitted at the instant of the explosion. The amounts radiated are so much greater than any produced in any laboratory that the intensity a few thousand feet away from an exploding aerial A-bomb may be great enough to produce injury. The remaining portion is emitted as delayed radiation from the fission products, and from any substance rendered artificially radioactive by the spray of neutrons.

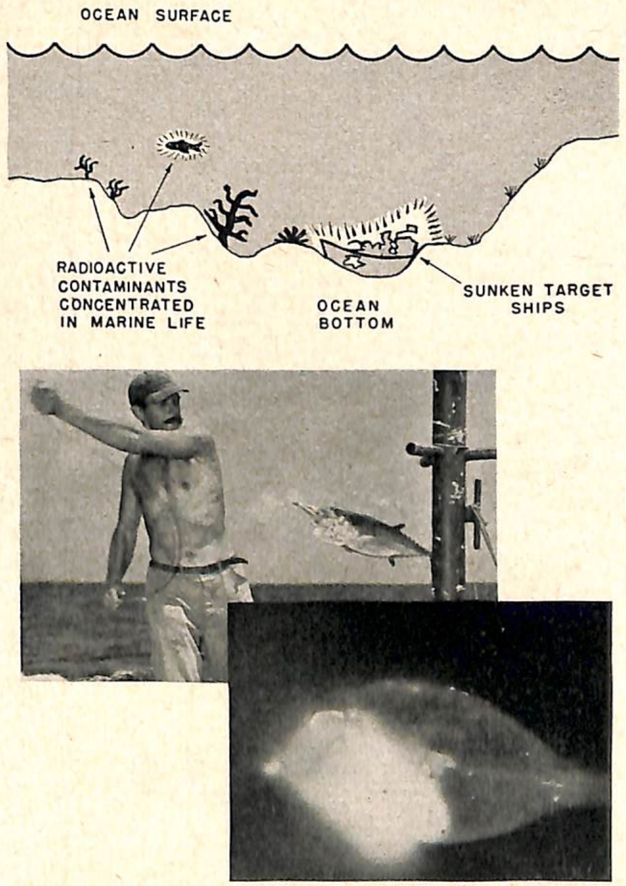


A vessel may pick up radioactive substances by sailing through a contaminated region. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery.)



Fall-out from mushroom cloud in an air detonation. An air blast is self-cleansing; unfissioned bomb material and fission products are carried away from the site of the explosion in the cloud, and immediately start to settle out. At Alamagordo, Hiroshima, Nagasaki, and Bikini, this fall out from the aerial detonation was not a serious hazard. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery.)

The intensity of the delayed radiation is considerably weaker, so that it is entirely harmless a few thousand feet away. In close proximity to the fission products, however, the local intensity is high and lethal. Proximity to the radioactive substances enhances their deadly effectiveness. An airplane pilot flying through the mushroom cloud or a sailor on the deck of a ship in the region of

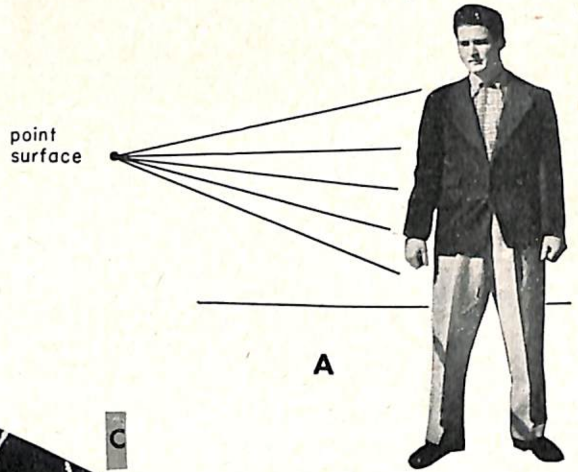


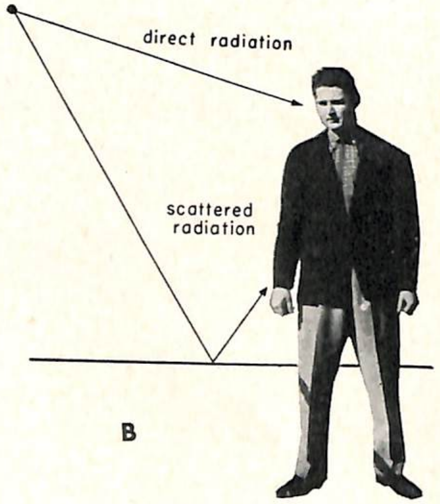
TOP—Residual contaminants from an underwater detonation concentrated by marine life and settled on the ocean floor. BOTTOM—A be-moustached commercial fisherman catches a fish at Bikini for studies of the effect of radioactivity on marine life. Such absorbed contaminants are shown by the glow in the internal organs of the fish. A potential hazard is present for divers and others. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery) and (Joint Army-Navy Task Force One.)

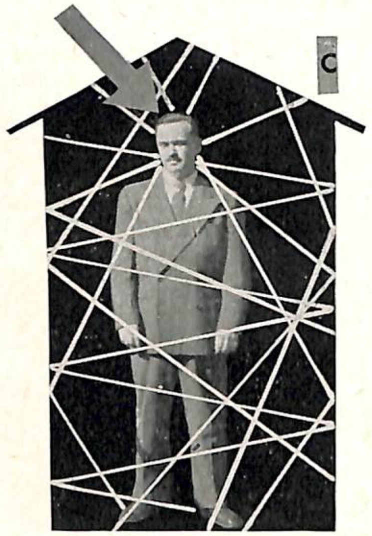
the base surge would encounter intensities far in excess of the maximum permissible tolerance—probably fatally so.

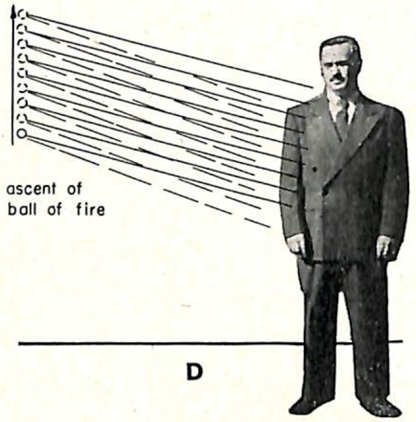
In an aerial blast most of the danger from radioactivity exists at the instant of detonation. The mushroom cloud transports away the major portion of the radioactive substances, leaving little residual activity. Hence, an aerial detonation is said to be *selfcleansing*. In contrast, an underwater explosion presents relatively little danger from radioactivity at the instant of the explosion, because of absorption by the ocean. However, it is not self-cleansing, and the hazard of residual radioactive contamination is serious. The proper use of radiac equipment for surveying and monitoring becames all-important. We wish to emphasize again that in an air blast the danger from nuclear radiations comes from the primary burst of gamma rays, and that in an underwater detonation the danger comes from radioactive contaminants, not from the primary blast.

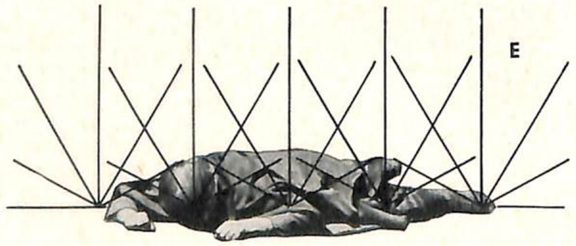
It is customary in discussing the manner in which a person may be exposed to external radiation to speak of the "geometry" of the radiation. This takes into account the way in which the radiation flux is distributed in space as it falls on the individual. A man exposed in the open to the prompt γ-rays and neutrons of an aerial blast, for example, would, except for the effect of scattering, receive radiation on the side facing the bomb. Another individual in a mist uniformly contaminated with, say, γ-ray-emitting fission products, would receive radiation on all sides.

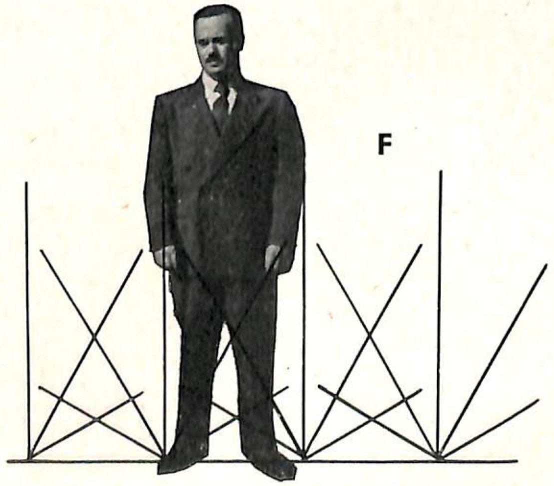




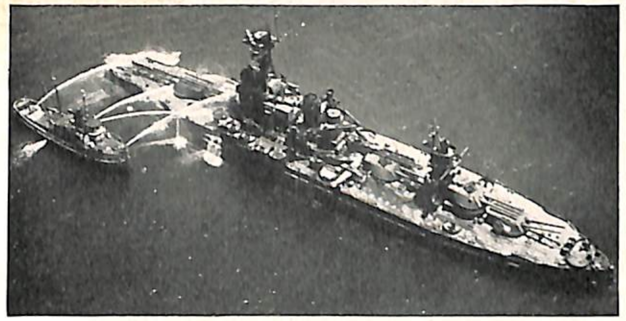








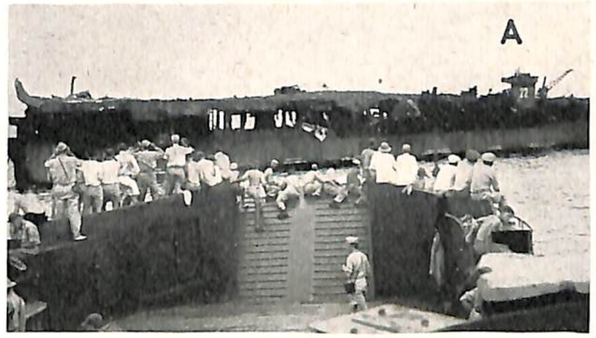
Some examples of aspects of the "geometry of the radiation". (A) At the instant of detonation of an aerial A-bomb, a person would receive radiation on one side of the body from a "point source." This situation is chiefly theoretical, scattered radiation adding to the direct point-source radiation (B). In (C) is shown a victim in a building, receiving radiation on all sides because of scattering. This scattered radiation may build up to a fatal level in a case where the direct radiation alone might not have been fatal. In (D) is shown how the ascent of the fireball may increase exposure. In (E) and (F) we see radiation from contaminants deposited on a deck. The man in (B) is receiving a heavier dose than in (A), since a greater portion of his body is exposed to radiation of the same intensity. (Adapted with permission from NAVMED P-1283, the *Manual of Radiological Safety* of the Bureau of Medicine and Surgery.)

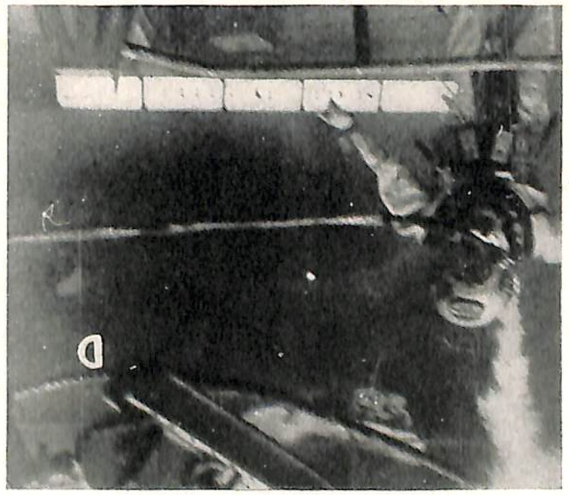


Cleaning a Bikini target vessel of radioactive contaminants *(USS New York)* before boarding her for studies of bomb damage. In an underwater detonation, contamination is a serious probem. (Joint Army-Navy Task Force One.)

Very intense beams of external, penetrating radiation may occasionally be applied to very small areas of the body without lasting harm, as in X-ray therapy. These are, however, very carefully-controlled special cases, and do not allow us to relax our standards of radiological safety. Exposure is usually over a greater area. For peace time, the official maximum permissible dose of external, penetrating, ionizing radiation is 0.1 roentgen total accumulated in any 24-hour period over the whole body. Four hundred roentgen would probably be fatal to most people, but, below twenty-five, lasting damage is improbable.

There is a great deal of evidence to show that the total amount of radiation accumulated during the period of exposure over the whole body is more important in determining the extent of the injury than the length of time within which the radiation was received. Thus, the injury from a 100-roentgen dose received in one-thousandth of a second would be about the same as a 100-roentgen dose accumulated over a period of several weeks. When exposure is over a period of years, the healing processes of the body may nullify the damage, and invalidate this statement. Since the amount of accumulated radiation is the chief determinant of the seriousness of the injury, it is clearly vital to have radiac





Atomic-bomb ship damage (Bikini). (A) the public views the damage from the A-bomb. Newspaper correspondents at Bikini observe damage to a carrier in the "Able" blast. (B) Close-up damage to the *USS Skate* ("Able"). (C) End of the veteran "Sara". The *USS Saratoga* sinks seven hours after the "Baker" blast—too "hot" to board for repairs. (D) Studying bomb damage 185 feet below. (*USS Carlisle* "Able" blast). (Joint Army-Navy Task Force One.)

equipments which record the total integrated sum of all the dosages received. Fortunately, suitable radiac equipments are now available.

As far as the internal hazard is concerned, the maximum permissible tolerance of radium-like substances (including α-emitters like plutonium and U-235) is usually stated as one-millionth of a gram during an entire lifetime.

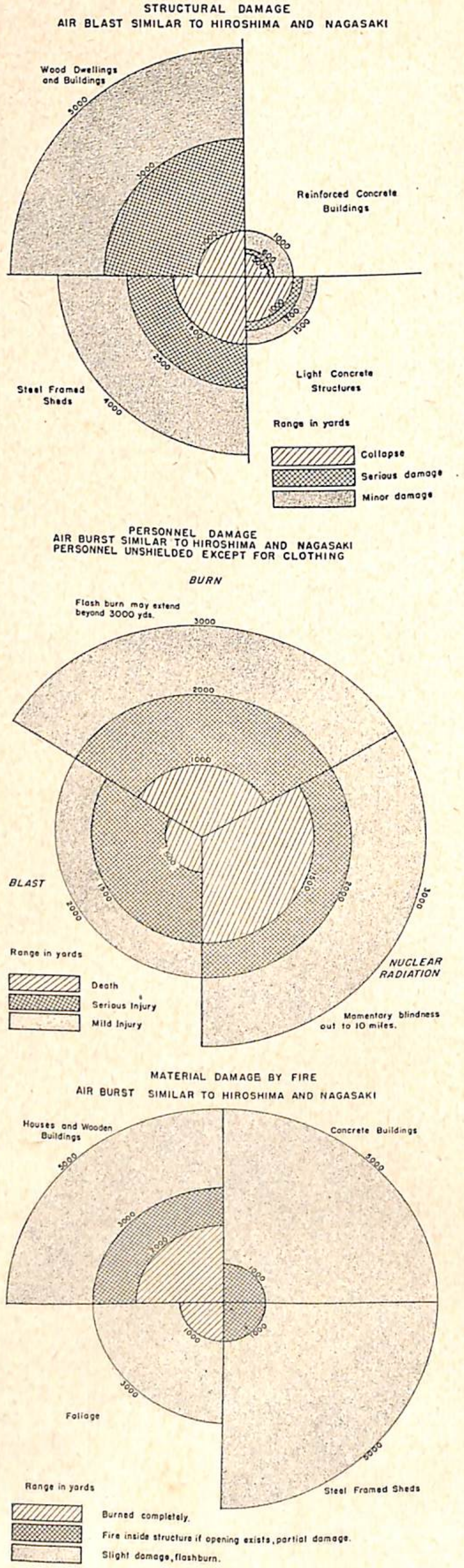
Radiation hazards, we have emphasized, are of two types: external and internal. Sometimes the hazard is external, sometimes it is internal, and sometimes it is a combination of both. It is essential to understand the hazards; the accompanying diagrams from the Radiological Safety Manual of BuMed (P–1283) visually describe some of the ways in which these hazards might be encountered, and special attention should be paid to them.

The Psychology of Atomic Warfare

There is no question about it: the atom bomb can produce a great deal of damage. In its wake, it may leave latent dangers which are unseen, and hence all the more hazardous. Nuclear warfare is so new, however, and the bomb so dramatic, that *it is difficult for us to see them in their proper perspective.* Rational thinking and feeling is imperative. Irrational, panicky fears should be recognized and rendered impotent by calm, dispassionate separation of fact from fantasy. Real dangers can then be understood, realistically faced, and measures undertaken to counteract them. Only a thorough indoctrination into the facts of nucleonics will lead a man through the morass of thinking on a subject as new as nuclear warfare.

It is related, for example, that when steam power plants were first built, the workers in the plants had many unrealistic fears that the plant boilers would blow up. After they became accustomed to the fact that, while improperly constructed boilers may blow up, properly built and operated boilers will not, their fears disappeared. The situation is exactly the same here.

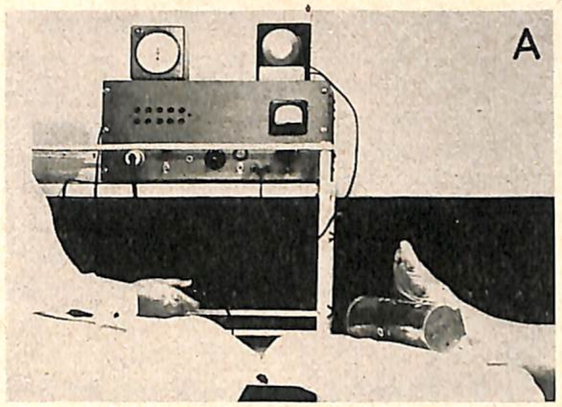
We can avoid a lot of unnecessary panic by properly identifying explosions. There have been many large explosions, such as the Texas City disaster a few years ago, but no atomic bomb was involved. If we can identify explosions properly, we may squelch unnecessary panic due to the assumption that because a large explosion has occurred, it must have been caused by an atomic bomb. It is helpful, for example, to remember that, in general, *the hazards typical of the atom bomb were all well-known* (though not necessarily in military life) *before it first appeared.* What is new is the intensity of the phenomena. Moreover, it is probable that unreasoning panic was felt when every new kind of weapon first came on the scene. When cannon were first trained on formerly impregnable Medieval castles, and thunderously brought down their high walls in rubble, the defenders must have felt just as keen a panic as did the Japanese.

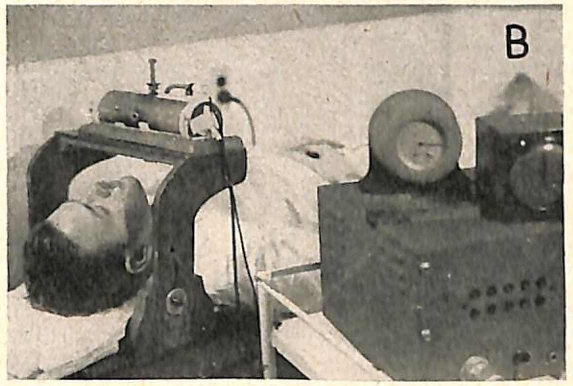


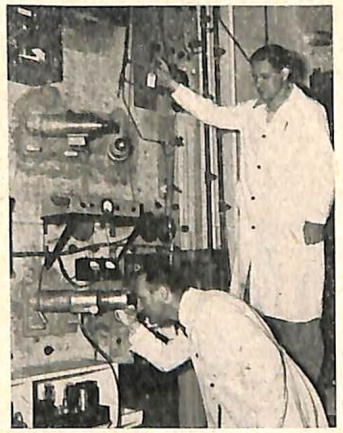
Range of A-bomb damage. (Reprinted with permission from USF 85, *Manual of Radiological Safety* of the Office of the Chief of Naval Operations.)

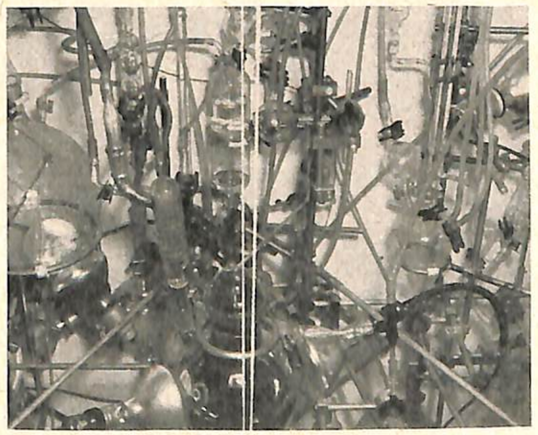
When man became accustomed to each new weapon, and could see it for what it was (as well as for what it wasn't), he was able to rationally approach the task of counteracting it. Knowledge conquers fear of the unknown. In addition, a part of the picture is the practical civilian and military benefits to come from the distribution to factory, laboratory, and hospital of useful radioactive materials, available in quantity from the nuclear pile. Distorted perspective will be corrected by understanding, by education, and by the passage of time.

A middle course must be followed between overemphasizing the danger of radioactive contamination and discounting it. When it is dangerous, it is *intensely* dangerous, as dangerous as a stick of dynamite with a burning fuse. The fuse can be snuffed out; dangerous radiations from radioactive contaminants *can* be detected with the help of radiac equipment. As an example of what can be done with proper precautions, skilled and responsible supervision, and suitable monitoring, we are glad to report that, in spite of the large numbers of people involved in our atomic energy factories, potentially one of the most dangerous spots in the world, *not one single case of injury from radiations was reported up through October 1947!* The A.E.C. accident rate was









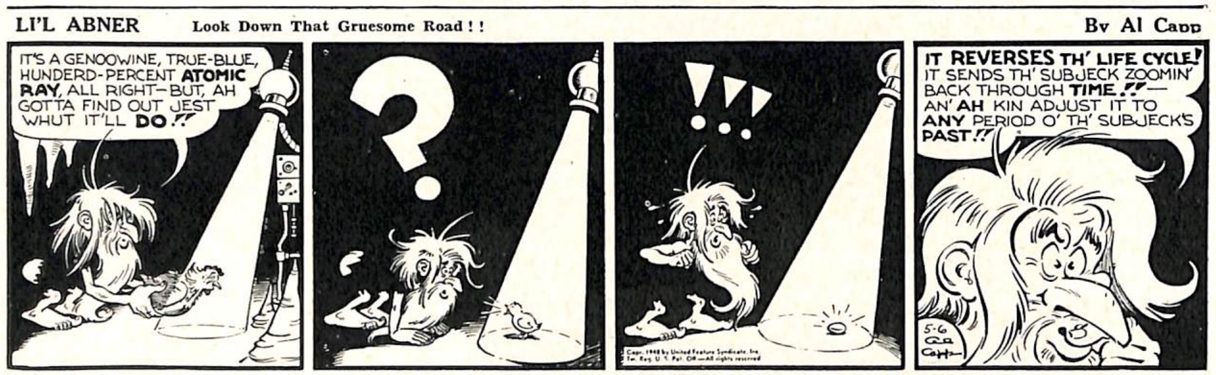
As much a part of the story of atomic energy (and of more ultimate importance) as the bomb damage just surveyed, are the beneficial uses of artificially-radioactive isotopes produced for peacetime use in atom-smashing and in the bomb plants. We are on the threshold of the atomic age. In (A) and (B) we are present at the birth of the beneficial uses of atomic energy. These two photos were graciously supplied by Dr. Edith H. Quimby of Columbia University, a pioneer in the application of radioactive isotopes to medicine. (A) shows the use of artificially-radioactive sodium in improved diagnosis of impaired blood circulation in the leg. The Geiger-Mueller counter placed in the patient's foot detects a radio-sodium salt injected into the blood stream. (B) shows the use of radio-iodine in cases of thyroid disease. The remaining photos show steps in the chemical separation of radio-isotopes at the bomb plants. Processing goes on behind thick concrete walls, and is watched by using special periscopes. (Dr. Edith H. Quimby, and *Radiology* magazine) and (U.S. Atomic Energy Commission.)

the lowest of any industry in the United States. This was the happy result of a safety regime which was probably more strict than any the world had ever seen. In wartime attack, of course, this would be impossible. The point is that the effects of dangerous radiations may be counteracted in many cases, if they are detected by radiac equipments operated under mature, responsible, and informed supervision by mature, informed, and responsible personnel, and if proper procedures are carried out. Radiac equipment can help tell us of the danger before it becomes harmful. Radioactivity is like nitroglycerin: safe when properly handled, and cataclysmically dangerous when it is not.

Radiac Equipment for Detecting Nuclear Radiations

General

Nuclear radiations are detected by observing the secondary phenomena they initiate—chiefly ionization. The principal nuclear radiations which radiac equipment must detect are α, β, and γ radiations. In the future, it may be necessary to develop radiac equipment capable of detecting nuclear radiations other than those listed above.



Radiac equipments in the comic strips: The statements made in this cartoon do not constitute official policy of the Bureau of Ships! The atomic-ray machine developed by the "Li'l Abner cartoon character "Ole Man Mose" was made from a "busted sewing machine, 712 box-tops, a auty-matic butter-churner, and the wreck of the old "97.". He says, "them stoopid amachoors at Oak Ridge lot will be mighty hoomiliated when they hears 'bout this!!" (Courtesy of Mr. Al Capp, the cartoonist; reprinted by permission of United Features Syndicate, Inc.)

To detect these radiations, the following devices are utilized:

1—electroscopes.
2—ionization chambers.
3—proportional counters.
4—Geiger-Mueller tubes.
5—photographic film badges[1].
6—scintillation-photomultiplier counters.

The first four devices are all based on the ionization developed in a volume of gas through which the radiations are passing. Ionization is defined as the process of stripping off one or more electrons from a neutral atom.[2] Charged electrodes collect the electrons and ions produced during the ionization process. The resulting currents indicate the presence of nuclear radiation. We will have much to say later about how these devices are employed in radiac equipment. The next device in the list relies on the fact that, in a photographic emulsion, ionization developed by nuclear particles has the property of activating silver halide grains just like visible light rays. When the emulsion is chemically developed in the darkroom, the presence of nuclear radiations is shown by a darkening of the film, which, under the powerful objective lens of a microscope, takes on the appearance of a pattern of streaks, the individual tracks of the particles. The last device in the list is based on a phenomenon familiar to us in everyday experience in our luminous radium watch dials. Under the impact of nuclear radiations, notably α-particles, screens coated with certain substances scintillate or flash at the point of collision. Zinc sulfide is a commonly-employed example of such a fluorescent substance.

Most radiac equipments have chambers which enclose the gas in which ionization currents are produced by the surrounding radiations. Into these chambers, gamma-rays penetrate matter very easily, so that no special windows have to be built into radiac equipment to admit them into the measuring space; they enter anyway. With β-rays and α-rays, however, apertures covered with thin sheets of glass, mica, plastic, or aluminum must be provided in hermetically-sealed units. These films are of the order of a few thousandths of an inch thick for α-rays, and only a few ten-thousandths of an inch for β-rays. By including shields on these windows, we can separate the radiations. With the shields off, the reading of a certain radiac equipment will, for example, be a measure of combined α-, β-, and γ-radiation. Moving the first shield into position eliminates the α-rays, and the reading is now a measure of combined β- and γ-radiation. Inserting a thicker shield eliminates both α- and β-particles, and the reading is of γ-rays alone. By subtracting readings then, we can obtain separate estimates of the amounts of α-, β-, and γ-radiation present.

Alpha-particles are energetic, but have a characteristically-short range, as we have emphasized. This means that, once admitted to the measuring volume through a very thin window, they will almost certainly come to rest and expend all their energy by ionization within the chamber. Every α-particle which penetrates will, in all probability, be detected. Beta-rays have a much longer range, so that fewer ions are developed per centimeter of path length. It is possible for a β-ray to enter the chamber, expend only a fraction of its energy in ionization, and leave the chamber with a still-appreciable quota of energy. Nuclear detecting devices, however, are usually designed in such a way that all but the most exceedingly energetic β-rays expend all their energy within the chamber. Thus every β-particle, too, which penetrates, will in all probability be detected, and all its energy utilized. In general, all α- and β-particles which penetrate are recorded. Here the chief problem is to get them inside the chamber.

The situation is somewhat different with γ-rays. They enter the chamber whether we like it or not. Here the problem is the opposite one, to get them to produce enough ionization so they can be detected at all. In spite of the fact that they may carry high energies, they have very long ranges, which is equivalent to saying that they produce a relatively small number of ions per centimeter of path length. In fact, 90-99% of the incident γ-rays will pass right through the chamber (just as if it were not there) and not produce any ionization at all. The relatively-small percentage of γ-rays which do produce ionization in the chamber expend only a small fraction of their potential quota of energy in the chamber, and pass out with their energy diminished only a little. How then, if γ-rays are so elusive, do we detect them? Well, fortunately, those few electrons produced by direct γ-ray ionization are high-speed electrons, fully capable of ionizing on their own. It is the ionization produced by these secondary electrons, be they ejected from the walls of the chamber or from the gas in the chamber itself, which we detect, and which betray to us the passage of γ-rays through the chamber. Much of the design of γ-ray detectors is concerned with increasing the number of these secondaries. In contrast to α- and β-ray detection, as has been metioned, we detect only a small fraction of all the γ-rays entering the chamber. But this is no hardship, for we may calibrate our radiac equipment with standard radioactive sources; moreover, only a fraction of the γ-rays falling on a person actually produce the injurious ionization, a situation which corresponds to that in our detecting devices[1].

Special techniques must be resorted to for detecting neutrons. Having no electric charge, they produce almost no direct ionization. It is necessary, therefore, to design radiac equipment in such a way that other characteristics of the neutron may be utilized to provide secondary ionization which can be measured. This is like "going around Robin Hood's barn," but such must be done. The usual stunt is to introduce a substance which becomes artificially radioactive upon neutron bombardment, emitting secondary radiations which are more-or-less strongly ionizing. Remember the boron-steel and cadmium control rods in the chain-reacting pile? Cadmium and boron nuclei capture neutrons readily, and have achieved popularity in this application. In any of the four types of gas-ionization detectors, for example, boron trifluoride gas is often added. The neutron collides with the boron nucleus, transmuting it into a speeding lithium nucleus, and freeing an α-particle (He nucleus)

$${}_0n^1 + {}_5B^{10} = {}_3Li^7 + ({}_2He^4)$$

Both the lithium nucleus and the α-particles are ionizing, and betray the presence of the neutrons. In a similar application to photographic film, the emulsion is impregnated with a boron compound, although a more common procedure is to place sheets of cadmium over the film. If it has not already been done, it is probable that boron compounds could also be used to sensitize fluorescent zinc-sulfide screens.

It will be shown that later radiac equipments indicate the presence of radiations in several different ways, supplying their data, as it were, in different styles. Some register individual sub-atomic events as they occur, such as the entrance of individual particles into the measuring chamber. With the Geiger-Mueller tube, for example, the arrival of individual particles is heralded by a series of pulses, which may be heard as a series of clicks in earphones, or used to actuate a rapid mechanical recorder, or even fed to the plates of a cathode-ray oscilloscope. Other radiac equipments indicate the average rate at which radiation is impinging on it at the moment. These are called count rate type equipment. The indication is furnished by the more-or-less steady deflection of the needle of a meter such as a milliammeter or microammeter. If the intensity of the radiation is not constant, the needle will shift slowly as the average rate varies. Geiger-Mueller tubes may be operated in this manner by feeding the series of pulses to a meter—perhaps with

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[1] *Photographic film badges are not radiac equipment. Radiac equipment is defined as equipment employing electronic devices.*

[2] *A negative ion may be formed by adding electrons.*

[1] *There are three ways electrons are produced when x-rays interact with matter. Submitted without further elaboration, they are: 1—photo-electric effect, 2—Compton effect, and 3—pair-formation. Those readers who are interested will find further details in more advanced expositions, such as "Radiological Defense, Vol. I."*

an R-C averaging-circuit—which wipes out the individual pulse variations.

Still other radiac equipments furnish a cumulative measurement, indicating the total amount of ionization developed in the chamber subsequent to the instant of time when it was set to begin recording. These are called integrating or cumulative type radiac equipment. The photographic film is an example of a cumulative recorder—a darkening in direct proportion to the total detectable radiation to which it has been exposed. Cumulative recorders are particularly-well adapted to evaluating the external exposure hazard leading to radiation sickness. Physiological injury of this type, it will be recalled, is chiefly dependent upon the total sum of the radiation falling on the body during the period of exposure, and it is just this quantity which the integrating meter evaluates. Incidentally, there is a certain amount of interchangeability in the functions of count-rate and integrating types of equipments, if the intensity of the radiation is constant. Clearly, multiplying the rate by the estimated time of exposure will supply an estimate of the total dose received, and dividing the reading of the integrating type by the time of exposure will give us the rate of dosage, if we want it.

The size and shapes of nuclear radiation detectors are legion. In general, almost all of the detectors of nuclear particles may be modified in some manner to indicate the presence of α- β- and γ-rays, and neutrons, although not necessarily at the same time. Requirements for field use, consisting as usual of ease of operation, dependability, relative ease of maintenance, light weight, ruggedness, small size, and portability, may eliminate some specific device from our consideration, however well-suited it may be for laboratory use. Among the uses of field equipments are:

1—Measurement of accumulated dosage for reasons of personnel safety.

2—Measurement of the rate of irradiation for rapid survey of ships, shore activities, etc., so that we may determine levels of activity or predict how long personnel may work in a given area before they must be evacuated.

3—Monitoring of air and water supplies.

4—Monitoring of personnel to determine if and to what extent they have become contaminated.

Radiation Detectors Based on Ionization in Gases

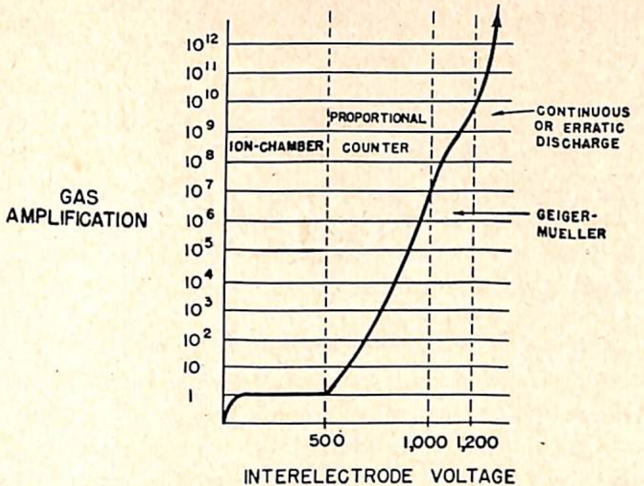
These detectors include the electroscope, the ionization-chamber, the proportional counter, and the Geiger-Mueller tubes. They are by far the most important class of radiac equipment in practical use at the present time.

When an atom of a gas is ionized, one of the outermost planetary electrons is pulled out of its orbit and escapes from the atom. The freed electron and the positive-ion left over comprise an *ion-pair.* Whatever the nature of the ionizing particle, be it another electron, an α-particle, or a γ-ray photon, the chief proviso for ionization upon collision is that the ionizing agent carry at least a certain critical energy. This energy varies for different gases and is 32.5 ev for air. If it has less than this amount, no ionization will occur—the particle will bounce from atom to atom, losing a little of its kinetic energy to each, until it comes to rest. If it has more than this energy, in air it will produce one ion-pair for each 32.5 ev it possesses. An α-particle of one Mev energy, for example—slow, heavy particles are strong ionizers—leaves no less than 30,000 ion-pairs in its wake in air, after it comes to rest! Now, if electrodes are inserted in the volume of gas, and are connected to sources of potential, they will collect the constituents of the ion-pairs—the electrons go to the positively-charged electrode or anode, and the positive-ions to the cathode. The resulting collected charge or the current produced by it will measure the ionization for us and hence the incident radiation. This is the principle of the above detectors.

If the voltage impressed on the electrodes is relatively small, we have an electroscope or ionization-chamber. If it is somewhat greater, we have a proportional-counter tube, and if it is greater still, in a rather narrow range, we have a Geiger-Mueller tube.

In the electroscope or ionization-chamber, the energy of each electron freed during each ionization event is relatively small and is not increased much by the accelerating electric field set up in the volume by the electrodes. No further secondary ionization by collision is produced by the freed electrons. In other words, all that happens is that ion-pairs are produced by the radiation, and are swept out of the volume and collected at the electrodes, without additional phenomena.

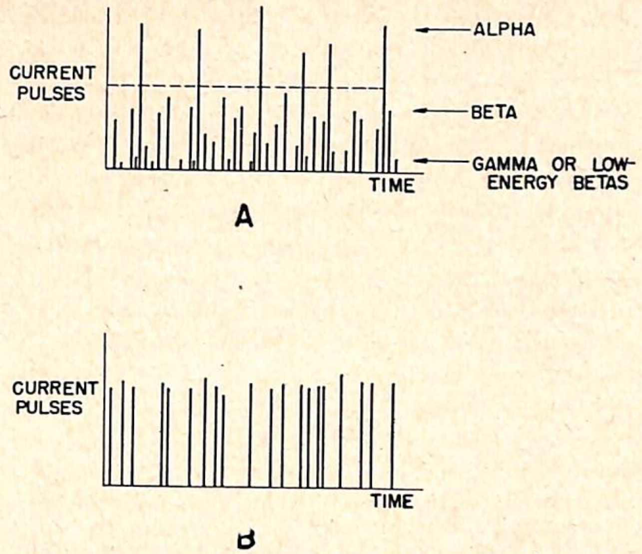
In the proportional counter and the Geiger-Mueller tube, however, there is a new phenomenon. Not only are electrons freed during each ionization event, but the accelerating field is now so great that the electrons of the ion-pairs speed up and acquire enough energy to cause ionization on their own. The resulting new quota of electrons also is capable of producing ionization in turn, and so on. The process is cumulative, and in a way is a chain-reaction. It is aptly and vividly described by the name *avalanche ionization.* Avalanche ionization increases the response enormously, producing *gas amplification,* as it is called. As much as one billion-fold amplification may be reached by this means, and is highly beneficial, for by utilization of this phenomenon exceptional sensitivity may be achieved in rugged field equipments. The gas amplification ranges from one to about ten million in the proportional counter, and perhaps ten million to a billion or more in the Geiger-Mueller tube. These figures will vary in practice, of course, but are representative. An accompanying illustration portrays graphically the distinction between radiac equipments functioning on the basis of ionization in gases.



Plot of gas-amplification factor vs. electrode voltage. Shows inter-relation of certain radiac devices.

In both the proportional counter and the Geiger-Mueller tube, the gas amplification is enhanced by constructing the anode in the shape of a thin wire, whereby an intense local electric field gradient is set up in the region of the wire. Each individual particle instigates a surge of current which enables that particle to be detected. In the proportional counter, indeed, the surge is roughly proportional to the ionizing power of the incident ionizing particle, thus enabling us to discriminate between and identify different types of particles. In the Geiger-Mueller tube, however, the gradient near the wire is so high that all incident particles produce the same current pulse strength, independent of their energy. So many electrons cluster around the wire that a local space charge is set up which limits the pulse size to one value. In the proportional counter each current surge dies out quickly, leaving the radiac equipment free to register the next particle. In the Geiger-Mueller tube, on the other hand, each discharge, once it is turned on by an incident particle or photon, will maintain itself as a continuous discharge (blanking out all subsequent particles), unless some means is provided to shut it off. Apparently the positive ion concentration near the cathode is so great as to rip electrons right out of the metal, thus supplying a source of electrons to maintain the discharge. Much of the design of Geiger-Mueller tubes or of the external circuitry is concerned with providing means to shut the discharge off in time.

To recapitulate, in the electroscope and the ionization-chamber, the electrons and positive ions formed by the ionizing radiation are swept out of the detecting chamber and collected at the electrodes without additional gas amplification. In both proportional counters and G-M tubes, individual particles can be detected, and are evidenced by surges of current which are built up to easily observable strength by gas amplification during avalanche ionization. In the proportional counter, the current surge is approximately proportional to the ionizing-power of the incident particle. In the G-M tube, however, the current surge is the same for detectable particles of all energies. In the latter device means must be provided to shut the discharge off in time to detect the next particle.

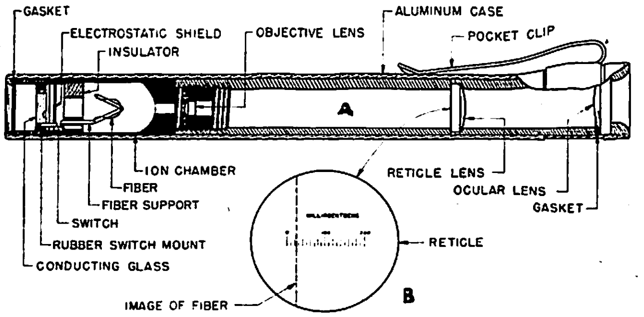


Current-pulse size. (A) Pulse in proportional counter is approximately proportional to ionizing-power of radiation. (B) Particles of all ionizing powers produce about the same pulse size in a Geiger-Mueller tube.

Lest one get lost at this point in the details of the process, it is helpful to think of the G-M tube as a cold-cathode discharge tube on the verge of firing, but operated at a potential just below the firing potential. A single ionizing particle is enough to "push the tube over the edge," and to self-register its arrival by the discharge which it triggers off.

The ionization-chamber and the electroscope are really two forms of the same device. In the former, the electrodes are maintained at a constant potential by permanect connection to a source of voltage, and in the latter they are not—that is the chief difference. The electrodes of the electroscope are first charged by momentary connection to a voltage source. As ionizing radiation enters the detecting chamber, a charge from the ion-pairs collects on the electrodes and partially neutralizes the charge already present. The loss of charge is a direct measure of the integrated sum of the radiation which has entered the chamber since the electrodes were charged. In the ionization-chamber (also called ion-chamber), ionization charge collected at the electrodes flows through an external circuit. The resulting current is amplified and fed to the registering meter. In principle, electroscopes and ion-chambers are capable of measuring the arrival of individual particles; in practice, however, electroscopes are almost always used in integrating types of equipments, and ion-chambers are almost always used in count-rate types of equipments. In general, (although capable of being used for α-, β-, and γ-radiation) these devices are chiefly used in the field by the Navy to evaluate high-intensity γ-radiation and to measure γ-dosage. The amount of ionization charge collected is very small, and since we are without the benefit of the enhanced response which comes with gas amplification, it is difficult to make an equipment which will measure lower intensities without more elaborate apparatus.

The electroscope has been essentially a laboratory device. There is one form, however, in which it occupies a prominent place among field equipments. This is the *pocket dosimeter electroscope.* Made in the size and shape of an ordinary fountain-pen, complete with pocket-clip, the pocket dosimeter may be charged up and conveniently worn on the person. Included is a sectional drawing which exhibits the internal construction of a typical dosimeter. The cap is removable, and the positive contact of a charging battery or power supply is inserted in the tube until it touches the metal cylinder. Mounted on this cylinder is a sensitive quartz fiber. Metal-coated so as to be conducting, it consists of a U-shaped loop, connected to the support at the open ends. As positive charge flows from the battery through the mounting cylinders to the fibers, they separate like the hinges of a door because of the mutual repulsion of the like charges they carry. The stronger the charge, the greater the separation. An optical magnifying system focusses on the end of the movable fiber, and makes it visible to an observer peering through the eyepiece as a fine hairline silhouetted against a transparent scale. This scale is marked in units of γ-ray dosage (milliroentgens). The voltage of the power supply is adjusted by a potentiometer until the movable fiber just lines up with the zero mark; the electroscope is now fully-charged. As ionizing radiation falls on the electroscope, the charge on the quartz fiber is slowly neutralized, the loop begins to move towards the support, and the hairline slowly moves across the scale, registering the integrated or cumulative exposure in milliroentgens.



Pocket dosimeter electroscope. (A) Longitudinal section. (B) Field of view after exposure to radiation.

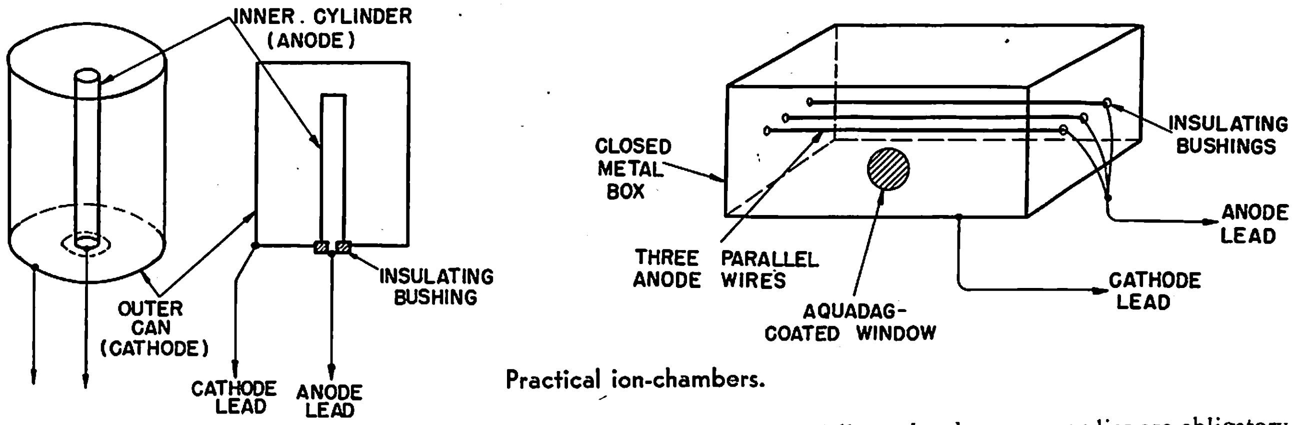
The insulating ring must have an extremely-high resistance, of the order, perhaps, of a million-billion (10^{15}) ohms. A good electroscope not exposed to radiation may retain its charge for weeks before most of it leaks off. Often, if an electroscope is not charged or used for some time, it will be found that the electroscope, when charged, will discharge in a relatively short period. This phenomenon is called *insulator soak-in,* and may be cured by charging up the equipment for a day or so before it is to be used, thus giving the insulator a chance to "soak in." The electroscope may then be recharged and employed in the usual manner.

Practical Electroscopes and Ionization-Chambers

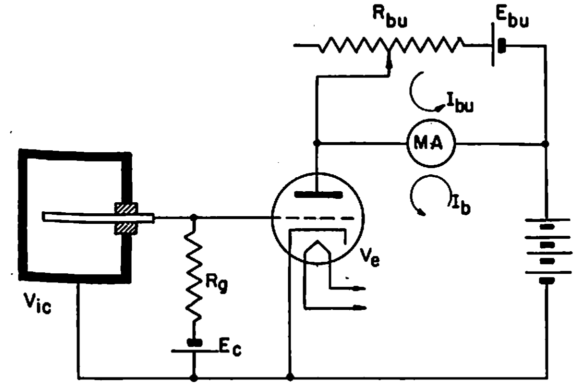
Ionization-chambers appear in a wide variety of forms, depending on the application and the type of energy of the radiation to be measured. Some chambers are about three feet wide, and some measure only a few centimeters on a side. In some, the two electrodes are arranged like the two plates of a condenser. Hence ionization-chambers are filled with air under a pressure of several atmospheres. Since γ-rays produce relatively few ions per centimeter of path length, the number of ions may be increased by concentrating the air molecules (i.e., increasing the gas pressure), thus furnishing a higher probability of collision between an air molecule and a γ-ray photon. This is one of our schemes for making as many as possible of the photons incident into the chamber produce ions and secondary electrons. The gas pressure inside the chamber also varies with the application. For instance, the problem in detecting γ-rays is to get them to produce enough ionization to be detected at all. Another scheme is to make the walls of the chamber of the right material of the requisite thickness; secondary electrons are ejected from the wall material, and the thickness and composition of the wall should be such as to produce the optimum number of secondaries. Wall materials of low atomic number are used, such as Bakelite or other carbon-containing substances. Without the carbonaceous material, or other material of low atomic number, the measurements might be distorted because of the "wall-effect." Very small ionization-chambers, filled with air under pressure and usually walled with Bakelite, are widely-used to measure high-intensity X- and γ-rays, and are called *thimble chambers* because of their shape.

Illustrated are two styles of ionization-chambers which are adapted to Navy field use. The first is for high-intensity γ-radiation, while the second has a window for admitting β-rays (or α-rays too, if desired) to furnish a β, γ reading.

In ionization-chambers, as mentioned above, the collecting electrodes are maintained at a constant potential by an external battery. As the collected ionization neutralizes the charge on the electrodes, current naturally flows from the battery to maintain their potential at a constant value. This current can be measured, but is very small, of the order of a micro-microampere. Measurement of such tiny direct currents poses quite a problem in circuitry. Conventional voltage-amplifier tubes are useless. Although more than adequate for ordinary applications, the grid current of the conventional tube, even with a negative potential on the grid, is several orders of magnitude greater than the ion-currents to be measured, and will completely mask the latter. The problem, however, may be solved by using special electron tubes called *electrometer tubes.* In these tubes, the grid currents have been reduced until they are negligible. A typical ionization-chamber electrometer-tube circuit, accompanies this article. Passage of the ion-current through the grid leak resistor develops a grid potential which is amplified by the tube. The first amplifier must be followed up by additional amplification if enough current is to be achieved to operate a microammeter. Often a bucking-circuit is used so that the meter may be set to read zero with no incident radiation present.



Practical ion-chambers.



Ionization-chamber detection circuit with electrometer tube (V_e) and bucking-circuit for zero-setting.

With the ionization-chamber, the output meter gives a steady reading. It indicates the *rate* at which ionizing radiations are falling on the chamber. Although it does not measure the energy of an individual particle, it does give a reading fairly-closely proportional to the *average energy per second* of incident radiation of a given type.

As has been indicated, the electronic circuit problems associated with ionization-current measurement are somewhat formidable, but have been overcome to a considerable extent. Well-regulated power supplies are obligatory, of course, and careful shielding and insulation must be employed in all designs.

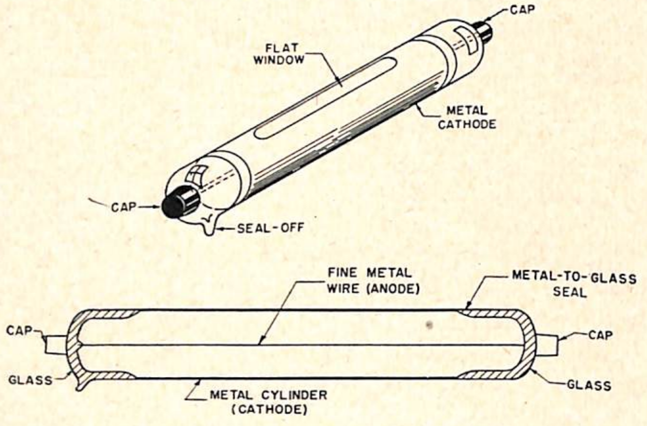
Practical Proportional-Counters and Geiger-Mueller Tubes

In the proportional counter, avalanche ionization leads to gas amplification. The amplification achieved may be as much as one thousand. This is a great help, for only one or two stages of amplification may be all that is necessary, ordinary high transconductance vacuum tubes may be employed, and shielding is not as critical. With the electric field superimposed, the electrons from the ion-pairs travel rapidly to the positive electrode, and the arrival of individual particles may be measured.

Proportional-counters are especially adapted to detecting α-particles, particularly when the latter are mixed with β- and γ-rays. The reason for this we have already mentioned—in the proportional-counter, the current pulse size generated by the incidence of each particle or photon is roughly proportional to the ionization produced by the particle in the chamber. Alpha-rays give up all their energy within the chamber, and, being such heavy emitters, develop a "really hefty" current pulse. Beta-rays develop smaller pulses, and γ-rays smaller yet, if we except the very weak β-rays. This variation is good, for we may feed the output of the tube to a discriminating circuit which passes all current pulses stronger than a certain discrete value, and refuses all weaker current pulses. We have a "filtering" action.

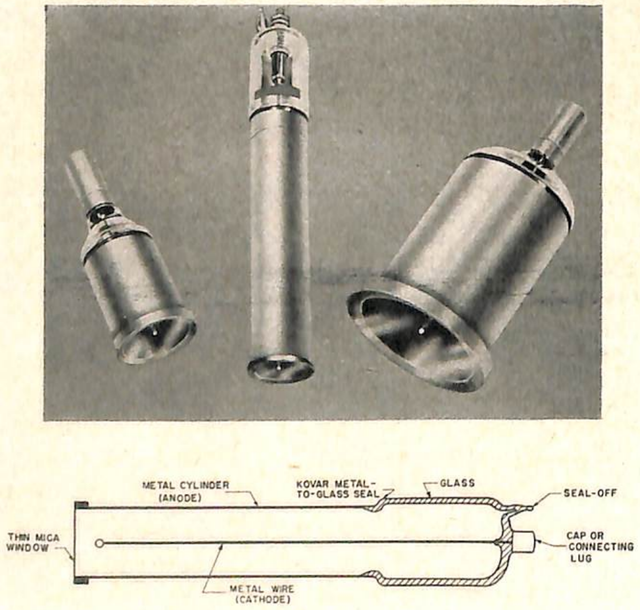
Proportional-counters are operated with different gas pressures. Some have the same gas pressure as G-M tubes—of the order of one-tenth of an atmosphere—while some may even be operated at atmospheric pressures. Because of the use of this principle to measure individual particle energies, it is called a *proportional counter*—"proportional" because of its energy- discrimination, and "counter" because it detects or counts individual particles. Amplifier circuits are of the conventional voltage-amplifier type, except that a bucking-circuit may be included for the convenience of zero-setting the meter.

Radiation tubes used in proportional counters are usually small glass or metal-envelope tubes with the positive electrode in the shape of a thin wire, and with an outside cylindrical cathode. With a moderate potential on the electrodes, a strong electric field is set up near the thin wire. The avalanche ionization and the gas amplification take place in this region. A typical proportional-counter tube is exhibited below.



Typical Proportional-Counter Tube

Geiger-Mueller tubes are somewhat similar to proportional-counter tubes. They employ a fine wire (tungsten is a favorite material) as the anode, and contain a concentric cylindrical cathode, usually constructed of copper. The anode is connected to a high-voltage power supply. The tubes are filled with carefully-chosen gases, often argon, at a reduced pressure of about 10 cm of Hg (1/7 atm). The name of these tubes is taken from the names of pioneer workers who first developed them.



Typical Geiger-Mueller tubes. The tube shown in cross-section is for beta-gamma detection.

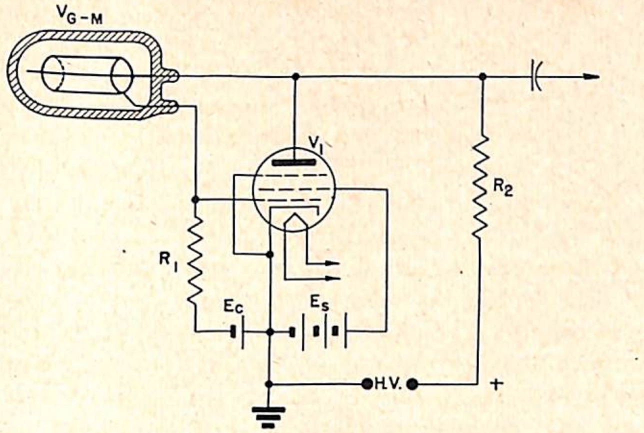
Geiger-Mueller tubes, as indicated in the preliminary discussion above, employ the phenomena of ionization by collision and very high gas amplification. The current pulses are about the same for all particles.

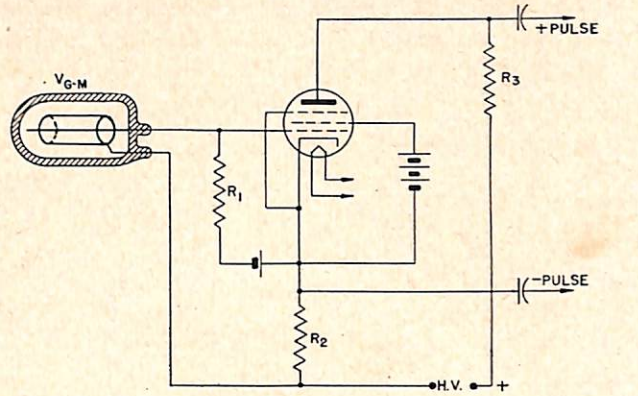
If no method were devised to shut off the discharge after a particle enters and triggers it off, the tube would be worse than useless. Only one particle would be detected, and all succeeding particles would be masked out. Consequently, in early tubes, the power supply was connected to the tube through a high resistance. When the discharge occurred, the current surge set up an IR drop which was enough to lower the anode potential below the point necessary to maintain the discharge. The rate of recovery, of course, depended on the resistance and capacitance of the circuit. Such tubes were rather slow, however, and better procedures had to be devised.

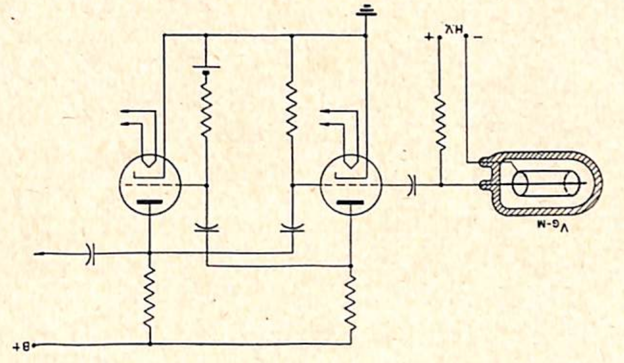
In modern G-M tubes the discharge is shut off in time by either of two procedures. In *self-quench* tubes, a vapor of some complex organic chemical or halogen is added to the gas mixture. Ethyl alcohol, xylene or chlorine are common constituents. The vapor automatically shuts the discharge off, allowing a current pulse to be sent on to the recording apparatus. Apparently what happens is that these vapors are highly absorbing to ultra-violet radiation and inhibit the photoelectric process which would tend to maintain the discharge.

In *external-quench* tubes, advantage is taken of the versatility of an electronic circuit to do the job. Special circuits automatically shut off the discharge. Perhaps the most common of these is the *Neher-Pickering Circuit*, illustrated in an accompanying figure. With no incident pulse, the grid-potential on the triode is positive and saturation current is drawn. The G-M anode potential is the power supply voltage minus the small saturation-current voltage drop in the triode. With the entrance of an ionizing particle on the scene, the current surge drops the triode grid potential below cut-off, and the G-M anode potential falls rapidy below the point necessary to maintain the discharge. In another common circuit, the *Neher-Harper circuit,* the triode is operated below cut-off with no incident pulse. No current flows through the supply resistor. When the radiation arrives, the triode grid-current swings up above cut-off and the tube conducts. The resulting IR drop from the plate current drain through the resistor then lowers the G-M tube anode potential below the extinguishing point. A third circuit is often seen, the *multivibrator quenching-circuit.* A multivibrator circuit is a square-wave oscillator. Arranged as a quenching-circuit, it is designed by proper tube bias so that it does not oscillate. When the G-M tube fires, the bias is neutralized, and the circuit generates a square-topped pulse. This pulse shuts off the G-M tube and the multivibrator before the next ionizing particle intrudes into the chamber.

In general, external-quench tubes employing electronic circuits such as those described have the disadvantage of requiring external circuits. Existing self-quench tubes, however, have shorter lives, for each discharge dissociates some of the atoms of the organic vapor. The chemical by-products of this dissociation react on the sensitive surface of the cathode. The life is measured in terms of particles detected, not the passage of time. Moreover, these tubes are apt to be temperature-sensitive. Both types have opposing advantages and disadvantages, but are widely used. Recently Naval Research Laboratory scientists have found that the introduction of a small amount of a halogen gas (chlorine, for example) produces a self-quenched tube with the advantages of the long life and relative stability of external-quench tubes, as well as a much greater pulse output and low operating voltage. This discovery is of great practical importance in radiac equipments employing G-M tubes.



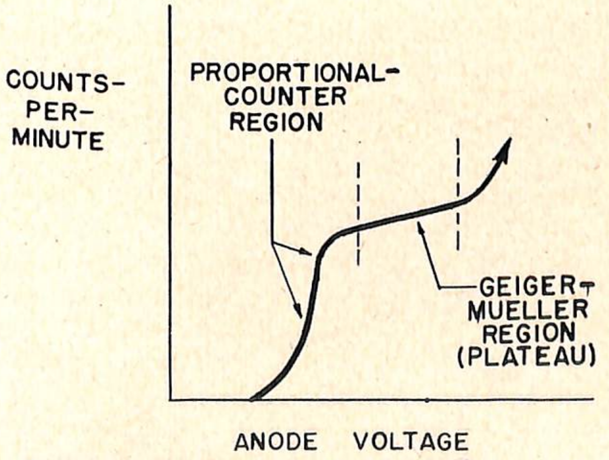




Geiger-Mueller tube external quenching circuits. ABOVE—Neher-Harper circuit. TOP RIGHT—Neher-Pickering circuit, and LOWER RIGHT—Multivibrator quenching circuit.

It is customary in work with Geiger-Mueller tubes to make use of the characteristic shown in an accompanying figure. It is a plot of the number of particles counted per minute against the anode voltage. It is taken using a radioactive source supplying a constant amount of constant-energy particles per second. Of particular significance is the flat or *plateau* region, for it is here that Geiger-Mueller tubes are operated. The small slope of the plateau is fortunate. It means that careful voltage regulation of the supply voltage is unnecessary. Proportional-counters are operated in the linear portion of the curve just below the plateau. Above the plateau, the discharge is erratic or even continuous, independent of the quenching gas action.

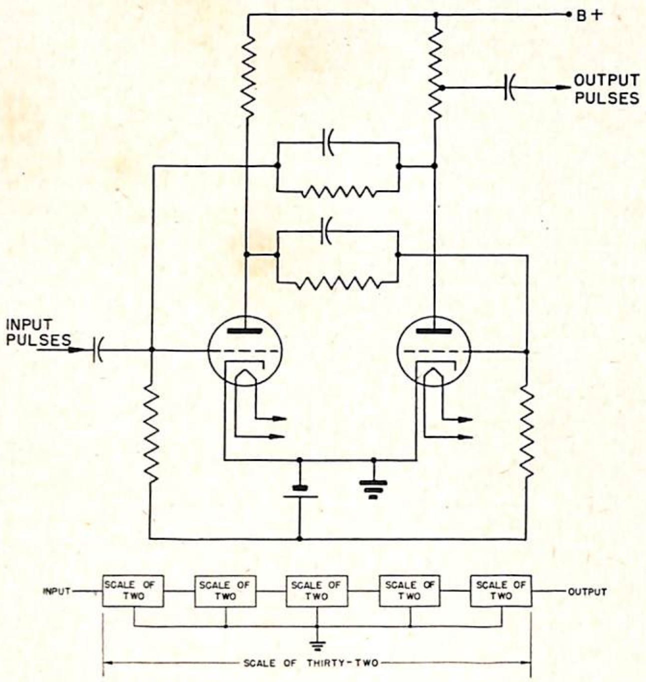
The manufacture of Geiger-Mueller tubes is an accurately controlled process. The filling gases must be carefully chosen, and gases which can produce negative ions, such as oxygen, water vapor, and carbon dioxide, must be rigorously excluded. Elaborate precautions must be taken to keep the cathode surface from certain types of chemical contamination. With proper skill in construction and processing, however, reliable G-M tubes may be regularly turned out.



Geiger-Mueller tube characteristic. Taken with a constant-strength radioactive source.

Counting Circuits

Designers of electronic counting circuits used in recording the detection of particles in G-M tubes have displayed considerable ingenuity. The typical electronic counter is the *scaling circuit,* of which there are many varieties. These are usually operated in conjunction with mechanical counters, especially when the particles arrive faster than the unaided counter can record them. The scaling circuit sends out one pulse each time a certain number of pulses is sent into it. In the scale-of-two counting circuit, for example, one pulse comes out for each two that go in. Such dividing circuits can be made scale-of-ten or scale-of-one-hundred with ring circuits. A typical scale-of-two circuit is illustrated. In this circuit only one of the two tubes is on at one time. A negative input pulse from the G-M tube reduces the positive grid-potential on the conducting tube, cuts down its plate current, and shuts it off. As its plate current drops, its plate potential naturally goes up. By a small coupling condenser, the positive voltage surge is immediately fed back to the grid of the other tube and turns it on. As the ionizing particles fly into the detector, the two tubes switch on-off, on-off, on-off, as the plate current flow switches alternately from one tube to the other. The pulses from either tube come out at half the rate at which the pulses arrive from the G-M tube, and thus our scaling is achieved.



Scaling circuits. TOP—Scale-of-two circuit puts out one pulse for each two pulses fed in, and BOTTOM—Five scale-of-two circuits may be operated in tandem to produce a scale-of-thirty-two circuit.

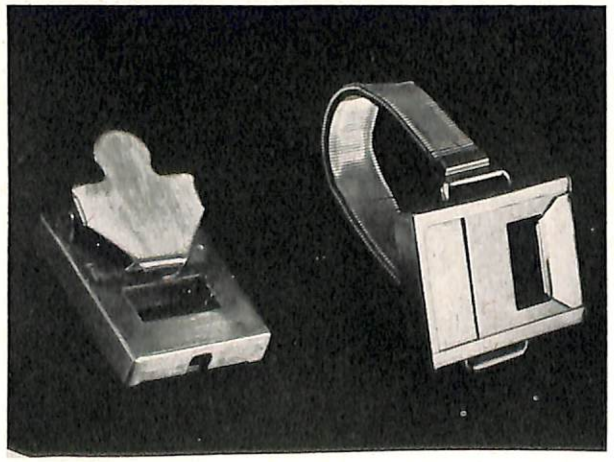
Geiger-Mueller tube type radiac equipments are highly-useful devices and have come into wide-spread use because of their convenience. They are literally among the most sensitive equipments ever devised by man, for they indicate the presence of individual minute, invisible, subatomic particles.

Miscellaneous Nuclear Detecting Devices

There is little more to be said here about photographic film badges, except to point out again that they measure accumulated radiation. They are made in various forms to be worn in the vest-pocket or on the wrist, etc. The wrist-form is especially useful when work with radioactive chemicals is to be performed, since it is worn close to the hands, the part of the body subjected to the greatest exposure in such work. An approximate measure of the amount of accumulated exposure may be obtained from the film of such badges by measuring the darkening of the film (after development) with a device known as a *densitometer*. A lead cross is often included with film badges; the cross filters out the β-rays, and furnishes secondary electrons so that some estimate may be made of the γ-radiation present. Outside the cross the darkening is due to β- and γ-rays, and underneath it, the darkening is due to γ-rays alone.

The newly-developed scintillation-photomultiplier counter is a "Dagwood sandwich" sort of affair. Flashes of light or scintillations occurring when α-particle or other radiations collide with or are absorbed in a fluorescent screen activate the photoelectric element of the photomultiplier tube releasing secondary electrons from this element. The resulting surges of current are amplified by the electron-multiplier elements or dynodes of the photomultiplier, and actuate the usual types of recording devices. An electron-multiplier, of course, is a tube in which great amplification of current is obtained by multiple secondary-emission from specially-sensitized tube-elements operated in series. This type of counter may be adapted to detect any of the four nuclear particles or radiations previously enumerated (alpha, beta, gamma, or neutron).

There are a few other devices which have not been used in the field. One of these, the venerable *Wilson cloud chamber* is not readily adaptable to field use, but is one of science's strong arms in the domain of nuclear research. Modern nuclear physics probably owes more to this one experimental device than it does to any other. Its importance is of the first order in research, because it makes visible the paths of electrons and nuclear particles, and shows what is going on in nuclear transformations. In simple but rather appropriate terms, it may be said to be a chamber filled with air and water vapor, with humidity conditions such that a miniature rain-fall is just on the verge of taking place inside. When an ionizing particle enters, it leaves positive ions in its wake. These ions are all that is needed to cause "rain to fall," and many microscopic droplets of condensed moisture cluster about the path of the particle. When a black background and side-illumination are used, the chamber shows white streaks where the ionizing particle has traveled, just as if its path had been drawn in with white ink.



Photographic film badges.

What Equipment Do We Use and Where?

In general, all of the field-type radiac equipments we have described may be constructed so as to measure α-rays, β-rays, and γ-rays, although not necessarily at the same time. The characteristics of each type, however, may render that type particularly useful in measuring one kind of radiation in a certain set of circumstances. The following text material and Table 3 are to be taken as indicative of present Naval thinking on the subject, expressing some trends in radiac implementation.

Alpha-particles are rather difficult to detect because, although they are heavy ionizers, they do not penetrate easily, and may be masked out by the more-readily-penetrating β's and γ's. Ion-chambers with very thin windows may be used to detect α's. The proportional-counter with its discriminating circuit is able to selectively count α-particles. The scintillation-photomultiplier counter which is being developed at present, is also particularly well adapted to α-particle detection. These last two devices are probably more closely associated with α-particle detection than any other type of equipment.

Ion-chambers are employed for β- or γ-ray detection as well as α-ray detection. Electroscopes are chiefly used for dosage measurement of γ-radiation. Photographic film badges are primarily employed for β- and γ-radiation. Geiger-Mueller tubes are especially used to detect β-, and γ-, or (less often) γ-radiation alone.

For military purposes there is no need to measure neutrons as the only place they are found outside of atomic piles or laboratories is in the neutron flash of the bomb, and the range here is less than that of lethal gamma rays.

The material in the above paragraphs is summarized in Table 3.

It is important to note that none of these devices are absolute measuring equipments (at least those for field use), and must be calibrated with standard radioactive sources. Such calibration is important, and is a subject in itself; we do not have the space here to delve into it, but future articles on this, as well as other subjects, will be forthcoming.

Nuclear Units

The specialist who interests himself in nucleonics and radiac, will want and will need to know something about nuclear units. So new is nucleonics that the units have not yet been thoroughly classified and established. However, a few are in common use.

A beam of radiation consists of a stream of particles or photons, which impinge on a surface or enter a volume. At times our attention is focussed on the beam of radiation itself, while at other times we are much more interested in the *effects* produced by the radiation.

A beam of radiation is a shower of particles or photons, and is analogous to a shower of raindrops. Sometimes in a rainstorm, we know, we see either a dense or light shower of fine droplets, at other times either a heavy or weak downpour of large raindrops. In the same way, we may encounter photons or particles of radiation of low or high energy which may fall in a weak or a dense beam. Therefore, if our description is to be com-

Table 3—Nuclear Radiation Detectors[1]

Detector	*Alpha-Radiation*	*Beta-Radiation*	*Gamma-Radiation*	*"Style" of Recording*	*Remarks*
Electroscope	....	....	Personal Dosimeters	Cumulative exposure	Very convenient for overall dosage.
Ionization-Chambers	With very-thin windows	With thin windows	No windows needed	Rate of dosage	Used in high intensity radiation fields
Proportional-Counters	With very-thin windows	....	....	Rate (individual particles)[2]	Discriminates between different types of particles.
Geiger-Mueller tubes	....	Very useful	Very useful	Rate (individual particles)[2]	Very sensitive, convenient, and rugged. Counts individual particles, but does not discriminate. Used in low intensity fields.
Photographic film	....	Darkening of negatives	Darkening of negatives	Cumulative	Very convenient for cumulative dosage. Gives permanent record.
Scintillation-photomultipliers	With zinc-sulfide or other screens	With organic or inorganic phosphor crystal	With organic or inorganic phosphor crystal	Rate of dosage	Have great promise and are being rapidly developed for survey work.

[1] All these types may be modified in some way to detect neutrons, if only in the laboratory.

[2] With counting-circuits and a recorder, a cumulative measurement is possible.

plete, we must simultaneously describe both the radiation "shower" and the nature of the photons or particles of which it is comprised. We may use such units in describing a shower as photons-per-second or particles-per-second falling on a given area, or, if we are concerned with the density of the shower, may use photons-per-cm^2-per-second or particles-per-cm^2-per-second. The energy of the individual photons or particles may be specified in any convenient unit of energy: ergs, joules or watt-sec, etc. We may refer to the energy density of the beam in ergs-per-cm^2-per-sec or watts-cm^2. Throughout this article we have met at various times a unit of energy which has come to be commonly applied to photons or particles. This is the *electron-volt,* from which is derived the *mega-electron-volt,* equal to one million electron-volts. One electron-volt is the energy acquired by an electron when it is accelerated through a potential difference of one volt. In terms of ergs, it is 1.60 x 10^{-12} ergs. The abbreviation of the electron-volt is "ev," and, of the mega-electron-volt, "Mev." In speaking of the "mega-electron-volt, we prefer not to be formal, and usually just pronounce the letters of the abbreviation ("em-ee-vee"). When we sometimes read in newspapers that atom-smashers have produced, for example, "300 million-volt particles," that doesn't mean that if we were struck by one of those particles we would be blasted the same as if we were struck by a 300 million-volt bolt of lightning. It just means that the particle had an energy of 300 Mev (3 x 10^8 x 1.60 x 10^{-12} = 4.80 x 10^{-4} ergs); on the scale of which we live, this is a negligible amount of energy; on a *subatomic* scale, however, this is a pretty hefty amount of energy for a particle to carry around with it.

Most of the units for the exact description of a beam of radiation fall in the province of the physicist rather than that of nucleonics technician, who is more apt to be concerned with the effects produced by a beam of radiation. We could probe this aspect of the subject of nuclear units more deeply, but it does not seem necessary. The facts for us to retain are that a beam of radiation is analogous to a shower of raindrops, and that both the radiation "showers" and the nature of the "raindrops" (photons or particles) must be described for completeness. We should, however, have an intimate speaking acquaintance with the electron-volt and the Mev.

When our attention is focussed on the effects produced by a beam of radiation, we measure the "amount" of radiation by units describing these effects, chiefly ionization. Three units become our concern, the *roentgen* (abbreviated "r"), the *roentgen-equivalent-physical* ("rep"), and the *roentgen-equivalent-man* ("rem"). In all these units we are interested in the effects produced, and do not so much care about the physical characteristics of the radiation which produced these effects.

The first of these, the roentgen, may be properly applied only to X- or γ-radiation (remember this). It was named after the pioneer German scientist who first observed X-rays. The roentgen measures the dose of radiation received. It describes the "punch" of all the X-rays or γ-rays received during a certain period of exposure as measured by ability to ionize air. When we come to formal terms in defining the roentgen, we have to use a complicated and apparently clumsy definition, solely because we are dealing with a unit which involves so many variables. One roentgen is that quantity of X- or γ-radiation which, under specified standard conditions, produces one electrostatic unit of electric charge of either sign in one cubic centimeter of dry air. Since one e.s.u. of electric charge is equivalent to 2.083 x 19^9 ion pairs, and, on the average, 32.5 ev of energy is expended to form each ion pair, it turns out that one roentgen corresponds to the expenditure by the radiation of 85.8 ergs-per-gm of dry air in the process of the ionization of that air. It is a little different to see just what a roentgen means. *It is best to think of the roentgen as a measure of radiation dosage, as measured by the ability of the radiation to ionize air.* In other words, a person who has been exposed over some period of time to one roentgen of X- or γ-rays has received a sufficient number of X- or γ-ray photons during that period such that, if one cubic centimeter of dry air had been exposed to these photons under standard conditions during that or some other period of time, ionization by the production of 2.83 x 10^9 ion pairs would have occurred in that sample of air. Seems complicated, doesn't it? Well, anyway, we are "measuring" X- or γ-radiation in terms of the effects it produces. It may help to use our rainfall analogy. Suppose we take a water-absorbent material like wood. We may measure how much the rainfall has "wet" or dampened the wood by the amount of water it has absorbed (grams of water absorbed per cubic centimeter of wood, if you like). Then (neglecting evaporation), if rain falls in a shower during a certain period of time on a certain plot of ground, we might say one "roentgen" of rain has fallen on that plot of ground if the amount of water which fell would have "wet" one cubic centimeter standard sample of wood to a specified dampness had it fallen on the sample. This analogy is not as foolish as it may appear at first glance. Just as the amount of water which would have produced the specified dampness in our standard sample may fall on the plot of ground in one sudden downpour, or may fall in a slight drizzle over a longer period of time, so one roentgen of X- or γ-ray radiation may be received in a short burst of great intensity such as from the primary blast of γ-rays in an aerial atomic-bomb detonation, received in less than one millisecond, or a slow spray of weak radiation such as leakage from an X-ray machine, received over a period of years by a dental technician. Just as the rain may fall in several showers, one roentgen of X- or γ-radiation may be accumulated during several exposures. Just as the "roentgen" of rain may fall in the form of a fine mist or of large raindrops, so one roentgen of X- or γ-radiation may be received by exposure to low-energy ("soft") X-ray photons, or to very energetic ("hard") γ-ray photons. Just as the rain may fall on one small section of the plot of ground or be distributed over the whole plot, so one roentgen may be received by local exposure to a very small area of the body (cancer X-ray therapy, for example) or exposure to the whole body (the maximum peace time industrial tolerance of 0.1 roentgen per 24-hour period is based on *total* body radiation, it will be remembered). It will be noted that the definition of the roentgen said nothing about the quality of the radiation producing the specified ionization, or the period of time during which the ionization occurred.

The roentgen gives an integrated or cumulative measure. This is just the kind of a measure we need to estimate external hazards, for, within limits, the factor determining the hazard of external exposure to γ-radiation is the total amount of radiation received, and the period of time during which exposure occurred is of much less importance. Therefore, cumulatively-recording radiac equipments such as electroscopes are often calibrated in roentgens or derived units like milliroentgens. (1000 milliroentgen = 1 roentgen). Incidentally, the milliroentgen is very common in radiac specifications.

The roentgen (or occasionally the rep or rem) is often combined with a unit of time measure to specify the *rate* of radiation. Thus we often encounter the *roentgen-per-hour* and similar units.

The roentgen-equivalent-physical is the "punch" of the ionizing radiation received during the period of exposure, measured in terms of the ionization produced in tissue, rather than in air. Unlike the roentgen, it may be applied to ionizing particles (α-rays, β-rays, neutrons, etc.) as well as to X- or γ-rays. One roentgen-equivalent-physical is that quantity of ionizing radiation (electromagnetic or particulate) which dissipates by ionization in tissue the same energy which would be dissipated by one roentgen of X-rays in ionizing air (83.8 ergs-per-gram of dry air). The relation "1 rep of photons = 1 r of photons," sometimes stated, is only approximate.

The roentgen-equivalent-man (or mammal) is the "punch" of the ionizing radiation received during the period of exposure, measured in terms of the biological effect produced by the ionization, rather than in terms of the ionization itself. One roentgen-equivalent-man is that quantity of ionizing radiation which produces the same biological effect in human tissue as would be produced by one roentgen of X-rays in the tissue. It may be applied to particles. We have no data on human beings, of course, so researchers have extrapolated biological effectiveness in mammals to apply to man, and our data has been obtained from experiments on mammals.

To review these units, the roentgen is a measure of X- or γ-radiation dosage as measured by its ability to ionize air. The roentgen-equivalent-physical, which may be applied to X-, γ-, or particle-radiation, is a measure of radiation dosage by its ability to ionize tissue (using the ionization-energy of X-rays in air for comparison to evaluate this ability). The roentgen-equivalent-man, which may be applied to X-, γ- or particle-radiation, is a measure of radiation dosage as measured by its ability to produce a given biological effect in human or mammalian tissue, as compared to the biological effect of X-rays. All are different ways of evaluating radiation dosage in terms of the effects produced.

We have specified the units which measure nuclear radiations, but have yet to look at the units for measuring radioactivity.

The *curie* measures the "radioactive activity" of members of the radium family of naturally-radioactively-disintegrating elements. Such elements include radon, polonium, and many others. When radium is in radioactive equilibrium with its disintegration products, just as many radon atoms are disintegrating per second into polonium as radium atoms are disintegrating into radon. One curie of radon is the amount of radon in radioactive equilibrium with one gram of radium under standard conditions. It corresponds to a rate of radioactive disintegration of 3.7 x 10^{10} atoms-per-sec. The curie was defined for radium, but has been officially extended to other members of the radium family. We may, then, consider the curie as that weight of a member of the radium radioactive family which disintegrates at the rate of 3.7 x 10^{10} atoms-per-sec. The curie has often been "promiscuously" applied to radioactive substances outside the radium family, but confusion and error have followed, so the tendency of official standardization committees is to recommend the restriction of the curie to the radium family.

With the growing use of artificially-radioactive isotopes, it has become necessary to have a unit available which will describe the activity of substances outside the radium family. The proposed unit, which seems to be acceptable all around, is the *rutherford,* defined as that weight of the substance which decays at the rate of one million atoms-per-sec. It is abbreviated "rd" to distinguish it from the roentgen ("r").

The radioactive "hotness" or strength of a sample of radioactive material cannot be completely specified by the number or curies or rutherfords—these units merely describe the rate at which atoms are disintegrating, but say nothing about the energy or other characteristics of the emitted particles or radiations. For this purpose (radioactive "hotness" or strength), at least for γ-ray emitters, the unit sometimes employed is the *roentgen-per-hour-at-one-meter* (abbreviated "rhm").

Two units often used with equipment capable of detecting the arrival of individual particles or photons are the *count* (cumulative), and the corresponding rate unit, the *count-per-minute*. They are or can be employed with proportional counters, and Geiger-Mueller tubes. They furnish no information about the energy content or quality of the radiation; moreover, unless the counter has an efficiency of 100%, so that all particles arriving are recorded, they do not even give the true picture of the number of particles which have entered the detector or the rate of entry. In G-M tubes, for example, some of which have efficiencies of the order of 99% for β-rays but only 1% for γ-rays, a count of 1000 per-minute with the shield in place to exclude β-rays may actually mean that 100,000 γ-ray photons arrived in one minute instead of the 1000 indicated. For α-rays, the counts-per-minute is a fairly accurate statement of the rate of particle incidence. In general the counts-per-minute is a relative measure for the particular G-M tube and associated circuits used; with a different counter and the same source, the counts-per-minute will be different. For this reason, standard sources of known strength should be used for calibration.

As has been described, the subject of nuclear units is in a state of flux, but the convenience and widespread use of the above units bid fair to establish them permanently in our list of physical units.

Table 4 lists the various units mentioned.

Representative Navy Radiac Equipments

Thus far in this discussion of nucleonics we have described the structure of the atom, natural radioactivity, and nuclear fission; we have surveyed the hazards of nuclear warfare; we have discoursed at some length on the types of nuclear radiation detectors and the physical phenomena involved in their operation; and we have considered the various nuclear units in common use. The question naturally arises, "What actual radiac equipments is the Navy employing at this time?"

As was mentioned before, nucleonics is so new and its military application so sudden that much solid effort is being put forth to design radiac apparatus adapted for Navy application and few are available for field use. Consequently, most of the present radiac devices are commercially-available units. It is expected, however, that before long various Navy-designed apparatus will make its appearance in Navy field applications.

Table 4—Nuclear Radiation Units

Quantity	*Unit*	*Abbreviation*
Energy "quality" of radiation.[1]	Energy of individual photons or particles in Mev or ergs.	Mev per photon (example).
Energy density of radiation.[1]	Energy-per-unit-area-per-unit-time (such as six 2-Mev photons per-cm^2-per-sec.).	Mev/cm^2-sec (example).
Relative number of particles or photons which have entered the chamber and been detected.	Count (G-M tubes; relative only).	count
Relative rate of arrival of individual particles and photons.	Counts-per-minute (eg. in G-M tubes; relative only, depending on individual tube).	counts/min
Quantity of radiation in terms of ionization in air (air ionization dosage).	Roentgen, restricted to X- or γ-rays.	r
Rate of air ionization dosage.	Roentgens-per-unit time.	r/hr for example
Quantity of radiation in terms of ionization in tissue (tissue ionization dosage).	Roentgen-equivalent-physical (any ionizing radiation).	rep
Rate of tissue ionization dosage.	Roentgen-equivalent-physical per unit-time.	rep/hr
Quantity of radiation in terms of physiological effect in ionized tissue (physiological ionized dosage).	Roentgen-equivalent-man (any ionizing radiation).	rem
Rate of physiological dosage in irradiated ionized tissue.	Roentgent-equivalent-man per unit-time.	rem/hr
Radioactive strength of a source.	Roentgen-per-hour-at-one-meter.	rhm
Quantity of radioactive material (radium family)—activity.	Curie.	c
Quantity of radioactive material (of any kind)—activity.	Rutherford.	rd

[1] Two units must be specified simultaneously to describe a beam of radiation: one descriptive of each ray, and one describing the distribution of these rays in the beam. The two units listed are examples of the type of units employed.

Radiac equipment is electronic in nature, and falls logically into the Navy system for design, maintenance, distribution, and use of electronic gear. Cognizance of the technical design of radiac equipments is almost entirely a responsibility of the Bureau of Ships. The manifold details of supply and maintenance are to be handled on the same basis as those for radio, radar, and sonar equipments and components are now. Radiac equipments, for instance, have "parts peculiar" and "parts common," and have a place in the AN nomenclature system (the AN/PDR–5 is an example). Radiac equipment becomes another type of gear for which the Electronics Officer must, at least to some extent, assume responsibility.

Compared to radar sets or radio transmitters, most radiac equipment is electronically relatively simple. A few principles such as we have been reviewing are introduced, but these are chiefly associated with the detection components, and are principles which can be readily understood. A background in electronics, such as is acquired from the training and experience of Electronics Officers or informed enlisted personnel, is a good preparation for the study of nuclear physics. Every nucleonics technician and every Electronics Officer should have a good understanding of the basic phenomena to be encountered in this branch of the physical sciences.

In general, the repair of radiac equipment can be accomplished with the aid of common electronic test equipment available at present at electronics repair shops. It is realized that certain special components, such as subminiature tubes, Geiger-Mueller tubes, and very-high-megohm resistors cannot be thoroughly checked with existing test equipment; as an interim measure, however, it is recommended that the "check-by-substitution" method be applied when such components fail or are thought to be defective.

In the first listing of radiac equipments in Supplement 1 (Jan., 1948) to the Catalogue of Naval Electronic Equipment, NAVSHIPS 900,116, the following radiological terms are defined:

Charger, radiac detector.—A device for providing an electrostatic charge to a radiac detector. May include means for measuring the amount of charge.

Computer-indicator, radiac.—A device which performs the combined function of computing and indicating radiac data.

Computer, radiac.—A device which receives information from a radiac detector and does one or more of the following: scales, integrates, or counts. Does not indicate.

Densitometer.—An item specifically designed to measure the optical density or opacity of material,

Detector, radiac.—A device that is sensitive to radioactivity or free nuclear particles and provides a reaction which can be interpreted or measured by various means.

Indicator, radiac.—A device which displays radioactivity detection, identification, or computation information.

Radiacmeter.—A device specifically designed to detect and indicate radioactivity. May or may not include radiac computer.

Radiac set.—All the components and items required for a complete radioactivity detecting and measuring system. May or may not include operating spares or the following items: electron tubes, fuses, cable assemblies, power sources, etc.

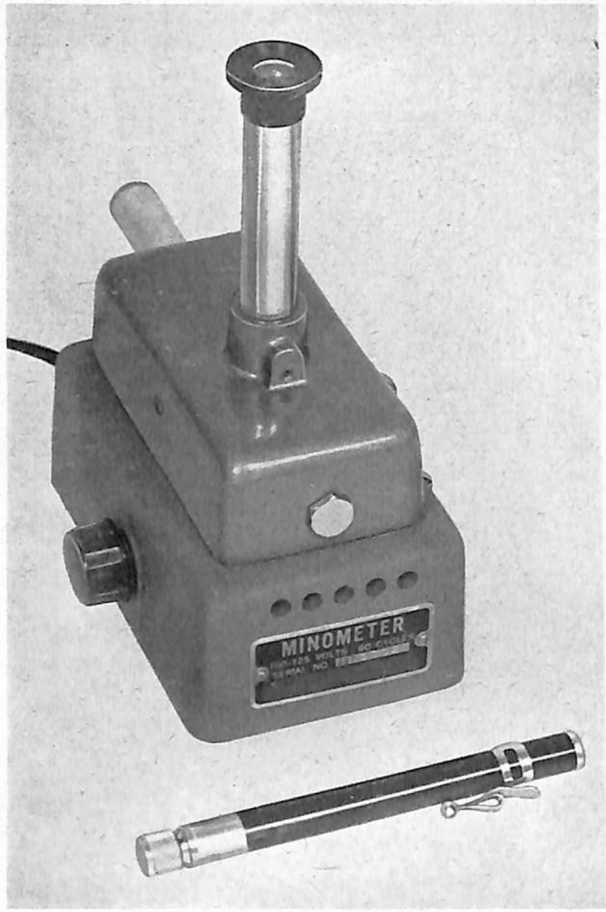
Transmitting set, radiac data.—All the components and items required to detect radioactivity and transmit radioactivity data as modulation on a carrier. May or may not include operating spares, or the following items: electron tubes, fuses, cable assemblies, power sources, etc.

The radiac equipments described below are not all the equipments available, by any means, but they do give a representative picture of the types in use at present. Some of these equipments may have been supplemented by newer and better ones by the time this article is published, but they were chosen to illustrate types, and to show how the principles of radiac implementation are applied, rather than to list all the up-to-date equipment available.

Electroscopes

A typical pocket electroscope or dosimeter is the AN/PDR–3A radiac set. Consisting of two units, the Radiacmeter IM–9A/PD and the Radiac Detector-Charger PP–311A/PD, it measures γ-ray dose. The radiacmeter is a pocket electroscope or dosimeter in the shape of a fountain pen and provided with a clip for fastening to the clothing of the wearer. At one end is an optical eyepiece and at the other a removable dust cap with a transparent window. The working mechanism consists of a phosphor-bronze wire frame and a quartz fiber. A scale is provided, calibrated in milliroentgens, and is read by holding the meter up to the light and looking into the eyepiece. The radiacmeter is, of course, of the integrating type in which the cumulative exposure to γ-radiation over a period of time is measured by the position of a charged quartz-fiber which shifts as its charge is neutralized by γ-ray ionization.

The Radiac Detector-Charger PP–311A/PD is a box-like unit made of black plastic, and may be used to charge any number of IM–9A/PD Radiacmeters. It contains one 1.5- and eight 22.5-volt dry cells. Mounted



Pocket dosimeter electroscope and chargers for gamma radiation (AN/PDR-4).

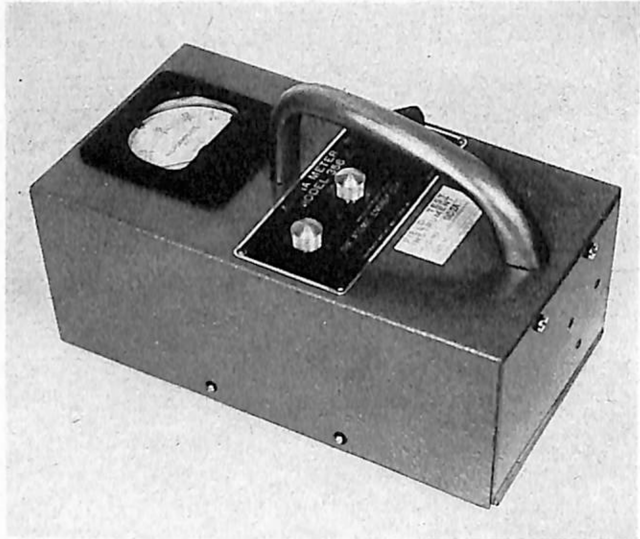
on top is a charging socket, an ON-OFF switch, and a potentiometer for varying the charging potential. The range of the AN/PDR–3A Radiac Set is 0-200 mr.

The AN/PDR–4 Radiac Set for γ-radiation is similar to the AN/PDR–3A, except that the pocket chamber is non-indicating and the measuring device is contained in the charger instead of the dosimeter. It consists of the Radiac Detector DT–16/PD and the Radiac Detector-Charger PP–316/PD.

Ionization-Chambers

The IM–3/PD Radiacmeter is a portable high-range survey equipment of the sealed ionization-chamber design which indicates the rate of incidence of γ-radiation. It employs three sub-miniature tubes, and provides visual indication of the rate by means of 0-20 microammeter. Self-contained batteries render it independent of external power supplies. Ranges are 0-0.2, 0-2.0, 0-20, and 0-200 r/hr.

The IM–5/PD Radiacmeter is a portable ionization-chamber type equipment with a pistol grip handle for convenience in hand-held β- and γ-radiation survey work. The dosage rate is indicated by an integrating 0-20 microammeter. A $1/8''$ Bakelite slide is used to screen out β-rays. With the slide out, the meter reading measures β- and γ-radiation combined, while γ-rays alone are indicated with the shutter in position. A Type VX–32 sub-miniature electrometer tube is utilized in the electronic amplifying circuit. The ranges of the equipment are 0-4, 0-40, 0-400 and 0-4000 mr/hr.



Portable ion-chamber survey meter for alpha, beta-, and gamma-rays (IM-4/PD).

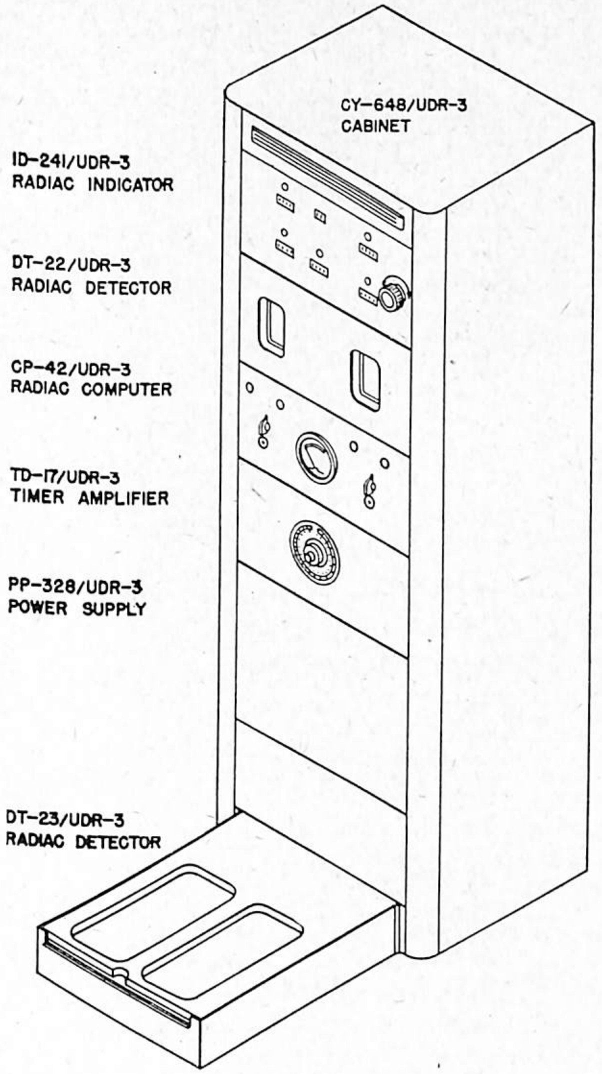
The IM–4/PD Radiacmeter allows α- as well as β- and γ-rays to be detected. It is the usual air-ionization-chamber type equipment with electrometer tube (Type VX–32) amplifying circuits. Two shutters or slide windows are supplied for separating α-, β-, and γ-rays. The range for α-particles is 0-6000 and 0-60,000 disintegrations per minute. For γ-rays or β- and γ-rays combined, the range is 0-4 and 0-40 mr/hr.

Geiger-Mueller Tubes

The convenience of Geiger-Mueller tubes and the relatively powerful impulse received from the detector tubes has justified the inclusion of many G-M tube types in this discussion.

The CP–37/PD Radiac Computer-Indicator, in contrast to the equipments already presented, indicates the relative strength and relative dosage rate in terms of particle or photon counts-per-minute. It is used in conjunction with G-M tubes, and employs scale-of-two electronic computing circuits. By means of a selector switch, the operator may cover the range of from 2 to 4096 counts/min in powers of 2. Neon interpolating lights are provided. An external power source of 115 volts, a.c., is needed.

The IM–12/PD G-M counter is a detector with aural indication provided by light-weight high-impedance head-phones. Of small size and weighing only two pounds, it may be slipped into the pocket and carried about by the operator, leaving the hands free for other work. The usual screening slide is provided.

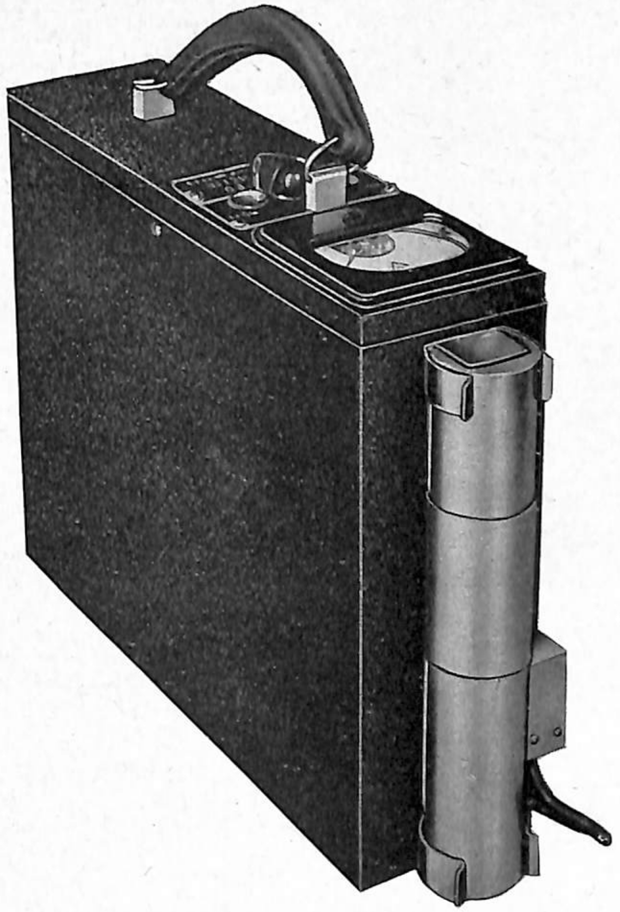


Beta-gamma, Geiger-Mueller detector for simultaneously checking the hands and feet for radioactive contamination.

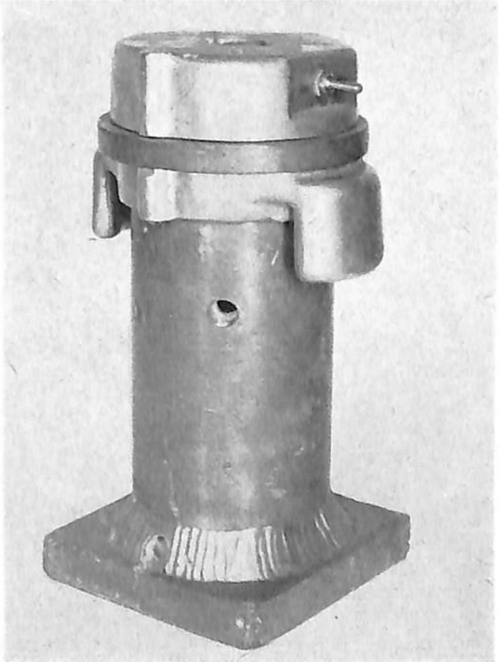
Radiac Sets

The low-intensity AN/PDR–5 Radiac Set is one of these. It consists of the IM–1/PD Radiacmeter and H–39/U Headset. Headphone and microammeter indication are provided. A single G-M tube is seated in the detector probe, which is connected to the rest of the apparatus by a flexible cable. A γ-β-discriminating shield is furnished, as is customary. Radiacmeter IM–1/PD has a carrying handle. The range is 0-0.2 mr/hr, 0-2.0 mr/hr, and 0-20 mr/hr.

For measurement of γ-radiation underwater, an equipment such as Radiac Set AN/UDR–2 may be employed. It also measures the radiation in counts per minute. It consists of Radiac Detector DT–21/UD and Radiac Computer-Indicator CP–39/UD, connected by a suitable four-conductor cable up to 220 feet in length. The detector is a heavy, brass probe with a low-voltage external-quench G-M tube and associated quenching and amplify-



Portable, beta-gamma, Geiger-Mueller tube type radiac set (AN/PDR-5).



Beta-gamma, Geiger-Mueller tube designed to detect contaminants in sea-water.

ing circuits. The range is 0-100, 0-500, 0-1000, and 0-5000 counts/min.

As an example of the type of radiac equipment that one may expect for personnel radiation-surveying, the AN/UDR–3 Radiac Set is presented. This equipment consists of several subsidiary units mounted in a panel. As may be seen from the illustration, both the hands and feet may be simultaneously monitored for β- and γ-radioactive contamination by placing them in the openings provided. Here is one case where "putting one's foot in it" may be beneficial. Six thin-walled, high-voltage G-M tubes provide the detection, while computation is furnished by five scale-of-eight counting circuits, augmented by electric timers and registers. The foot contamination may be removed for study by use of the roll of paper supplied as part of the equipment. Yale-type locks furnish protection against tampering. The counting-rate is approximately 120,000 counts/min.

Conclusion

In this survey we have covered fundamentals of nuclear physics, described radiation hazards, investigated the several types of nuclear radiation detectors, familiarized ourselves with common nuclear units and reviewed representative radiac sets in Navy use. Many subjects were treated; many, many statements had to be accepted at face value because space did not permit the elaboration of the subjects needed to provide real comprehension. This article did not survey the entire subject of radiac, but we did look at some of the more important aspects. It is the hope of the editor and staff of BuShips Electron that this introductory survey of nucleonics may be of some assistance to electronics personnel who decide to enter this fascinating field, and may pave the way for better understanding when individual, Navy-designed radiac equipments are described in future articles.

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