Radioactive Fallout and Radioactive Strontium

W. F. Libby

The radioactivity that falls out of the atmosphere after the explosion of a nuclear weapon is called the radioactive fallout. In the ordinary atomic bomb, for example, for each 20,000 tons of TNT equivalent of explosive energy, about 2 pounds of radioactive materials are produced. In these 2 pounds are some 90 different radioactive species varying in lifetime from a fraction of a second to many years. This mixture of radioactivity decreases in radioactivity in such a way that for every sevenfold increase in age, the total radioactivity is decreased tenfold. Thus the radioactivity by 7 hours after the explosion has decreased to one-tenth the radioactivity of 1 hour, and in 49 hours to 1/100, in 2 weeks to 1/1000, in three months to 1/10,000, and so forth.

The conditions of fallout are largely determined by the amount and type of material vaporized into the fireball of the bomb itself. A bomb fired in the air contributes such a relatively small amount of matter to the cloud that the particles formed after dissipation of the enormous energy released are of necessity very tiny and therefore very slow in settling. The result is that most of the radioactivities are expended in the air and the area over which the fallout occurs is rendered very large indeed, extending to the ends of the earth in minute although detectable amounts.

A bomb fired on the surface of the earth, however, may have an appreciable portion of its radioactivity reprecipitated within relatively short distances, while bombs fired beneath the surface of the earth may place essentially no fallout radioactivity in the atmosphere. Therefore, the question of the area of contamination to be expected from nuclear weapons cannot be answered categorically without specifying the degree of contact of the fireball with the surface of the earth and probably also specifying the characteristics of this surface. Obviously water would differ considerably from soil in its ability to precipitate radioactive fallout. The coral in the southern Pacific islands that are used for the larger United States weapons tests will under the great heat decompose to form calcium oxide, which will then rehydrate to form calcium hydroxide, which in turn will absorb carbon dioxide to form a crust of calcium carbonate. Obviously such a complicated series of chemical reactions will make the fallout particles from the great tests at Eniwetok differ from what would be observed if the same weapons had been fired over ordinary sand or granite. We cannot imagine all of the details in which the nature of the soil will affect the local fallout, but it is clear that the effects will be substantial.

In the weapon test operations, great care is taken to insure that no danger results from fallout. Criteria are used that are meant to insure that this is so. However, it is well to note that it is from the test operations that we have learned what we do know about the problem of civilian defense against fallout. We must speak of test experience, for it is the only source of experimental information about the phenomena of radioactive fallout.

The radioactivities resulting from the burst of a nuclear weapon can be classified as follows: (i) radioactivities induced in the environment and (ii) products dependent directly on the nature of the weapon. The environment can be made radioactive only by neutrons, but all nuclear weapons involve large numbers of neutrons, some of which are certain to escape into the surroundings.

Radioactivities Induced in the Environment

Taking air bursts first, our problem is: What do neutrons do to air? The answer is simple. They make radioactive carbon, C^{14}, which has a half-life of 5600 years. Fortunately, this radioactivity is essentially safe because of its long lifetime and the enormous amount of diluting carbon dioxide in the atmosphere. The cosmic rays themselves make neutrons, which, of course, make radiocarbon. In fact, the earth has on its surface a total of 80 tons of radiocarbon from the cosmic radiation. Now, since each neutron forms one C^{14} atom of mass 14 times the neutron's mass, this corresponds to 5.2 tons of neutrons, and we see that this enormous number of neutrons would have to be produced and escape in order that nuclear weapons would just double the feeble natural radioactivity of living matter due to radiocarbon. Such an increase would have no significance from the standpoint of health. The atmosphere itself contains only 1.5 percent of the total carbon with which the cosmic-ray-produced radiocarbon is mixed, the main part being dissolved in the sea, so we expect that nuclear weapons could produce a short-range rise in the radiocarbon content of the carbon dioxide in the atmosphere, which later would decrease as the atmospheric carbon dioxide mixed with the sea. Therefore, only 1.5 percent as many neutrons would be required to double the natural radiocarbon content of atmospheric carbon dioxide for this time before mixing with the sea could occur, or about 78 kilograms or 170 pound of neutrons. To orient ourselves, the 20,000-tons-of-TNT-equivalent atomic weapon involves the fission of 1 kilogram of uranium or plutonium and the liberation of about 10 grams of neutrons. If all these neutrons escaped into the atmosphere, it would obviously require 7800 such weapons to double the radiocarbon content of the atmospheric carbon dioxide even with no mixing with the sea, and about 520,000 with complete mixing. These correspond to explosive energies of 156 and 10,400 megatons of TNT, respectively, if all neutrons formed escaped. A reasonable escape figure might be 15 percent, so we can expect that nearly 1000 megatons of fission would be necessary just to double the atmospheric radiocarbon content, and that about 66,000 megatons would be necessary for the same effect on a long-term basis.

The interchange between the atmosphere and the sea water, which is constantly taking place, would deplete and remove the excess radioactive carbon dioxide. Now it is known from measurements of the radioactive hydrogen, tritium—which is also made in the atmosphere by the cosmic rays—that this interchange is slow. In fact, we learn that the radioactive water that is formed by the burning of the tritium made by the cosmic rays is not diluted by more than the top 100 meters or so of sea water in its lifetime of about 18 years. The carbon dioxide dissolved in this water is about equal to the total in the

The author is a member of the U.S. Atomic Energy Commission. This article is based on a speech given at Northwestern University, Evanston, Ill., 19 Jan. 1956.

air. In other words, a dilution by more than the twofold that corresponds to the dissolved carbon dioxide in the top 100 meters of ocean water would take longer than 18 years. However, the dilution by this factor of 2 would occur essentially immediately within a matter of weeks or months. Therefore, we would have to double our estimates for even the short time scale activation of the atmosphere to reach the enormous figure of 2000 megatons of fission required. Thermonuclear weapons, of course, also involve neutrons. For a given energy release, they produce somewhat more neutrons than fission weapons; however, the order of magnitude of atmospheric activation would not be greatly different. So our estimates apply to all nuclear weapons. The essential point is that the atmosphere is difficult to activate and the activities produced are safe. In addition to carbon-14, there are a few others produced in low yield; they include tritium and very short-lived products, but none is produced in sufficient amounts to be hazardous.

For weapons fired on the surface, the activation of the surface materials is a possibility, but in general it appears that most of the neutrons form stable isotopes and that the amount of radioactivity produced, at least with ordinary surface materials, is relatively small. The principal radioactivities produced by nuclear weapons are produced in the weapons themselves, and not in the environment.

Radioactivities Produced in Weapons

Turning now to the radioactivities naturally produced in nuclear weapons themselves, probably the most important is radioactive strontium, which has a half-life of 28 years. The first reason this is so important is that strontium is chemically similar to calcium, which is one of the main mineral constituents of the body. Bone consists principally of calcium phosphate, and for this reason radiostrontium, like calcium, is deposited in the bone. The amounts of ordinary nonradioactive strontium naturally present are so small that the radioactive strontium will follow ordinary calcium into the body. The second reason that radioactive strontium, Sr^{90}, is an important fallout radioactivity is that it has a long but finite lifetime—28 years half-life, 40 years average life—and thus has a persistent effect. Third, because of its bone seeking property, it stays in the body a long time. Fourth, the probabilities of body ingestion can be high. Finally, the fifth reason for its importance is that strontium-90 is produced in high yield in the fission reaction—about 4 or 5 percent of all fissioning atoms yield this isotope.

In order to orient ourselves about this, let us consider the maximum permissible concentration recommended by the National Committee on Radiation Protection for AEC workers for radiostrontium —1 microcurie for the standard man, whose body is taken to contain 1000 grams of calcium in total. The maximum permissible concentration is of course well below any level at which one would expect any damaging effects to appear. On the basis of experiments with animals, statistically observable increases in the number of bone tumors *should not* be expected to appear at *less than* 10 times this level. As we go above this figure, the chance for bone tumors occurring increases rapidly so that the likelihood of bone cancer with 30 to 40 times that figure is appreciable.

Intake of Strontium-90

Let us consider in some detail the mechanism by which this most important fallout radioactivity produced in nuclear weapons might be expected to enter the human body. The first point is that from the point of view of fallout there are essentially two classes of nuclear weapons—the high-yield megaton weapons and the lower-yield kiloton weapons. All nuclear weapons produce atomic clouds that rise to heights dependent on the energy released, and the clouds from the megaton class of weapons rise rapidly up through the tropopause and pass into the top layer of the atmosphere, which we know as the stratosphere. This part of the atmosphere is essentially isolated from the lower layer in which we live, the troposphere, and where all of our normal winds, storms, and so forth, occur. Therefore, radioactivity produced in megaton weapons is placed largely immediately in the stratosphere, while the smaller kiloton weapons produce clouds that in general do not reach into the stratosphere, but stop near the tropopause—the imaginary boundary between the stratosphere and troposphere—and have the bulk of their radioactivity left in the troposphere.

In the troposphere where rain occurs, any particulate matter will be washed down in a period of days or weeks. It is easy to show, for example, that 0.1 inch of ordinary rainfall will probably remove essentially completely all particulate matter except for that which is so small as to be almost of molecular dimensions. In other words, for 0.1 inch of rainfall one can be quite certain that the air between the layer in which the rain originates and the ground is washed clean of fallout activity, except for the minute fraction that may be so small that it moves with the air out of the way of the falling raindrops as they make their way toward the earth; and even this tiniest fallout material is likely to be precipitated also, for it will migrate rapidly by molecular-type motion and in this manner is likely to absorb itself on other particulate material and so be rained out. For these reasons, tropospheric radioactive fallout does not stay in the atmosphere for more than a matter of weeks. It may make two or three trips around the earth in a given latitude before being entirely removed, but its lifetime in the atmosphere will be a matter of weeks.

This is in very sharp contrast to the material that is placed in the stratosphere by megaton weapons; this material appears to stay there for a matter of years. Perhaps 10 years is a good average, at least for the weapons fired to date. It is well to bear in mind that this conclusion may be dependent on the nature of the material carried up in the cloud, but our present experience indicates that the fallout from megaton weapons that does not occur essentially in the first few hours or days, and is therefore deposited mainly locally, is deposited only at a very slow rate corresponding to an average time in the stratosphere of about 10 years. As a result of this long residence time in the highest layers of the atmosphere, the winds mix and distribute the radioactive material broadly over the earth and one finds, when the fallout does finally find its way down into the troposphere where the rain and snow wash it out, that the rates of precipitation are relatively uniform over the entire earth's surface.

Returning now to radiostrontium—at the rate of 1 kilogram of fission for 20 kilotons of TNT equivalent, 2 megatons of fission energy would be equivalent to very nearly 1 millicurie of strontium-90 per square mile of the earth's surface, or about 79 disintegrations per minute, per square foot of the earth's surface. The average soil of the earth has about 20 grams of calcium that is in a form available for plant metabolism in the top 2.5 inches for each square foot of area. Now, recalling the maximum permissible concentration level of 1 microcurie per standard man and noting, as will be shown later, that in order that this concentration not be exceeded, the topsoil of the earth should not contain any more radiostrontium than would correspond to 10 times the concentration in the human body that is just permissible—that is, 1 microcurie per 1000 grams of calcium, or 2200 disintegrations per minute, per gram of calcium—we find that 11,000 megatons of fission energy would produce this average level of radioactivity. Actually, as I will indicate, there can be a concentration of strontium-90 in the soil about 10 times greater than the recommended maximum permissible concentration before one would expect a man living in such an environment to accumulate a maximum permission concentration. The afore-mentioned 11,000 megatons of fission energy would yield a strontium-90 content in human beings just equal to the maximum permissible concentration (MPC); at less than 10 times this value, or below 110,000 megatons energy equivalent, statistically observable incidence of bone tumor should not appear; but at 30 to 40 times the MPC, or 330,000 to 440,000 megatons, the likelihood of untoward effects would be appreciable. Even the lowest of these figures is very far in excess of the total energy released to date.

Kinds of Fallout

High-yield weapons fired near the surface have a portion of their activity deposited in and on particles large enough to fall out in the first few hours or days. Thus we have three kinds of fallout from high-yield weapons.

1) The first, or local, is due mainly to large-sized particles. This may cover a considerable area depending mainly on winds. In the 15 February 1955 release of the Atomic Energy Commission that described the experience in the Marshall Islands in the Castle test series in the spring of 1954, some 7000 square miles were described as being contaminated by this type of fallout.

2) The second fallout from the high-yield weapons is that portion which resides on the small particles, but which never reaches the stratosphere and thus stays in the troposphere until it is carried down by rainfall or settles out. There is thus a band of fallout in the same general latitude as the test site; the material may circle the earth two or three times before it is precipitated, but it does fall out within the first few weeks.

3) However, a large part—half or more depending on firing conditions—of the radioactive yield from high-yield weapons resides in the third category, which is the fallout that occurs from the stratosphere itself. Of course, some of the large local fallout may form particles which were lifted into the stratosphere, but which were so large and so bulky that they fell out rapidly anyhow. The finely divided material that reaches the stratosphere apparently stays there for years in the main. A slow leakage through the tropopause into the troposphere occurs—apparently something like 10 percent per year descends. Measurements of the strontium-90 content of soils, rain and snow, and biological materials on a worldwide basis have all shown that strontium-90 fallout occurs all over the world at rates that are not very dissimilar from one another, except that there is a tendency in the middle latitudes in which the tests are conducted for an extra fallout, presumably of the afore-mentioned tropospheric variety. Since the completion of the Castle series of tests two years ago, this world-wide rate of fallout has approximated 1.5 millicuries of radiostrontium per square mile, per year. We thus see that radioactive fallout from the stratosphere is a very slow process. This is very fortunate indeed, since the high-yield weapons thus have a major part of their radioactivity dissipated in the atmosphere in a harmless way if they are fired in the air or on the surface.

The fallout apparently occurs in the final step by a washing down of the tropospheric air by rain together with direct falling. The radiostrontium descends from the stratosphere into the troposphere by the processes of diffusion and falling, and is then caught up by the tropospheric weather and in a matter of a few days is deposited. Reasonable estimates for the middle latitudes indicate that the average life in the troposphere is about 1 week.

Deposition of Strontium-90

The radiostrontium comes down mainly in raindrops although fine morning mists and fogs may be particularly effective in this regard also, as well as surface contact and direct falling. It descends on the foliage and on the soil. That fraction of it which falls on plant leaves has a good chance of being absorbed directly into the plant—much in the way that most modern leaf fertilizers operate. The Eniwetok tests were conducted on coral islands and as a result their fallout may be largely water-soluble. In any case, direct measurements of the radiostrontium content of alfalfa and other crops showed them to be appreciably higher in radioactivity than the soils on which they grew, strongly indicating that a leaf assimilation mechanism is important. The rain falls and carries radioactivity, but when it runs off to the rivers and the seas it is nearly pure because of the action of the soil in absorbing the fallout, so that rivers are essentially free from radiostrontium. Lakes and reservoirs have a content that corresponds approximately to their surface areas only. The radiostrontium is absorbed in the top 2 or 3 inches of soil and held there very tenaciously. Plowing, of course, buries it more deeply, but it appears that in unplowed soil the radiostrontium does not move in a matter of 2 or 3 years.

The researches on radiostrontium conducted by the Atomic Energy Commission have been extensive. The AEC has sampled soils on a world-wide basis and submitted the samples for analysis of radiostrontium content to the Health and Safety Laboratory of the New York Operations Office of the Atomic Energy Commission, the Lamont Geological Observatory of Columbia University, and the Enrico Fermi Institute for Nuclear Studies at the University of Chicago. Direct fallout collected on gummed papers, milk and cheese, alfalfa, animal meat and bone, and even human bodies has been extensively studied. On the basis of the information so obtained, it is possible to say unequivocally that nuclear weapons tests as carried out at the present time do not constitute a health hazard to the human population insofar as radiostrontium is concerned, and it is believed with good reason that radiostrontium is likely to be the most important of the radioactivities produced. It is well to note that since radiostrontium is assimilated in the bones it constitutes essentially no genetic hazard, for its radiations do not reach the reproductive organs.

The milk and cheese radiostrontium content is not as high, relative to that of the grass which the cows eat, as one might expect. There appears to be a discrimination against the fallout material such that the calcium in milk and cheese is roughly one-fifth to one-tenth as radioactive with radiostrontium as the grass that the animals eat. There are various possible physiological explanations of this, and the conclusion itself may not be completely certain, but the data available to date indicate this to be true. In addition, the plant uptake of radiostrontium from soil does discriminate somewhat against radiostrontium as compared with calcium. The calcium taken up from the soil into the plant has in general about one-half the radiostrontium content that the soil calcium has. These two results protect the human population against ingestion of radiostrontium, since milk and cheese are the principal sources of calcium in the human diet. We find, therefore, that the radiostrontium content of human bodies is the lowest of all animals measured and is lower than the average soil and the average foliage by tenfold. The Sr^{90}-to-calcium ratio in young people—whose bones are still forming—corresponds to about 1/1000 of the maximum permissible concentration recommended for adults—1 microcurie per standard man containing 1000 grams of calcium. The average soil in the United States contains about 10 times more, whereas abroad the radiostrontium content in other areas of the world not subject to the local test fallout is about one-third of that for the United States.

The surface air itself contains radiostrontium due to the fallout from the stratosphere and corresponding to the average time between rainstorms in which it can collect. Filtration of air at sea level discloses radiostrontium on filters if the filters are fine enough, even in periods when bombs are not being tested; thus the only fallout is from the stratosphere reservoir from the high-yield weapons. Measurements in the antarctic on snow samples collected there show that the fallout rate in January and February 1955 was comparable with that observed in the middle latitudes.

Conclusion

Finally, although the main part of the radioactivity from high-yield weapons fortunately dissipates in the stratosphere, the small but very significant part that falls out within a few hundred miles of the site of the explosion for weapons fired on the surface constitutes a very real hazard and nothing I have said should be interpreted otherwise. The weapons tests are conducted with great attention to this and the other dangers and every effort made to protect against misadventure. What we have learned from the studies I have described—which by the way have been conducted under the name Project Sunshine—is that these local precautions should be entirely adequate and the worldwide health hazards from the present rate of testing are insignificant.

Loyalty and Research

Report of the Committee on Loyalty in Relation to Government Support of Unclassified Research

The Federal Government now sponsors a substantial part of the total research activities of the nation. The major portion of this sponsorship relates to military defense and leads to information which, were it loosely guarded, might to some degree jeopardize the security of the United States. To protect the national interest, the Government has instituted measures designed to exclude from all projects involving such information persons that may be suspected of secret subversion including espionage, of serious moral defects of character, of indiscretion, or of vulnerability to blackmail. These measures are imposed upon each contractor and accepted voluntarily by each individual worker as a condition of employment. They are bulwarked by the vast Federal machinery of investigation and moderated or controlled through boards of review. Projects of this character are referred to as "classified" or "sensitive" and both their prevalence and the conditions that govern them appear to be a reflection of the times in which we live.

But above and beyond its present huge commitment to classified research the Government invests also in research of a more fundamental character in the physical, biological and other sciences through grants and contracts to universities, hospitals and other nonprofit institutions. By their inherent nature the results of such investigations are unlikely to affect directly our immediate military security. Nevertheless, this great body of knowledge, when published, disseminated, and taught in our universities, becomes the basis upon which scientists and engineers will build the economic welfare and military strength of our country. This is the national investment in the future of science and the very life line of our continuing growth, and it is incumbent upon the Government to discover and maintain those conditions under which it will best thrive.

In the administration of grants and contracts for unclassified research, which by its very definition has no implication of secrecy, the government has refrained by and large from initiating inquiries into the personal character of those carrying on the research. There have, however, been incidents when doubts have been raised with respect to the loyalty of specific individuals. Such cases will in all probability continue to occur from time to time. The question then arises as to the extent to which the Government is obligated to ascertain the loyalty of a scientist—not in the employ of the Government—who utilizes public funds on a project that clearly requires no security classification.

To assist in the establishment of policy in these matters, Governor Sherman Adams on behalf of the President of the United States invited the National Academy of Sciences on January 11, 1955 to counsel with the Government. He pointed out in his letter that the Academy acts under Congressional charter "to advise the Government in the formulation of policy to the end that the scientific resources of our country may be fully and effectively utilized." Governor Adams stressed moreover the tremendous importance which he attached to the handling of this problem so as to avoid misunderstandings between scientists and the Government which might impair the cordial relationships which are so vital to the national welfare, and added that "it is equally important that people outside the scientific community understand the nature of the problem and that their confidence in the Government's handling of this important phase of the public trust be maintained."

On January 28, 1955 Dr. Detlev W. Bronk, President of the Academy, accepted the task on behalf of the Academy

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The Committee on Loyalty in Relation to Government Support of Unclassified Research was appointed by Detlev W. Bronk, president of the National Academy of Sciences, in response to a request for counsel about matters relating to loyalty made by The Assistant to the President, Sherman Adams, on 11 Jan. 1955 [*Science* 121, 7A (11 Feb. 1955)]. The report was dated 13 Mar. and released by the White House on 4 Apr. along with a letter of acceptance from Adams. Whether or not the report will lead to an Executive Order putting some or all of the recommendations into effect remains to be seen.

The members of the committee were Robert F. Bacher, professor of physics, California Institute of Technology; Laird Bell, attorney, Chicago, Ill.; Wallace O. Fenn, professor of physiology, University of Rochester; Robert F. Loeb, professor of medicine, Columbia University; E. Bright Wilson, Jr., professor of chemistry, Harvard University; Henry M. Wriston, former president of Brown University; and J. A. Stratton, *chairman*, vice president and provost, Massachusetts Institute of Technology.