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Radioactive Fallout from Bomb Clouds

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There has been considerable public interest, and not a little apprehension, since the announcement that some of the inhabitants of the Marshall Islands had been exposed to radioactive fallout from one of the weapons tested in the Pacific in the spring of 1954. The wide variety of reactions to this announcement indicates a lack of detailed information about the mechanisms by which fallout particles are produced and about the biological implications of the radioactivity associated with the particles. Scientific data are not now available to answer all questions with certainty, but some features are sufficiently well understood to warrant public presentation.

Fallout is not a new thing to those charged with the responsibility for conducting tests of nuclear weapons. From the time of the first nuclear detonation at Alamogordo, N.M., it was clearly recognized that the now familiar stem-and-mushroom cloud contains enormous quantities of radioactive isotopes. Some of the radioactive material in the cloud will fall to the surface of the earth before it has decayed to stable forms, and it will produce areas of radioactive contamination. Monitoring teams followed the Alamogordo cloud and found some desert areas moderately contaminated with radioactive fallout.

At Operation Greenhouse, conducted at Eniwetok Atoll in 1949, a wind shift brought a portion of a bomb cloud over the testing area, and the atoll received fallout over a period of several hours. Detailed measurements were made of the radiation doses received by the task force personnel, and there seemed to be no reason to consider evacuation from the atoll.

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When peacetime weapons testing was authorized within the continental United States, the fallout problem was recognized, and an advisory panel was set up to advise the test manager and test director on all matters of public safety. Such a group has considered and approved every shot fired at the Nevada Proving Ground. Each panel is made up of specialists in the fields of atomic medicine, radiation health protection, blast, and meteorology. The panel has a changing membership but has included such capable men as John Bugher, AEC; J. P. Cooney, U.S. Army; and Shields Warren, Deaconess Hospital, Boston. The U.S. Public Health Service has had a representative on each panel.

Each detonation is carefully considered by such a panel several times before the firing. The first detailed consideration typically occurs about 24 hours before shot time. The expected blast and radiation are evaluated in terms of the predicted meteorology, and the shot is either "on" or "off." If it is "on," a second evaluation of both on-site and off-site hazards is made at minus 8 hours. Better weather forecasts are then available and a sounder judgment can be made. From then until shot time the panel may be in almost continuous session, watching for unfavorable meteorological developments that might call for a postponement. Winds are notoriously fickle, and even with this very careful study the radioactive debris may not go in the expected direction. A substantial error is anticipated, however, and only a very poor weather verification can lead to a situation requiring more than routine precautionary measures.

The biological hazards associated with fallout can be better appreciated with a clear understanding of the nature and mechanism of formation of the fallout particles. When an atomic bomb is detonated, nuclei of the fissionable material, U^{235} or Pu^{239}, are split into two approximately equal parts, the splitting taking place in any one of 30 or 40 different ways. The fission-product nuclei thus formed range over the middle of the periodic table from about zinc (atomic number 30) to europium (atomic number 63). The fission-product nuclei have an excess of neutrons and consequently are unstable. They emit beta particles, followed in many cases by gamma rays. After a series of successive beta-particle emissions, the neutron excess is relieved, and each fission chain terminates in a stable isotope that presents no hazard.

In a typical fission ${}_{92}U^{235}$ splits into ${}_{40}Zr^{97}$ and ${}_{52}Te^{137}$, both of which then undergo radioactive decay:

$$ {}_{40}Zr^{97} \xrightarrow[17\text{ hr}]{} {}_{41}Cb^{97} \xrightarrow[75\text{ min}]{} {}_{42}Mo^{97}\ \text{stable} $$

$$ {}_{52}Te^{137} \xrightarrow[1\text{ min}]{} {}_{53}I^{137} \xrightarrow[22\text{ sec}]{} {}_{54}Xe^{137} \xrightarrow[3\text{ min}]{} {}_{55}Cs^{137} \xrightarrow[27\text{ yr}]{} {}_{56}Ba^{137}\ \text{stable} $$

Each isotope decays with its characteristic half-life, which may be as short as a fraction of a second or as long as many years. The composite fission-product mixture, composed of more than 100 active isotopes, has no half-life, as ordinarily defined, but shows an activity that decays according to the expression $1/t^{1.2}$. As decay proceeds, elements of short half-life essentially disappear; old fission-product mixtures consist primarily of long-lived isotopes. Twenty-year Sr^{90} is one example of a long-lived fission product occurring with a rather high yield.

Most data on weapons performance are given in terms of a "nominal" bomb of 20 kilotons, which is to say a weapon with an explosive power equal to that derived from the detonation of 20,000 tons of TNT. Table 1 lists the gamma-ray activities of the fission products from a nominal detonation as a function of time after detonation (*1*). These figures seem appalling when one remembers that the unit of activity, the curie, is the rate of disintegration of 1 gram of radium, and that rather elaborate precautions are taken in handling even a few millicuries of radioactive materials. The situation appears overwhelming when these figures are scaled up for weapon sizes greater than that of the nominal bomb. For example, simple scaling from 20 kilotons to 2 megatons means an increase of activities by a factor of 100, which would result in a figure of 8.2×10^{13} curies 1 minute after detonation. The figures must, however, be considered in the light of the exact method for formation and subsequent fate of the fission products responsible for the radioactivity.

Each fission process is an independent event, and consequently fission products are formed as individual nuclei in a state of aggregation quite different from that in which they are usually observed. When a nuclear device is detonated, all the energy is released in a very short time, measured in millionths of a second. As a consequence, the temperature of a relatively small volume rises to fantastic levels, and all material in this "fireball" will exist as a gas. All the fission products and, consequently, all the radioactivity (if we except that activity induced locally by escape neutrons) are inside the high-temperature fireball.

The fireball, being less dense than the surrounding air, will rise to great heights, just as a hot-air balloon rises until it is in equilibrium with its environment. The cloud from a nominal bomb may rise to an altitude of 40,000 feet at an initial rate of 200 miles per hour (*1*). As long as the fission products remain at this altitude, no hazards are to be anticipated at the surface of the earth. Intensity attenuation by the inverse square law and atmospheric absorption will reduce radiation levels at the earth's surface to insignificant values. Although it would be unwise to linger near the cloud in its early stages, passage through the cloud is not necessarily a fatal operation. Ten minutes after detonation, a passage through the cloud at 300 miles per hour would result in a radiation dose of about 25 roentgens (*1*), which is about one-twentieth of the median lethal dose for man. Some fission products might adhere to the plane and raise the dose somewhat, but the dose would probably not be doubled.

In the simple case we have been considering, fallout, or the return of the radioactive materials to the earth's surface, will be greatly delayed or may not take place at all. In still air particles fall under the force of gravity according to Stokes' law, which requires that the speed of fall increase rapidly with particle size. Thus 70 days will be required for a 5-micron particle to fall 40,000 feet, while a 16-micron particle will fall the same distance in 7 days. Atmospheric turbulence complicates the practical situation, but it is evident that very small particles will remain at high altitudes for long periods of time. There will, therefore, be a negligible fallout hazard associated with a "clean" detonation as described.

Table 1. Gamma-ray activities from a 20-kiloton detonation.

Time after detonation	Activity (c)
1 min	8.2×10^{11}
1 hr	6×10^{9}
1 day	1.33×10^{8}
1 wk	1.3×10^{7}
1 mo	2.3×10^{6}
1 yr	1.1×10^{5}
10 yr	8×10^{3}
100 yr	6×10^{2}

The situation will be quite different if the detonation occurs at a low altitude, so that the fireball intersects the surface of the earth. There is then an opportunity for a thorough mixing of the gaseous fission products with dust and dirt from the earth or with the debris from shattered buildings. The hot cloud will rise as before, creating a low-pressure area behind it. There will be an inward rush of dust-laden air to relieve the low pressure, and a jet or column of particulate matter will rise beneath the cloud. The jet may overtake the cloud and mix with it, thus providing another chance for intimate contact between the atomic-sized fission products and macroscopic particles. During the mixing and cooling, many fission fragments will condense onto the particles; the rate of fall will then be determined by the size distribution of the particles rather than by the characteristics of the fission fragments.

Large, visible particles may fall out in a matter of minutes to produce the radioactive "snow" reported during the Pacific operations in 1954. Smaller particles will be carried away by the prevailing winds, to dribble down along the path of the cloud at places determined by each particle size. We thus have a contaminated area downwind from the point of detonation, of a shape and size determined by meteorological conditions. Each fallout pattern will present a unique situation, and general conclusions can be drawn only by making some reasonable assumptions.

Obviously, early fallout will be more serious than late, for there has been less chance for radioactive decay. We will consider the situation at plus 1 hour when fallout will under average conditions be occurring at distances of 20 to 25 miles from the point of detonation. If 1 million curies of activity are spread over 1 square mile, the resulting gamma ray dose rate will be about 8 roentgens per hour (*1*), and from the properties of fission-product decay we calculate that this will give an "infinity" dose of 40 roentgens. Infinity dose is the total radiation dosage received by an individual who was in the area when fallout occurred and who remained there for an infinite length of time. The calculation of infinity doses tends to exaggerate the hazard, but not seriously, for a relatively large fraction of the infinity dose is received in the first few days.

Detailed data on chronic irradiation effects are not available, but 40 roentgens is certainly not lethal. An infinity dose of 1000 roentgens, resulting from the deposition of 25 million curies per square mile, would undoubtedly be a serious hazard to occupants of the contaminated area. If all the activity from a nominal bomb came down at plus 1 hour we could expect the serious contamination of about 200 square miles. Extrapolating as before by a factor of 100, we arrive at 20,000 square miles of potentially dangerous fallout area for a hypothetical 2-megaton burst. These figures do not, of course, represent the actual situation, since uniform distribution is never attained.

The calculated areas are obviously too large, because by Stokes' law only particles larger than 200 microns can fall 40,000 feet in 1 hour. Many of the cloud particles will be smaller than this and will remain suspended for longer periods of time. It is probably realistic to reduce these figures by a factor of 100 to take care of this fact and the decrease in radiation intensities owing to weathering and the shielding effects of normal dwellings. With this factor of ignorance, the potentially dangerous areas shrink to 2 and 200 square miles, respectively.

These figures represent areas where survival is the criterion of acceptability and where only the effects of external penetrating radiation are considered. They are of interest in assessing possible effects of an enemy attack with nuclear weapons but are obviously not applicable when considering the peacetime testing of nuclear devices where national survival is not immediately at stake.

Before considering the peacetime situation it will be well to review briefly presently accepted standards for radiation exposure in industry. At the present time the National Committee on Radiation Protection recommends (*2*) that whole-body exposure not exceed 0.3 roentgen per week for personnel planning to work with radiation for long periods of time. This level allows a total yearly dose of 15.6 roentgens, but integration of the weekly dose is not recommended. That is, one should not plan to receive his yearly dose of 15.6 roentgens in 1 week, even though no further exposure is contemplated during the subsequent 51 weeks.

The 0.3 roentgen per week criterion is quite satisfactory for day-by-day exposures in the laboratory or in industry but is seriously restrictive to a weapons-testing program. Here, radiation exposure necessarily comes at irregular intervals, with maxima occurring after each contaminating detonation. The Atomic

Energy Commission has taken what appears to be a realistic approach to this problem. On the one hand they have reduced the allowable annual dose by a factor of 4 to 3.9 roentgens, and on the other hand they allow this to be received at any rate or over any period of time. Thus a single detonation might, because of adverse wind changes, result in a fallout pattern that would deliver 3.9 roentgens to a given community. If this is the case, that community has used up its yearly radiation allotment, and extreme care must be taken by the test group to insure that no further fallout is received there for at least 1 year.

During test operations at the Nevada Proving Ground an elaborate off-site monitoring program is maintained, manned by U.S. Public Health Service personnel, and careful records are kept of all radiation exposures up to at least 200 miles downwind from the test site. Experience has shown that beyond this range decay has reduced the radioactivity to levels incapable of exceeding the established exposure limits. It is true that fallout is readily detectable well beyond the 200-mile radius and that some people have been disturbed by traces of activity found on the east coast of the United States.

An examination of the records shows that the criteria laid down by the AEC have been well met. Large numbers of people have not been exposed to high levels of radiation, and if the 0.3 roentgen per week were the only criterion we could conclude that there had been no radiation injuries as a result of the continental test program.

Three other aspects of radiation hazards remain to be considered before a final conclusion can be drawn concerning both the safety of weapons test operations as now conducted and the radiological hazards to be anticipated from an enemy attack with nuclear weapons. The 0.3-roentgen-per-week figure is based on the assumption that all the radiation is received from external sources, with no radioactive materials entering the body by any route. This can scarcely be the case for a fallout exposure, for during the period of actual fallout there will be radioactive particles in the air at all altitudes from the surface of the earth to the height of the bomb cloud. The possibility of beta-particle burns and injury from particle inhalation must be considered.

During fallout, radioactive particles will settle out on the exposed skin of anyone outdoors, and the hazard of beta-particle burns is added to that arising from the more penetrating gamma rays. Beta particles from fission products travel through only a few millimeters of tissue and, consequently, do not produce the generalized injury associated with more penetrating radiations. However, beta particles give up all of their energy in a very short distance and hence the amount of ionization in the superficial layers of tissue will be relatively large. Beta-particle burns resulting from fallout are well known, the earliest example being the cattle contaminated from the detonation at Alamogordo.

A number of cattle about 10 miles from the Alamogordo blast received fallout on their backs. The fine fallout particles were retained by the hair, and in a few weeks epilation occurred and blister-like lesions developed. The lesions healed much like ordinary thermal burns, and hair grew again, although the original red color was replaced with white or gray. These animals have been carefully observed for several years and show no radiation effects other than the graying of the hair. The cows produced a normal number of calves and these, in turn, appear to be normal in all respects.

There was some epilation among the Marshall Islanders who received fallout during the 1954 test series. It is interesting to note that in the human cases the new hair returned a deep black color, with no sign of the graying seen in the cattle.

Relatively few data are available for estimating the beta-particle hazard. Unfortunately, most of our knowledge of acceptable radiation dosage must be based on cases of human overexposure. During the half-century of experience with x-rays a considerable number of cases of overexposure have been studied, but the number of well-documented cases of beta-particle exposure is very small. The National Committee on Radiation Protection (*2*) recommends a limit of 1.5 rep (*3*) per week of beta-particle radiation to limited areas such as the hands, and this seems to be a reasonable value for present discussion.

If 13 weeks of integration is allowed, as in the case of gamma-ray exposure, up to 19.5 rep is permissible for a single incident in 1 year. This is a more severe restriction than the allowable penetrating radiation restriction, for the limit has increased by a factor of about 5, while the ionization of tissue has gone up by a factor of 10 or more. Under peacetime testing operations this is not a serious limitation, because relatively simple measures can reduce the beta-particle hazard to negligible levels. The beta-particle hazard is primarily present only during the time when fallout particles are actually reaching the surface of the earth. Once down they contribute to the general activity of the area but do not contaminate skin surfaces to any extent.

Fallout can be readily detected with standard radiation survey equipment, and with an adequate monitoring service populations can be requested to stay indoors during the active phases of fallout if the intensities warrant such precautions. In general this will not prove to be a very disturbing request, for active fallout will usually last less than an hour.

People who have received fallout directly on their skin can remove practically all of the particles by washing or vigorously dry-brushing. An occasional individual is opposed to the use of soap and water, but he can usually be persuaded to wash when the situation is explained to him. Thus it appears that beta-particle hazards associated with test operations can be eliminated by an adequate downwind monitoring system with only minor inconveniences to a few people. People who have inadvertently received fallout on their skin can remove the contamination by washing. The same basic principles, avoidance and decontamination, can be used against larger weapons that may be employed against us. The activity levels will be much higher, and greater areas may be involved, but cover and cleanliness are still the guiding principles for reducing beta-particle hazards.

In considering high levels of radiation resulting from enemy action, one big difference between overexposure to gamma rays and beta particles should be mentioned. Overexposure to gamma rays will be followed by typical signs of radiation injury: weakness, nausea, vomiting, diarrhea, leucopenia, generalized infection, and death. External beta-particles, however, because of limited penetration, do not reach the hematopoetic system and sensitive organs, and signs of general radiation injury are absent. Exposures of a few thousand rep will result in epilation, followed by third-degree burns that may require long hospitalization and extensive skin grafting if late tissue breakdown is to be avoided. With adequate care, however, the inevitable fatal outcome associated with gross overexposure to more penetrating radiation is avoided.

During active fallout the air contains large numbers of slowly falling particles, and it is inevitable that some of these will enter the respiratory system. This has given rise to considerable concern that inhalation hazards may be the most serious aspect of the fallout problem. Lack of data prevents giving exact answers to the questions of inhalation hazard, but a few general comments can be made.

In the first place, only a limited range of particle sizes can enter and be retained by the alveoli. Particles smaller than 0.5 microns behave much like gas molecules and enter and leave the lungs without retention. Normal nasal efficiency in removing particles is practically 100 percent for particles larger than 5 microns, and consequently few of these particles reach the alveoli. The larger particles are removed by ciliary action and are swallowed. Their subsequent fate is determined primarily by the chemical composition of the particles. Some will be absorbed, and others will be excreted almost completely.

It is not possible to give the fraction of the total fission-product activity associated with particles of retainable size, because this will depend upon the size distribution of the particles mixing with the bomb cloud. The distribution will vary with each type of terrain, but in general it is evident that the fraction of particles in the 0.5- to 5-micron range will be small.

Except under very unusual circumstances, early fallout will not consist of retainable particles, because, by Stokes' law, a 5-micron particle requires more than 70 days to fall 40,000 feet. By this time radioactive decay has reduced the total activity by a factor of 7500 from the activity at 1 hour.

As an example, we may cite the results of an experiment in which sheep and dogs were exposed to early fallout of an intensity scarcely to be experienced by any survivors from an atomic attack. In this particular case the fallout cloud was so dense that the animal cages were hidden from view for well over an hour, and deposited fallout was so heavy that recovery operations had to be postponed for 24 hours to avoid overexposure of personnel. The original experimental design was ruined because all animals received a lethal dose of penetrating radiation and had to be killed well ahead of schedule. Hundreds of lung sections from 40 animals were examined and many nonradioactive particles were found. Only 56 particles showed any activity. There was active material in the gut, and some of this presumably came from the swallowing of large inhaled particles, although licking the fur undoubtedly contributed to some extent.

From these considerations it appears to be difficult for enough active particulates to enter the lungs and remain there to produce damaging average radiation doses. It does not follow that there is no radiation hazard, for it is conceivable that a single active particle might be sufficient to induce a radiation cancer. This seems unlikely because the total activity associated with a particle of size less than 5 microns is not great, but proof on this point is lacking. In this connection we may quote from Furth and Lorenz (*4*): "It is now well established that a single local exposure is likely to cause a neoplasm only under exceptional conditions, but a single massive exposure to either X or γ radiation over the entire body may often cause cancers in some internal organs."

Radioactive particles may also enter the body from the use of food or water exposed to fallout. The $Sr^{90} + Y^{90}$ complex is probably the most hazardous fission-product fraction, because it is produced in a good yield, has a long half-life, and tends to be retained by bone. Let us consider the situation previously discussed, where the fission products from a nominal bomb produced a serious external radiation hazard over an area of 2 square miles. It is easily calculated that about 1 kilogram of material must fission in a nominal detonation and that about 50 grams of Sr^{90} will be formed. If all of this Sr^{90} were spread uniformly over 2 square miles there would be about 1 microgram per square foot. About 23 percent of ingested Sr^{90} reaches the bone, and the maximum permissible body burden is 1 microgram (*5*). It appears, therefore, that in an area where fallout is serious because of external dose considerations, one could ingest without serious effects all the fission products deposited on 4 square feet of food. Since fallout particles can be removed from most surfaces by washing, it appears that food need not present a hazard even in heavily contaminated areas.

As an example of a water supply, we may consider Lake Mead, lying in close proximity to the Nevada Proving Ground. Conservatively, Lake Mead contains about 600×10^9 cubic feet of water. If all the fission products from a nominal bomb fell into Lake Mead and were thoroughly mixed, one would have to drink some 50,000 cubic feet of water to reach the tolerance value for Sr^{90}.

The most controversial facet of radiation injury is the possible genetic effect on future generations. This field can be discussed only by specialists, and I shall restrict my comments to a few relatively noncontroversial generalizations.

The fact that there are differences of interpretation of genetic data indicates that the exact situation is not known. It is certain that radiation can readily produce both gene and chromosomal changes and that these changes will tend to be perpetuated by the very nature of genetic materials. It is also certain that radiation can produce changes leading to genetic death in several generations. From data taken primarily on fruit flies, we can predict that a certain number of visible mutants will appear for each roentgen of exposure, and other, less obvious mutations can be inferred. We can predict that the number of genetic injuries will increase with the radiation dose.

Unfortunately, for present purposes, man is not a fruit fly, and extrapolations from fly to man must be modified by man's breeding habits and psychological reactions to a changing situation. It is too early to draw final conclusions from the experiences of Hiroshima and Nagasaki, and in any case these may not provide the real answer.

Decisions of great importance must be taken, decisions that may well affect the fate of mankind to the end of time. We must avoid treading the genetically downward path to the point of no return, to the point where race extinction or degradation is inevitable. We must, however, avoid the hysterical banning of all nuclear experiments likely to produce radioactive fallout.

If a force in being is necessary to maintain our way of life and keep an uncertain peace in a troubled world, then our atomic-weapon stockpile, both in quality and quantity, is a national asset of the first importance. Supremacy, or at worst parity, in nuclear weapons becomes a necessity for an adequate national defense. Granting these premises, a weapons development program becomes an essential part of our defense effort, and obviously such a program requires an adequate testing facility. Proving grounds should then be considered as facilities of considerable national importance and not mere playgrounds for the amusement of bomb-happy scientists.

There is a vast difference between a carefully prepared program for exploding a few nuclear devices under well-controlled conditions, and in such a way as to minimize radiological hazard, and an all-out war with both sides using nuclear devices of all sizes in the most effective and damaging ways possible. If the first alternative helps to prevent the second, we must accept the uncertainty of some information not yet known and take the calculated risk of some radiation injury now in order that we may prevent annihilation later.

References and Notes

1. *The Effects of Atomic Weapons* (Government Printing Office, Washington, D.C., 1950).
2. *Permissible Dose from External Sources of Ionizing Radiation.* National Bureau of Standards Handbook 59 (Government Printing Office, Washington, D.C., 1954).
3. The rep, or roentgen equivalent physical, is a unit used with particulate radiation, comparable to the roentgen and representing the absorption of 93 ergs per gram of tissue.
4. *Radiation Biology*, vol. 1, pt. 2, A. Hollaender, Ed. (McGraw-Hill, New York, 1954).
5. *Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water.* National Bureau of Standards Handbook 52 (Government Printing Office, Washington, D.C., 1953).