Chapter I

Radiation Characteristics of the Fallout Material and the Determination of the Dose of Radiation

C. A. Sondhaus
Robert Sharp, Lt. (jg) MSC USN
V. P. Bond, M. D., Ph. D.
E. P. Cronkite, Cdr. (MC) USN

and the analysis at 4 months represents only radiological decay. Thus, the results are not directly comparable to those obtained from animals which were returned alive, and in which biological turnover as well as radiological decay were operating.

The largest fraction of the gross beta activity in the fish was contributed by the concentration of radioactive material in the viscera. In two of the fish in which bones and muscle were separated and analysed, equal amounts of activity were found in each fraction. However, the storage of these fish in formaldehyde for 3 months may have permitted the diffusion of the radioelements from bone to muscle to take place. Further studies on fresh fish will clarify this point.

The contamination of the fish in the lagoon was considerably greater than that of the land animals studied. As fish form a large staple item in the diet of the Marshallese, the high level of contamination is important.

At the end of a 2½-month experimental period, the excretion by the chickens of both beta and gamma activity per 24 hours was 5 percent of the value measured at the start at 37 days post detonation (Fig. 5.1).

Analysis of pig excreta indicated a similar decrease of activity with time. In a 6-week period, the gamma activity excreted per 24 hours decreased to about 2.5 percent of the activity excreted at 44 days post detonation.

The excreta of the pigs from Utirik contained less than 10 percent of the gross beta activity found in the excreta of the pigs from Rongelap at the same time. This ratio of 10 was approximately the same ratio found between the activity of the food, water and soil samples of the two locations.

Radiochemical Analysis of Tissues and Excreta. Radiochemical analysis of pig tissues indicated that 62 percent of the skeletal beta activity was derived from Sr^{89}, 7 percent from Ba^{140}, and 10 percent from the rare earth group at 82 days post detonation (Table 5.8). The radioisotopic composition of the urine at this time was similar to that of the skeleton. The distribution of activity in the body of the pig may represent the distribution in human beings. The absolute amount of internal contamination in the Rongelap people was, however, only a tenth of that found in the animals.

At 4 months post detonation, the alkaline earths comprised less than 2 percent of the total activity in the clam (Table 5.10). The rare earth group constituted 33 percent of the total beta activity. The balance of the activity was contributed chiefly by Zr^{95} (21 percent) and $Ru^{103,106}$ (32 percent). About 50 percent of the material found in the viscera of the fish was of the rare earth group. Very small amounts of strontium and barium were found. In the tissues of the fish, strontium, barium and the rare earths contributed only about 10 percent of the total activity.

5.43 Autoradiographs

A number of autoradiographs of the tibiae and femurs of 1 chick, 4 pigs, 1 rooster and 2 chickens were prepared both at the USNRDL and at the Argonne National Laboratory (ANL) to determine the pattern of deposition of fission products. Contact printing on X-ray no-screen film was found to be the most satisfactory method of preparing the autoradiographs. The discussion and conclusions presented below summarize the findings reported by Norris (15).

The autoradiograph of a tibia from a chicken sacrificed at 45 days post detonation (Fig. 5.2) indicated a relatively uniform distribution of the activity throughout most of the bone, with the highest concentration of activity in the area adjacent to the epiphysis. This area of high activity corresponds to an area of dense trabecular bone.

The tibia and femur of a baby chick, which died spontaneously 47 days post detonation, showed the heaviest concentration of radioactive material in the diaphysis (Fig. 5.3). The end regions of the bone, which were laid down after the animals were removed from the contaminated environment, were relatively lacking in activity. The region of greatest activity was in the diaphysis, which appeared to be ab-

Outline

1.1 Nature of the Event and Description of the Exposed Groups

FOLLOWING THE DETONATION of a nuclear device at the Pacific Proving ground in the Spring of 1954, significant amounts of radioactive material fell on neighboring populated atolls. The Marshallese inhabitants of Rongelap atoll (designated as Group I) received the highest calculated dose of radiation. Some of the Rongelap people were located temporarily on Ailinginae atoll from the time of the fallout until they were evacuated (Group II). Their calculated dose was smaller than that of the other members of the parent group. The American service men (Group III) were located on Rongerik atoll. The largest group of Marshallese (Group IV) were located on Utirik atoll and received the smallest dose. The Marshallese were living under relatively primitive conditions in lightly constructed palm houses (Fig. 1.1).

The American military personnel had the second highest exposure. They were more aware of the significance of the fallout than were the Marshallese, and promptly put on additional clothing to protect their skin. As far as duties would permit, they remained inside of aluminum buildings. In contrast, most of the Marshallese remained out-of-doors and thus were more heavily contaminated by the material falling on the atolls. Some of the Marshallese, however, went swimming during the fallout and many of the children waded in the water, thus washing a considerable amount of the material from their skin.

The exposed personnel were evacuated to Kwajalein by air and surface transportation. Since a survey of all individuals showed that there was significant contamination of skin, hair and clothes, prompt decontamination was instituted. Clothes were removed and laundered and repeated washings of the skin and hair with fresh water and soap were carried out. In many of the Marshallese, it was difficult to wash the radioactive material from the hair because of the heavy coconut-oil hair dressing.

The exposure groups with individuals involved, the calculated doses of radiation, the probable times of beginning of the fallout and the evacuation times are given in Table 1.1.

Table 1.1—Exposed, and Control Unexposed Groups

Group Designation	Total Number in Group	Approximate Time of Commencement of Fallout	Time of Evacuation	Instrument Readings Used in Dose Calculations	Best Estimate of Total Gamma Dose in Air (r)
Group I.—Rongelap	64	H + 4 to 6 hrs.	H + 50 hrs. (16 people) H + 51 hrs. (48 people)	375 mr/hrs., H + 7 days	175
Group II.—Ailinginae	18	H + 4 to 6 hrs.	H + 58 hrs.	100 mr/hrs., H + 9 days	69
Group III.—Rongerik	28	H + 6.8 hrs.	H + 28.5 hrs. (8 men) H + 34 hrs. (20 men)	280 mr/hrs., H + 9 days	78
Group IV.—Utirik	157	H + 22 hrs.	Started at H + 55 hrs. Completed at H + 78 hrs.	40 mr/hrs., H + 8 days	14
Marshallese, Control Group A	117				
Americans, Control Kwajalein-American	105				

Total Exposed—267; Total Controls—222

FIGURE 1.1—*Typical construction of the Marshallese homes to illustrate the exposure environment of the Marshallese and the lack of shielding from gamma radiation.*

1.2 Whole Body Gamma Doses

THE ESTIMATED VALUES of external dose given in Table 1.1 were calculated from readings of radiation field survey instruments.* Averages of a number of dose rate measurements on each island at a given time were used. The readings were taken in air, approximately three feet above ground, several days after the inhabitants were evacuated. Before this time, adequate surveys with well calibrated instruments had not been possible, although readings had been taken with a single survey meter at the time of evacuation. However, preliminary calibration of this instrument had not been carried out, nor was its operating condition known to be satisfactory under the emergency condition prevailing at the time of use. For these reasons the later readings, which were higher than the early survey by an average of 50 percent when corrected to the same times, were used in computing the doses listed. The instruments used for the later measurements were calibrated just prior to the surveys.

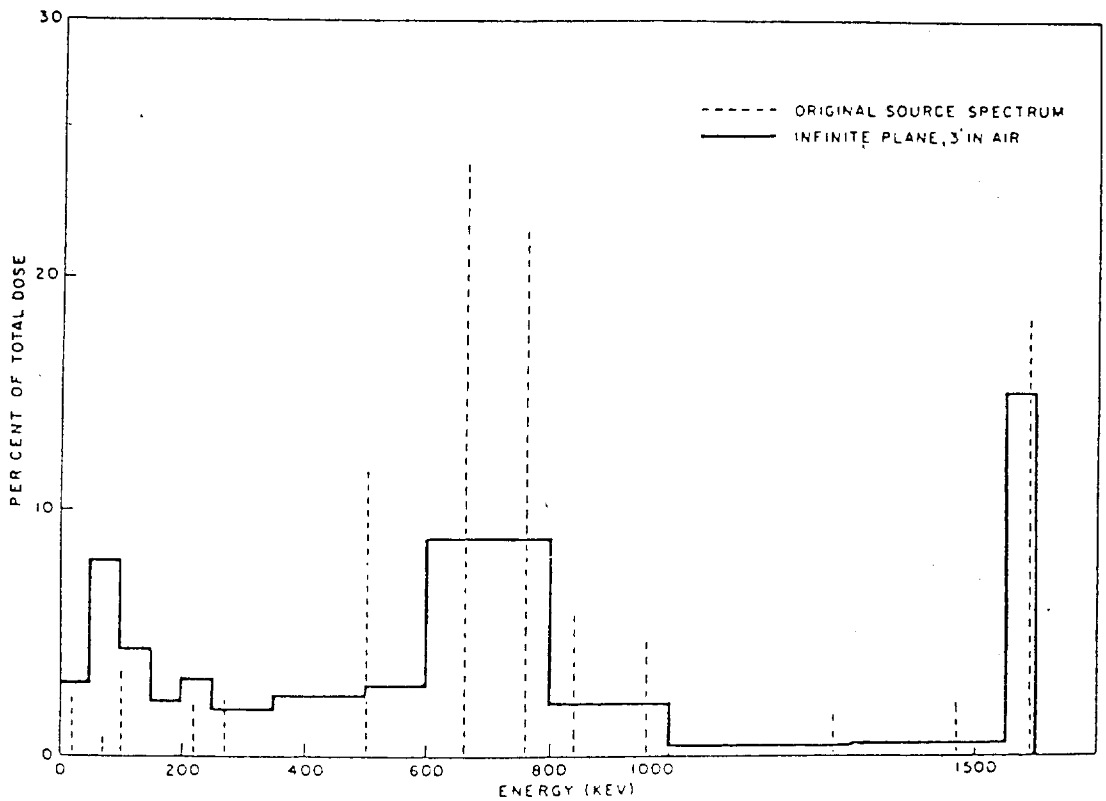


FIGURE 1.2—*Distribution of inherent energies of gamma radiation from mixed fission products, and histogram of degraded energies produced by Compton scattering at level of infinite plane 3 feet in air above uniformly-distributed fission products field.*

*Army Navy catalog AN/PDR-39.

1.21 Characteristics of the Gamma Radiation

The fallout material, when deposited on the ground, formed a large planar source of radiation. The energy distribution of the radiation reaching an exposed individual was influenced by its passage through the intervening air. A knowledge of the energy spectrum of the ra-

5002763

diation as it emanated from the material itself made possible an approximate calculation of the proportion of total dose delivered in each of several energy regions. Such a calculation, using spectrometric data on the source material of mixed fission products and taking into account this energy degradation by Compton scattering along the path in air, (1) led to the dose-energy histogram shown in Figure 1.2. Roughly there were three regions, with maxima at 100, 700 and 1500 KEV. The total exposure was thus the resultant effect of partial doses from each energy region, making the exposure energy condition significantly different from those of radiation therapy or experimental radiobiology.

The data in Figure 1.2 are based on the spectrum of 4 day old fission products from a fallout sample. In the absence of other data, this was taken as representative of the fallout on all of the islands to which the individuals were exposed. An energy correction factor for the radiation measuring instrument was calculated by weighting the dose from each energy interval by an average meter response factor for that energy (2). A geometry correction factor was also calculated. The total correction resulting from this procedure was found to be about twenty percent.

Using this correction, the dose rates on the islands at the time of survey were determined. Since radioactive decay of the fission products had occurred between the start of the exposure and this time, it was necessary to obtain a value for this decay rate during the exposure period in order to calculate a total dose in each case. A large number of radioisotopes are present in varying proportions in the fission product mixture, and the total rate of change of radiation intensity resulting from them may differ somewhat with place and time. The best data available in this case came from fallout samples taken soon after the detonation at points some distance from the contaminated atolls. Decay rates of these samples were measured in the field and in the laboratory, and a fairly consistent pattern was observed among various locations and samples. In addition, theoretical considerations based on the radiochemical composition of the fallout mixture permitted decay rates to be calculated for different intervals between the time of initial exposure and later survey readings (3). These agree well with the experimental data, and were used both in the dose calculations during the exposure intervals and in extrapolating the later survey readings to earlier times.

1.22 Duration of the Exposures

The time of evacuation is known accurately for all the islands; however, the time of arrival of the radioactive cloud was determined precisely only for Rongerik by means of a continuously recording dose rate monitor located at the weather station on that atoll. As the radiation intensity rose above the background, a material with a misty appearance began to fall. The times of beginning of fallout for Rongelap and Ailinginae atolls were estimated from similar visual observations. These estimates were consistent with the relative distances from the site of detonation and the known wind velocities. Fallout was not observed on Utirik, hence the estimate of arrival time was made on the basis of wind velocity and distance.

Two extreme possibilities exist relative to the duration of the fallouts: the first, that the fallout occurred entirely within a short time; the second, that it was gradual and extended over a longer period. The monitoring instrument on Rongerik went off scale at 100 mr/hr, one-half hour after the dose rate began to rise above background. If this rate of increase is taken as constant, and is extrapolated to a point for which subsequent decay would reduce the dose rate to the values found at later times, the assumption of a long fallout of about 16 hours is found to be necessary. This slow rate of fall and late maximum time of dose rate was one limiting case; however this situation was not considered likely. Existing data are inconclusive, but several indications favor a shorter "effective fallout time hypothesis" and are summarized below.

5002764

a. The estimated durations of fallout which result from the above extrapolation of initial fallout rate for Group I and III appear too long to have occurred at the distances of these people from the shot island, since the wind velocity in the area was high enough to move the cloud over the islands in a considerably shorter time, as little as one-half of the above indicated time.

b. The accounts of the visibility of the fallouts, although conflicting, do not indicate such late cessation.

c. Doses calculated on a long fallout constant rate of increase hypothesis are lower than those due to a short fallout, since a short fallout quickly deposits a large amount of activity. For both a 16 hour and 8 hour fallout assumption, a dose value was estimated. The ranges are then as follows:

Table 1.2

Location	Dose in r Fallout Time	
	16 hr	8 hr
Rongelap (Group I)	159 r	209 r
Ailinginae (Group II)	72 r	92 r
Rongerik (Group III)	70 r	106 r
Utirik (Group IV)	12 r	15 r

On Rongerik (Group III) a set of film badge readings were obtained which constitute the only direct evidence of total dose. Several badges worn both outdoors and inside lightly constructed buildings on the island read about 50 to 65 r, and one badge which remained outdoors over the 28.5 hour period read 98 r. Another group of badges, kept indoors inside a steel refrigerator, read 38 r. These dose values represent a variety of conditions, but, considering the shielding and attenuation factors, are consistent with the assumption that the dose outside during the first 28.5 hours after the beginning of the fallout corresponded to about 12 hours of constant fallout.

d. For Utirik atoll Group IV, only a fallout time of about 12 hours or less is consistent with the later dose rates observed, provided the fallout actually began as late as was estimated from wind and distance factors.

e. A long fallout probably would not be uniformly heavy throughout, the first portion being the most intense and the balance decreasing with time. The total phenomenon would thus tend toward the effect of a shorter fallout. This is supported by monitor data from other nuclear events, where initially heavy fallout is reported to produce a peak of air-borne radioactivity soon after arrival, with the airborne activity level then decreasing. The latter part of the fallout, though still detectable as dust, may then produce only a small fraction of the total dose from material on the ground. Hence the total dose may be estimated fairly accurately by assuming a constant fallout to have been complete in a much shorter "effective" time.

The dose values given in Table 1.1, based on film badge, meter and monitor data, are consistent with a constant fallout hypothesis of about 12 hours effective time.* One exception is made; the dose values for Group III are about 75 percent of the 12 hour fallout value, averaged for 28.5 and 34 hour exposures. This was felt to express most accurately the average air dose received by personnel who spent roughly half their time inside structures where the dose rate was later found to be roughly half that outdoors. On the other islands such shielding was not available.

Figure 1.3. illustrates the cumulation of radiation dose as a function of time after detonation. The dose rate varied continuously. The major portion of radiation was received at the higher dose rate prevailing in the early portion of the exposure period. By the time that

*Using 12 hours actually results in values which are higher than those of Table 1.1 by 3 to 11 r, Table 1.1 listing the values calculated before all spectrum data was available. Uncertainty in all the information is greater than this difference, which is neglected.

90 percent of the dose had been received, the dose rate had fallen to less than 40 percent of its initial value. Thus the dose rate also differed from the usual constant rate in the laboratory.

the dose at the center of the body is approximately 50 percent higher than would result from a given air dose with narrow beam geometry. Figure 1.4 illustrates the depth dose curve from an experimental situation using

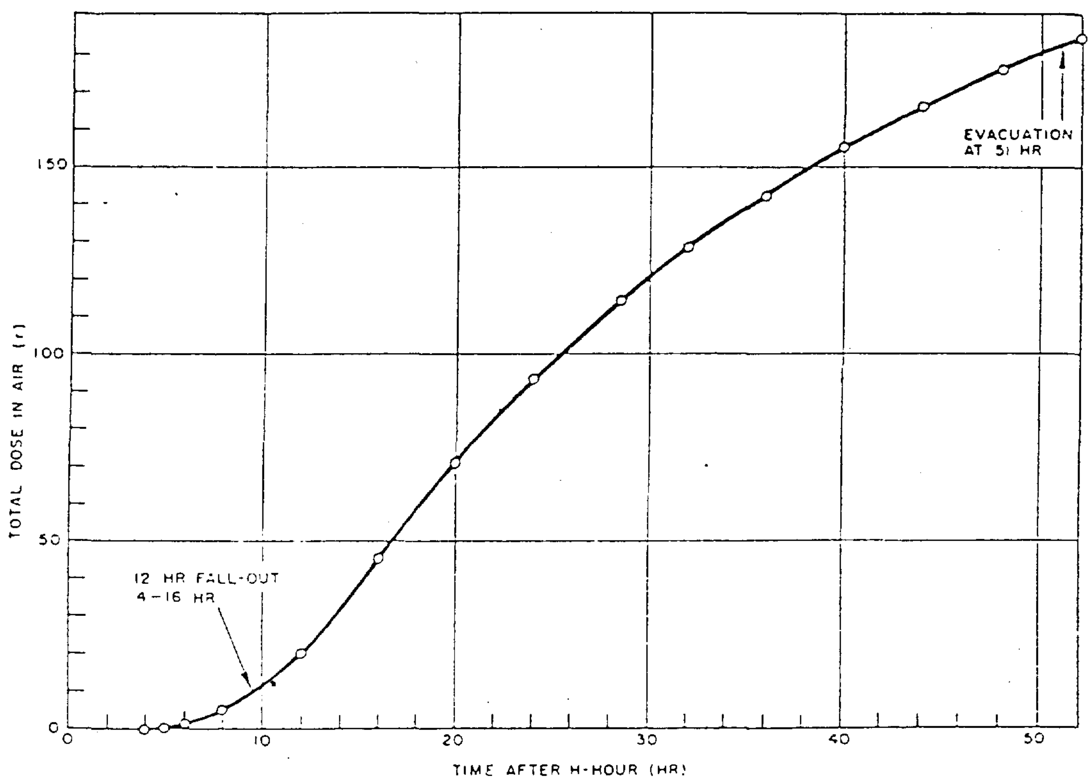


FIGURE 1.3—*The accumulation of gamma dose as a function of time after commencement of fallout on Rongelap atoll.*

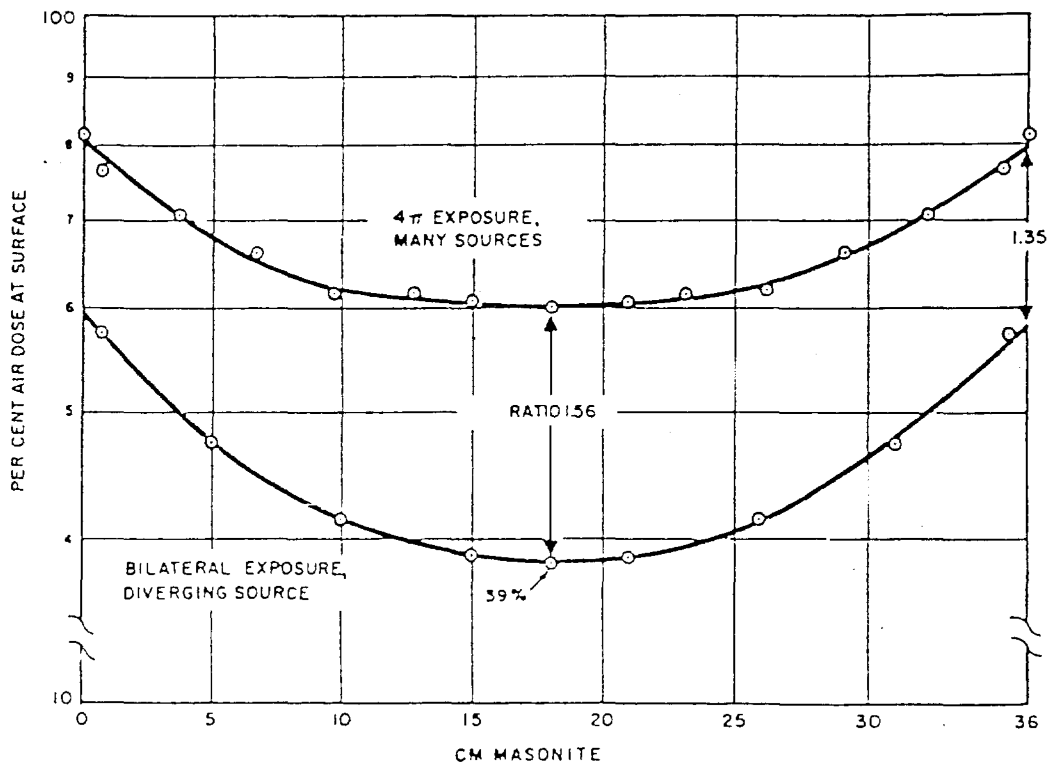
1.23 Geometry of the Exposure

In addition to the dose rate and energy differences the geometry of the exposure to fallout radiation is significantly different from the usual laboratory sources. Since fallout radiation is delivered from a planar source the usual narrow beam geometry is not applicable. In such a diffuse 360° field, the decrease of dose, with depth in tissue is less pronounced than that resulting from a bilateral exposure to an X-ray beam because falloff from inverse square is in effect neutralized. For the same energy, spherically oriented Co^{60} sources with a phantom placed at their center, compared with a conventional bilateral depth dose curve obtained with a single source (4). In the latter case, the air dose is usually measured at the point subsequently occupied by the center of the proximal surface of the patient or animal with respect to the source. For the field case, all surfaces are "proximal," in the sense that the air dose measured anywhere in the space subsequently occupied by the individual is the same. It is this air dose which is measured by a field instrument; it does not bear the same

5002766

relationship to the surface dose and depth dose as does the air dose measured in a "point source" beam in the clinic or laboratory. It would appear under these circumstances and in most experimental conditions that the midline dose, rather than dose measured in air, would be the source" beam air doses with comparable biologic effect are obtained:

Rongelap, Group I	260 r
Ailinginae, Group II	100 r
Rongerik, Group III	120 r
Utirik, Group IV	20 r



DEPTH DOSE DISTRIBUTION IN CYLINDRICAL PHANTOM, CO^{60} FACILITY, (NMRI)

FIGURE 1.4—*Comparison of depth dose curves in masonite phantoms from bilateral exposure to a single point source, and simultaneous exposure to multiple sources with a spherical distribution around the phantom.*

better common parameter in terms of which to predict biological effect. On this assumption, the air dose values stated in Table 1.1 should be multiplied by approximately 1.5 in order to compare their effects to those of a given air dose from a "point source" beam geometry delivered bilaterally. If this is done, assuming a fallout of 12 hours, the following "point

The geometry of radiation from a fallout field is not identical either to the geometry of bilateral point sources or spherically distributed sources since the plane source delivers the radiation largely at a grazing angle. However, the total field situation is better approximated by solid than by plane geometry. Exposure geometry in a radioactive cloud would be spherical.

1.3 Superficial Doses of Radiation From Beta and Soft Gamma Radiation

THERE CAN BE no doubt that the doses of radiation to the surface and the first few millimeters of the body were substantially higher than the mid-line dose of gamma radiation as a result of physical considerations of gamma energy and depth dose. In addition, the clinical observations of the skin lesions (see Chap. III) forcefully demonstrated that the dose to the skin varied considerably between individuals and over the surface of any given individual. As will become evident in the following discussions of surface dose, it is obvious that any numbers presented are at best only estimates and represent an approximation of some minimal value. In areas where lesions were severe the doses must have been significantly higher than in non-damaged areas.

To arrive at some physical estimate of the skin dose, an attempt must be made to add up the contributions of the high energy gamma, the very soft gamma, and the higher energy beta radiation from the large planar source in which the individuals were of necessity existing. However, as alluded to above and emphasized in Chapter III, the largest component of skin irradiation resulted from the spotty local deposits of fallout material on exposed surfaces of the body. The dose from deposited material is impossible to estimate; however, that from the large planar source may be roughly estimated as follows:

The beta dose rate in air 3 feet above the surface of an infinite plane contaminated with mixed 24 hour old fission products is estimated to be about three times the total air gamma dose. The mid-line gamma dose is approximately 60 percent of the air dose remaining after excluding that portion of the dose below 80 KV. This portion in turn is estimated to be 40 percent of the gamma dose measured in air by the instrument. Thus the dose at the surface of a phantom exposed to mixed fission product radiation from an external plane source might be expected to be 3/(0.6) (0.6) or about 8 times the mid-line dose, if both are taken at 3 feet off the ground. Such a depth dose measurement has in fact been made experimentally at a previous test, using a phantom man exposed to both the initial and residual radiation (5). The depth doses for each situation are shown in Figure 1.5, with all data as percent of the 3 centimeter dose. With the diverging initial radiation from the point of explosion, the exit dose was seen to be 63 percent of the 3 cm. dose, but with the diffuse residual field of fission products providing a semi-infinite planar source, a surface dose some 8 times greater than the 3 cm. and deeper dose from the harder gamma components was observed. This is seen to be of the same order of magnitude as that estimated above. At heights above and below the 3 foot level this surface dose would become lower and higher respectively, but since it is due to soft radiation of short range, it probably would not exceed 50 times the 3 foot air gamma dose or 80 times the midline dose, even in contact with the ground. An estimate of skin dose due to ground contamination for the Rongelap case would result, for example, in a figure of about 2,000 rep at the level of the dorsum of the foot, 600 rep at the hip level and 300 rep at the head *if continuous exposure with no shielding occurred*. Unknown variation in dose undoubtedly resulted from shielding and movement. It thus seems probable that the external beta dose from local direct skin contamination far outweighed that from the ground in importance, since the latter was not high enough to produce the observed lesions. Clothing probably reduced the beta dose from the ground by 10 to 20 percent.

1.4 Summary

RADIATION DOSES from gamma rays originating externally were calculated for the 267 individuals who were accidentally exposed to fallout following the nuclear detonation at the Pacific Proving Ground in the Spring of 1954. The dose estimations were made using information resulting from radiological safety surveys on

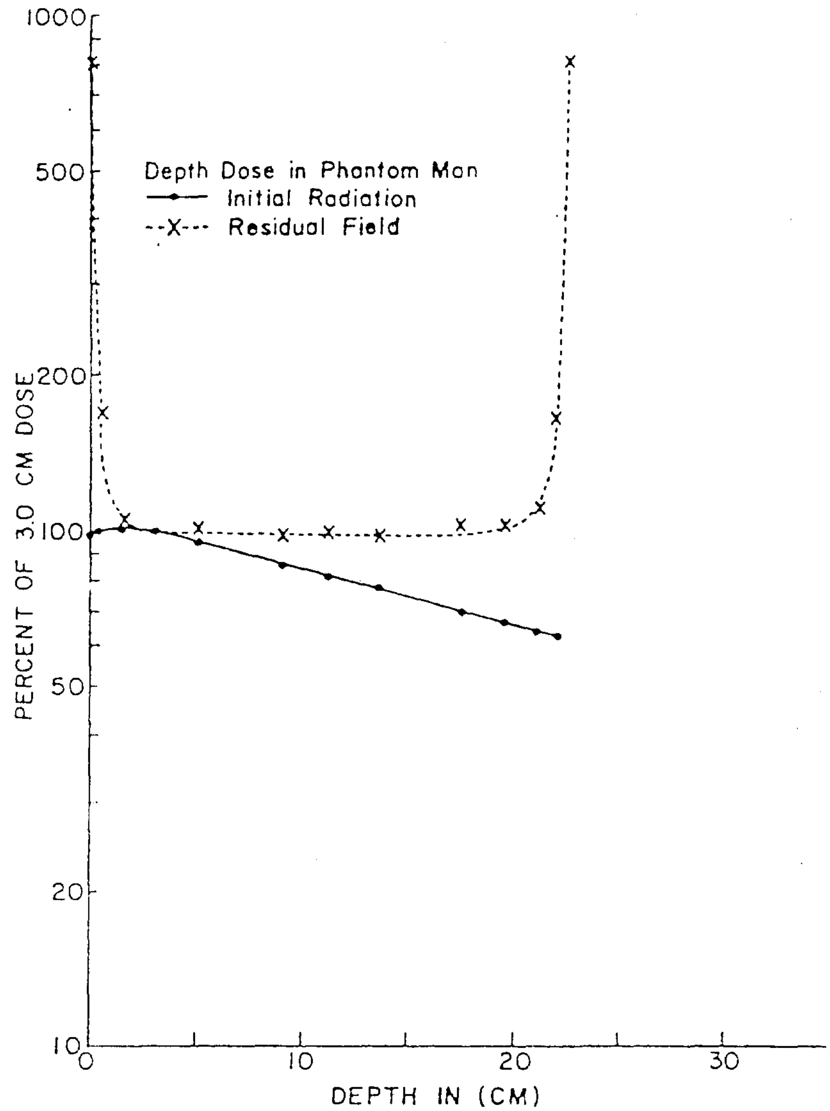


FIGURE 1.5—*Comparison of depth dose curves in a masonite phantom man, of the initial atomic bomb gamma radiation and of gamma radiation from a planar field of fission products deposited on soil after an experimental nuclear detonation.*

the atolls, and spectrometric and radiochemical data. The actual duration of the radioactive fallouts was not known, and the values for length of exposure were subject to uncertainties in the times at which the fallouts began. A range of possible whole body gamma doses was calculated, and the values considered to be most probable are presented. Diffuse geometry from the semi-infinite planar source was believed to increase the biological effect of the whole body dose expressed as an air dose, compared in the geometry of the usual X-ray exposure. Soft gamma and beta radiation from fallout on the ground and especially on the skin itself resulted in a superficial dose which was high enough to produce lesions. No quantitative data were available on the beta radiation intensity from either the skin contamination or from the ground, but a rough estimate of superficial dose from the latter was made.

References

1. Gates, L. G., and Eisenhauer, C.: Spectral Distribution of Gamma Rays Propagated in Air; Armed Forces Special Weapons Project Tech Analysis Report 502A (Jan. 1954), Washington, D. C.
2. Turke, J. K., and Reardon, D. A.: NRDL Instrument Evaluation Report NE 051555 (5 October 1951); Gamma Survey Meter. U. S. Naval Radiological Defense Laboratory, San Francisco, Calif.
3. Hunter, H. F., and Ballou, N. E.; Fission Product Decay Rates; *Nucleonics* 9, 5, pC1–C7 (1951). Also unpublished data, N. E. Ballou.
4. Unpublished data, C. A. Sondhaus.
5. Personal communication from F. W. Chambers, Jr., Naval Medical Research Institute, Bethesda, 14. Md.