Chapter 6

RADIATION DOSES FROM RESIDUAL RADIOACTIVITY

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Most of the dose to survivors of the Hiroshima and Nagasaki explosions came from direct radiations produced by the weapons, the radiations discussed in the preceding chapters. There was, however, residual radioactivity produced by neutron activation of materials near the hypocenters and radioactive fallout of activation and fission products from the cloud formed by the explosion. Radiation from these two sources was not considered in previous major assessments of the survivor doses. This omission led to some criticism in the press and scientific literature.[1,2]

If the radiation doses from either induced radioactivity or fallout are as high as a few rad, they will have to be considered in the overall dose assessment. This is particularly true where such doses were delivered to individuals who are presently classified as being in the control (distally exposed) groups.

Because the measurements made at the time were fragmentary, doses for all individuals exposed to residual radioactivity cannot be developed from the available data. Calculations have been helpful in confirming and in interpolating between measurements at different points. This chapter attempts to put a reasonable upper limit on doses from the two sources of radiation for Hiroshima and Nagasaki.

A number of relevant exposure measurements were made in the first three months following the explosions, and these provide the principal basis of the exposure estimates reported in this chapter (time following the explosion is given as H+n for Hiroshima and N+n for Nagasaki, where n is the number of days after the explosion). Since the induced radioac-

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tivity occurred around the hypocenter and the fallout occurred only about 3000 m from the hypocenter in each city, different groups of individuals were exposed to the two sources. Exposure rates decreased rapidly with time, but measureable rates persisted for days in the case of induced activity and for months for fallout. Since the exposures were received over different periods of time, they are designated here as cumulative exposures to distinguish them from the instantaneous exposures to direct radiation from the explosions.

In addition to the decrease in exposure rates with time, they also decreased with distance from the hypocenter for induced radioactivity and from the point of maximum deposition for fallout. The exposures calculated in this chapter apply to the specific areas described. Their application to individuals is a complex process which involves following the movements of the person whose exposure is being assessed and adding the exposure received from each area the person was in. The time of entry into a fallout-contaminated area and movement within the area determines the exposure rate and cumulative exposure of the person involved (Table 1).

Table 1. Effect of Time of Entry into a Fallout Area that has an Exposure Rate of 1 R/h at One Hour After the Explosion.[a]

Time of Entry	Exposure Rate (R/h)	Cumulative Exposure from entry to ∞, (R)
0.5 h	2.3	5.7
1 h	1.0	5.0
2 h	0.44	4.4
4 h	0.19	3.8
8 h	0.082	3.3
1 day	0.022	2.6
1 week	0.0021	1.8
1 month	0.0004	1.3

[a] The fission product decay was calculated as $t^{-1.2}$. The actual decay was possibly more rapid[3] so the values shown may be considered as upper limits.

The size of the groups exposed to the two sources of radiation in the two cities is relatively small and depends on how large an area is considered (i.e., the smallest dose considered).

Many factors affecting the accuracy of the measurements are not well known 40 years after the bombs, therefore exposure estimates must be rough approximations. In general, the exposure rates were not measured soon enough to avoid some weathering and they were not repeated often enough to account for subsequent weathering or to provide a time distribution of radioactivity. The number of sites monitored was too small to develop a good estimate of the detailed geographic distribution of the radioactivity. Also, in such surveys, it is difficult to avoid unrepresentative sampling and it is not known whether such a sampling bias exists. Finally, the details of calibration and measurement are not always available.

We emphasize that the precision of many of the measurements and all of the extrapolations is very low. Although two significant digits are carried through the calculations, the second one should not be viewed as being accurate.

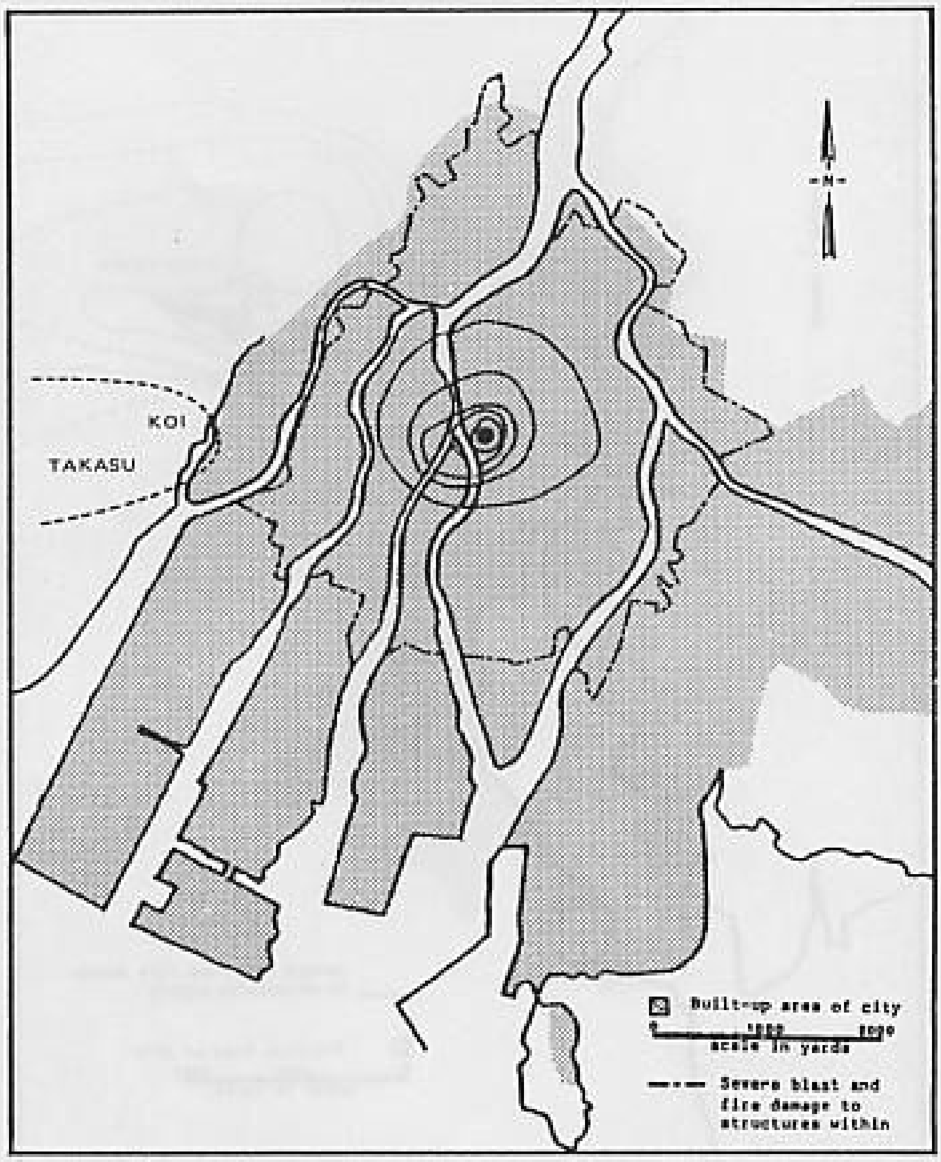

Figure 1. Map of Hiroshima showing the hypocenter and the Koi-Takasu Fallout area.

EXTERNAL GAMMA RADIATION FROM FALLOUT

Radioactive fallout occurred at a distance of about 3000 m from the hypocenter, to the west in Hiroshima and to the east in Nagasaki (Figures 1 and 2). Survivors reported a "black rain" in both cities about one half-hour after the explosions. This was rain carrying down soot and dirt from the explosion; and presumably also radioactivity. Such a phenomenon has not been observed in the many nuclear tests carried out in the arid Nevada desert. The water involved in the Japanese fallout could have come from the high relative humidity of the air, the high soil moisture content, or from surface water drawn up into the cloud.

Both the "black rain" and heavy rainfall in the two cities over the following three months minimized the possibility of significant exposure from inhalation by removing radioactivity from the air.

Ideal data for producing an estimate of the fallout exposures do not exist, because mea-

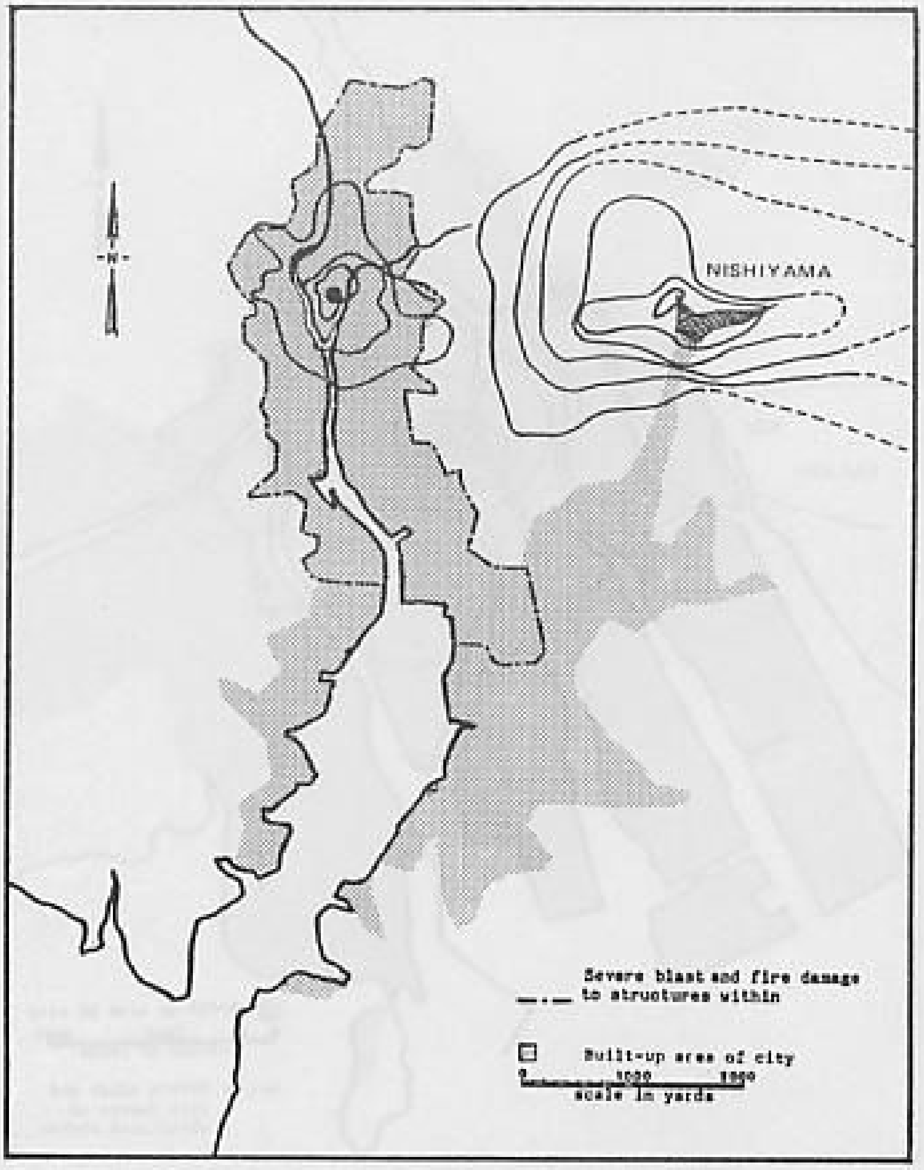

Figure 2. Map of Nagasaki showing the hypocenter and the Nishiyama fallout area.

surements were made under difficult conditions some time after the explosions. The available information is summarized here, and cumulative exposures have been estimated for each set of data. The same data has appeared in several different papers; thus, it was necessary to make an arbitrary selection of references.

A second approach to estimating exposures from fallout would be to model the deposition of radioactivity based on weapon and meteorological information, including all of the various factors considered in environmental modeling. Other models could then provide estimates of the doses. However, many of the parameters required by the models for the conditions existing at the time of the explosions are lacking. The immediate task, therefore, will be to extract as much information as possible from the existing measurements.

A confounding factor, separate from the measurements themselves, is determining the time that individuals spent in areas with different exposure rates. The fallout patterns were not large and the exposure gradients were steep; differences of only a few hundred meters in the location of an individual for example, would have had a large effect on exposure rate. Okajima et al[4] collected information on the movements of some residents of the Nishiyama district in Nagasaki and these data are useful in estimating doses to typical individuals. Okajima (Appendix 6-1) reviewed the exposures of 80 Nishiyama residents and estimated that 24 of them, whose homes had been destroyed, might have received about two-thirds of the cumulative exposure at a point out of doors near their home.

With the limitations described, it did not seem worthwhile to carry out elaborate, precise calculations of the quantities entering the determination of exposures. Examples of simplifications: decay of mixed fission products was assumed to follow a simple power function, and radium calibrations in mR/h were assumed to be adequate for the measurements of exposure.

Fallout Calculation Methods

The available data on fallout from the Hiroshima and Nagasaki explosions are either measurements of exposure levels one or more months after the bombs or measurements of radionuclides in soil. Rather than merely summarizing the data of the various authors, the original measurements of exposure rates were integrated to give a cumulative exposure in roentgens (R) at a height of 1 m by the methods described here. The integration of the exposure rate to give cumulative exposure was carried out for the period from one hour after the bombing to infinity. This choice of times is somewhat arbitrary, but the transformation permits a better comparison of the various data sets. The cumulative exposures are converted to absorbed dose in the Summary.

All exposure measurements were made with portable instruments calibrated against radium standards. In some cases, background measurements were made outside the fallout zone - if not, a background of 8 μR/h was assumed.[5] The net measured exposure rate at the time of measurement was then converted to the exposure rate at one hour following detonation by the equation:

$$X_t = X_1 t^{-1.2} \tag{1}$$

where X_t is the measured exposure rate and X_1 is the calculated exposure rate at one hour, and t is the time after the explosion in hours. The cumulative exposure from one hour to infinity is:

$$\int_1^\infty X_t dt = X_1 \int_1^\infty t^{-1.2} dt = 5X_1 \tag{2}$$

Yamasaki[3] reported an exponent of -1.31 rather than -1.2 for the exposure rate (Equation 1), on a single sample collected in Hiroshima. For the extrapolation periods reported here, use of the larger exponent would double the calculated exposure rate at one hour. This would only increase the cumulative exposure to infinity by less than 40%, since the cumulative exposure to infinity becomes about three times X_1. Tabulated values given in this chapter are based on the exponent of -1.2, but the use of -1.3, or any other exponent, can be made readily.

The selection of one hour for the start of integration is arbitrary. If integration is started at one-half hour the cumulative exposure is larger by about 15%. Fallout in the two cities apparently began about one-half hour after the explosions but the precipitation continued for some time (Uda et al, as quoted in Reference 6).

It is not known how representative the fallout area data are because the stress of the situation and the scarcity of instruments and trained personnel did not allow systematic grid measurements over the area of interest. In the case of fallout, it is possible that the radioactive deposits may have been redistributed by weathering before the measurements were made. The three months following the explosions showed high rainfall of 900 mm in Hiroshima and 1200 mm in Nagasaki.[7] In addition, both cities were subjected to a typhoon on 17 September 1945, and Hiroshima was struck by a second typhoon on 9 October. In general, rainfall tends to wash surface material from slopes onto low-lying areas or into drainage systems, while flat areas may retain the fallout. Without detailed knowledge of the sampling sites, it is not possible to evaluate weathering effects. Therefore, measured data were used without correction for weathering.

The indirect estimates of exposure from radiochemical analysis of soil required a number of steps and were based on determination of the mCi/km^2 of ^{137}Cs at the time of the explosion. This quantity is converted to cumulative exposure in roentgens for total fission products with a modification of the factors derived by Hicks[8,9] and by Beck and Krey[10,11] which gave the cumulative exposure from three hours to infinity. The authors combined data on several tests in Nevada to give a relationship between the deposition of ^{137}Cs and the cumulative gamma ray exposure to infinity from all fission and activation products in fallout. Beck and Krey[10] estimated an uncertainty of 20% for the conversion. Their factors for 1 mCi/km^2 of ^{137}Cs gave exposures from three hours to infinity of 92 mR for debris with no fractionation of the fallout radionuclides and 73 mR with 50% fractionation, (fractionation is the distribution of the fission products according to their time of condensation, with consequent change in the composition of fallout with distance). These factors were corrected to 340 and 270 mR for the period from one hour to infinity using Equation (1). Since the degree of fractionation in Japan is unknown, a rounded value of 300 mR was used here.

The ^{137}Cs deposition can be measured on samples collected in 1945 or even a few years later, without correction for later fallout from weapon tests. Later samples do need correction. Measurements of ^{137}Cs could still be made on samples that were collected then but not measured.

Hashizume et al[12] measured ^{137}Cs activity in soil samples collected from various locations in Hiroshima and Nagasaki, using a Ge(Li) semiconductor detector with a heavy radiation shield. In the Nishiyama area of Nagasaki, they detected a significantly high level of ^{137}Cs activity. In Hiroshima, however, they did not identify an excess of ^{137}Cs over fallout from the tests after 1945.

Where available, the original author estimates of deposition per unit area were used. Since some of the radiochemical data are in terms of ^{137}Cs radioactivity per unit weight of soil, for uniformity they are converted to unit area by assuming a 10 cm depth and a soil density of 1.6. This procedure may not account for the small amounts of ^{137}Cs penetrating to greater depths but it does prevent the good radiochemical data at higher concentrations from being overwhelmed by the less accurate determinations of small concentrations in the large mass of deeper soil.

Originally, it was hoped that exposure estimates could be based also on Pu deposition in Nagasaki. This has not yet been possible, but the data have been useful in establishing where fallout occurred. Similar additional information could probably be obtained in Hiroshima by isotopic uranium analyses of soils collected before the major global fallout.

Direct Measurements in Nagasaki

Estimates of cumulative exposure at Nagasaki are considerably higher than at Hiroshima and the subtraction of background is not a problem for the direct gamma radiation measurements. The major fallout was in the Nishiyama district, about 3000 m east of the hypocenter.

Shinohara et al[13] reported the results of a survey made, starting on 1 October 1945, with a Lauritsen electroscope at 15 cm above the ground. The instrument had been calibrated against radium, but the data were reported in multiples of leakage current. The range of radiation levels for the fallout area shown on their map, including Nishiyama, was 0.1 to 2.7 mR/h when corrected to a height of 1 m. The calculated cumulative exposures are shown in Table 2.

Table 2. Estimates of Cumulative Exposure at a Height of 1 m from Measurements of Radioactive Fallout in the Nishiyama District of Nagasaki.

Investigator	Days after bomb	Measured Exposure Rate (mR/h)	Kind of Measurement	Exposure Rate at 1 h (R/h)	Cumulative Exposure (R)
[13]Shinohara et al	N+53	0.1-2.7	Range	0.5-14	2.5-70
[14]Tybout ([16]Wilson)	N+57	1	-	5.8	29
([17]McRaney)	N+48	1-1.8	Max.	4.7-8.5	24-43
[15]Pace and Smith	N+73	1.08	Max.	8.4	42
	N+96	0.7	Village	7.6	38

Tybout[14] reported the results of a survey made from 21 September to 4 October 1945, by the Manhattan Engineering District (MED). Data quoted by Wilson[16] list 1 mR/h for 3 to 7 October, while McRaney and McGahan[17] of the US Naval Medical Research Institute (NMRI) give a range of maximum values near the Nishiyama reservoir of 1.0 to 1.8 mR/h for 26 September and show a map of isodose contours for the complete survey. The calculated cumulative exposures are shown in Table 2.

Pace and Smith[15] reported the results of a survey made 15 to 27 October 1945, by NMRI. They give a maximum exposure rate, near Nishiyama, of 1.08 mR/h and a mean of 0.7 mR/h for the village of Nishiyama. Redrawn contours are presented in McRaney and McGahan.[17] The calculated cumulative exposures are shown in Table 2.

^{137}Cs and Plutonium Measurements in Soil

The first analysis of soil from Nishiyama was undertaken by Kimura et al[18] in 1945 and was repeated with improved methods in 1951. Although the analyses were only qualitative,

Table 3. Estimates of Cumulative Exposure from Fallout in the Nishiyama District of Nagasaki Derived from Soil Analyses.

Investigator	Year Taken	Year Measured	Deposition of ^{137}Cs (mCi/km^2) Nishiyama	Nagasaki	Net	1945[a]	Cumulative Exposure (R)
[19]Miller	1956	1982	62	7	55	130	40
[22]Mahara and Miyahara	1981	1981	600	200	400	900	270
[23,24]Okajima et al	1969	1970	1520[b]	1040	480	760	230
	1969	1970	740[c]	290	450	710	210

[a] The extrapolation of measured values back to 1945 includes only radioactive decay of ^{137}Cs.
[b] Uncultivated soil.
[c] Arable soil.

they were important in that they demonstrated the presence of long-lived fission products and transuranics. More recently soil samples were analyzed for ^{90}Sr, and the results are indicative of the original concentrations of other radionuclides. Four soil samples were taken for ^{90}Sr analysis by the Health and Safety Laboratory of the US Atomic Energy Commission (AEC) in January 1954, including two in the Nishiyama area, but they have not yet been located and no data are available from them.

Two samples were taken for the same group in 1956, before the heavy global fallout began, one in the Nishiyama area. The latter was identified only as being in a bamboo grove near the reservoir. At the time, this sample showed a very high ^{90}Sr concentration (about 50 mCi/km^2 compared to 2 for Kita Hill, outside the fallout zone). The Kita Hill value agreed with the general average for the hemisphere. In 1982 these samples were analyzed for ^{137}Cs by gamma-ray spectroscopy and values of 62 and 7 mCi/km^2 were found for the two sites.[19] The ^{137}Cs deposition in 1945 that would have been required to produce the 55 mCi/km^2 difference between the two areas would have been 130 mCi/km^2. It is worth noting, for comparison, that the ^{137}Cs deposition in 1980 from all nuclear tests was about 100 mCi/km^2 in the 30 to 40° latitude band.[20]

The dose from ^{137}Cs deposited in 1945 itself is negligible; it would give an initial dose rate of only 4 mrad/y or a dose to complete decay of 200 mrad. The dose from the accompanying short-lived radionuclides is more difficult to calculate. UNSCEAR[21] showed empirically that it was about equal to the ^{137}Cs dose for global fallout. Their data, however, represent thermonuclear tests with a delay in fallout and consequent decay of the short-lived nuclides before deposition, so doubling the ^{137}Cs dose is not applicable in the present case. As described in the methods section, a factor of 300 is used here to convert mCi/km^2 of ^{137}Cs in 1945 to cumulative exposure from all radionuclides in mR from one hour after the explosion to infinity. The 130 mCi/km^2 gives an estimate of cumulative exposure for Nishiyama of about 40 rad beginning one hour after the explosion (Table 3).

Sakanoue and Tsuji,[25] Okajima,[23] Okajima et al,[24] and Mahara and Miyahara[22] reported elevated concentrations of Pu in Nishiyama soil. The levels are several times higher than those from global fallout and readily indicate the location of fallout areas, even though the Pu was measured more than 20 years after the explosion. These data have been confirmed by analysis of the Hiroshima and Nagasaki soil samples mentioned earlier that were collected for the US AEC in 1956. Hardy[26] reported very high Pu concentrations in Nishiyama soil, while the concentrations in the samples from other areas were similar to that expected from global fallout. The data, however, are only of qualitative interest at the moment. They cannot be used for dose estimation because the effects of weathering and the relation between exposure rate and activity density are not known.

Three of these papers also reported data for ^{137}Cs in soil and showed elevated concentrations for Nishiyama as compared to other sites in Nagasaki. Estimates of the cumulative exposures are included in Table 3, although estimates based on measurements made so long after the explosion are subject to errors because of possible redistribution of ^{137}Cs in soil in the interim.

Direct Measurements in Hiroshima

The only data currently available for Hiroshima are measurements of exposure rate, although stored soil samples from the fallout area might still become available. The fallout area in this case was in the general Koi-Takasu district about 3000 m west of the hypocenter. The fallout levels were much lower than at Nagasaki and it is necessary to subtract background from the gamma readings.

Table 4. Estimates of Cumulative Exposure at a Height of 1 m from Radioactive Fallout in the Koi-Takasu District of Hiroshima

Investigator	Days after bomb	Exposure rate at time of measurement			Exposure rate at 1 h (R/h)	Cumulative exposure (R)
		Gross		Net		
[28]Miyasaki and Masuda	H+188	22 I	Max.	17 I[a]	0.6	3
		20 I	Average	15 I	0.5	2.3
[29]Fujiwara and Takeyama	H+49	6 × Bkg.	Max.	40 μR/h	0.19	1
	H+920	2.4 × Bkg.		11 μR/h	1.8	9
[14]Tybout ([30]Arakawa)	H+60	45 μR/h	Max.	37 μR/h	0.23	1.2
[15]Pace and Smith	H+87	19-20 μR/h	Range	11-34 μR/h	0.11-0.33	0.6-1.6

[a] I, the unit of ionization obtained with the Neher electrometer is about 1.5 μR/h.

Miyasaki and Ikeda[27] and Miyasaki and Masuda[28] reported the results of a survey made from 27 January to 7 February 1946, with a Neher cosmic-ray chamber. They found a maximum net value of 17 I (I is the common unit for cosmic-ray ionization and is approximately equal to 1.5 μR/h) and the general area shown on their map appeared to average about 15 I, corresponding to 22 μR/h. The calculated cumulative exposure is shown in Table 4.

Fujiwara and Takeyama[29] reported the results of surveys made in September 1945, and January 1948, with Lauritsen electroscopes at a height of 1 m. Two sites about 4000 m west of the hypocenter showed multiples of 4.0 and 6.0 times the natural background reading of the instrument, so the maximum net exposure rate is taken here as 40 μR/h. The date was not specified but was assumed to be 24 September 1945, when other measurements were made in the area (Table 4).

The same authors reported a value of 2.4 times background in the Koi area on 12 February 1948. The net exposure rate of 11 μR/h was used to calculate the cumulative exposure shown in Table 4. The high value may be due to the long extrapolation back to the time of detonation and should be given less weight than measurements made at earlier times.

Tybout[14] reported a few measurements at Takasu made by the Manhattan Engineering District (MED) from 3 to 7 October 1945, that were quoted by Arakawa[30] as a maximum of 45 μR/h. The net value of 37 μR/h was used to calculate the cumulative exposure shown in Table 4.

Pace and Smith[15] reported the results of a survey made by the NMRI on 1 to 2 November 1945, with Geiger counters calibrated against radium. The maximum value, in the Takasu area, was 42 μR/h and the range of other values on their map was 19 to 37 μR/h. The overall range of net values has been used to calculate the cumulative exposure in Table 4.

Takeshita[5] summarized much of the Hiroshima data. In his paper he developed a weathering factor for correcting the activity in the process of extrapolating measurements back to one hour after the explosion. This factor was not adopted here because of uncertainties in the forward extrapolation which would also be required.

Best Estimates of External Fallout Exposure

The majority of the estimates for cumulative exposure at 1 m are in reasonable agreement. The fallout contribution to the cumulative exposure in the Nishiyama region is probably in the range of 20 to 40 R and that in the Koi-Takasu region is probably in the range of 1 to 3 R. These exposure estimates represent the center of the fallout deposition which encompass areas of a few hectares (ha). If these values can be accepted with some confidence, it should also be possible to use the general contours presented in several of the papers for lower exposure rates.

Exposure rates at greater distances may be estimated from the areas shown in Table 5, which have been calculated for Nagasaki from the maps shown in McRaney and McGahan.[17] For Hiroshima, there is only the indication that a 30 ha area at Takasu had an exposure rate of 4 mR/h. It would appear that fallout does not make a significant contribution to the total dose in Hiroshima but might in Nagasaki. Estimates of the time spent within various contours will be necessary for calculating individual exposures. These estimates do not have to extend over a long time, since about one-half of the dose is delivered in the first day and three-quarters in the first month.

INTERNAL RADIATION DOSE FROM ^{137}Cs

There are several possibilities for exposure to internal radiation following a nuclear explosion, including inhalation and ingestion of radionuclides in the residual radioactivity. At the time of the bombings, it was not known what measurements would be required and the available technical personnel were already working to capacity. Thus, we are limited to the reconstruction of internal doses and, more particularly, to those from the long-lived gamma-ray emitting radionuclide ^{137}Cs.

Estimates were made of the internal dose from ^{137}Cs in the residents of the Nishiyama District, an area where radioactive fallout from the bomb was most heavily deposited in Nagasaki. The estimates are based on the measurements of Okajima[23] and Okajima et al.[4,24,31] In 1969 they measured, with a whole-body counter, the internal burden of ^{137}Cs in 20 males and 30 females living in the Nishiyama District, along with the same number of controls. The results in terms of pCi/kg of body weight were, for Nishiyama males 38.5 and females 24.9 and for the controls, males 25.5 and females 14.9.

It was assumed that the contribution from the Nagasaki A-bomb fallout is equal to the difference between the Nishiyama residents and the controls (i.e., males 13 pCi/kg and females 10 pCi/kg).

Table 5. Areas with Specified Exposure Rate Contours from Fallout in the Nishiyama District of Nagasaki.

Group	Exposure rate contour (mR/h)	Days after bomb	Exposure rate contour at 1 hour (R/h)	Area (ha)
[17]Manhattan Engineering District	1.0	N+50	5	5
	0.9		4.5	37
	0.8		4	140
	0.5		2.5	(460)[a]
	0.2		1	(920)[a]
	0.1		0.5	(1500)[a]
[17]Naval Medical Research Institute	1.08	N+73	8.4	Point
	0.555		4.3	220
	0.13		1.0	(780)[a]
	0.019		0.15	(1200)[a]

[a]Indicates areas that are poorly defined.

In order to see the longitudinal change in ^{137}Cs content, 10 of the 15 persons (including males and females) who had shown a relatively high burden in 1969 were measured for a second time in 1981.[31] The result revealed a decrease from an average of 48.6 pCi/kg in 1969 to 15.6 pCi/kg in 1981. Assuming that the body burden decreased exponentially, the effective half-life is estimated to be 7.4 years. It should be noted that this is an environmental half-life, where ^{137}Cs in soil contributes to dietary intake, not the biological half-life for cesium in the body, which is only about 100 days.[32]

Using the above data (i.e., assuming that the ^{137}Cs burden from fallout was 13 pCi/kg for males and 10 pCi/kg for females in 1969 and that the body burden decreased exponentially with an effective half-life of 7.4 years) the internal dose in the 40 years from 1945 to 1985 is estimated as 10 mrem for males and 8 mrem for females (the mrem are equivalent to mrad in this case). This dose was calculated by the Medical Internal Radiation Dose (MIRD) Committee method,[33] assuming uniform distribution throughout the body.

Table 6. Induced Radionuclides of Possible Dosimetric Interest.

Nuclide	Half-life	Comment
^{28}Al	2 min	
^{56}Mn	2.6 h	
^{31}Si	2.6 h	Not significant
^{42}K	12.4 h	Not significant
^{24}Na	15 h	
^{59}Fe	44.5 d	Not significant
^{46}Sc	83.8 d	
^{134}Cs	2.1 yr	
^{60}Co	5.3 yr	

EXTERNAL GAMMA RADIATION FROM INDUCED RADIOACTIVITY

Various elements in the soil and other materials near the hypocenters of the two explosions were made radioactive by the neutrons released by the weapons. A number of exposure measurements were made during the next few months. It was also possible to estimate the amount of radioactivity formed and the consequent dose from the neutron fluences and the soil composition. Thus, it is possible to give a better dose estimate for induced radioactivity than for fallout.

The exposure rate falls off rapidly with distance (at 1000 m it is a few percent of that at the hypocenter) and with time; therefore, the application of the exposure estimates summarized here is highly dependent on the location and the time the individuals concerned spent at that location. The hypocenter received very high doses of direct radiation and the area was subject to intense fires for several hours. The chance of survival by anyone near the hypocenter at the time of the bomb is negligible, so we are concerned with individuals entering the area, probably no sooner than the following day.

The neutrons released by the nuclear explosions in Hiroshima and Nagasaki produced a number of radionuclides by activation of soil and other materials in the vicinity of the hypocenter. The radionuclides presently thought to be of dosimetric interest are listed in Table 6.

It is apparent from the half-lives listed in Table 6 that the ^{28}Al nuclide would disappear well before any person could have entered the hypocenter area, so it will not be considered further. What is of consequence with respect to half-lives is that all of the recorded measurements of gamma-ray exposure were made after the ^{56}Mn and ^{24}Na had also decayed away. Thus any estimates of exposure in the first few days following the explosions must be calculated from data on the long-lived radionuclides. It should be noted that exposure rates at $t=0$ are calculated here for convenience in comparison with other work, but these exposure rates do not include any contributions from ^{28}Al.

It is possible to calculate the quantities of radionuclides formed from an estimate of the neutron fluence and the chemical composition of the materials irradiated. This was done by Hashizume et al[34,35] and Arakawa.[30] Since the values used for neutron fluences for the two

Table 7. Concentrations of Precursor Elements in the Soil of Hiroshima and Nagasaki; Milligrams of Element Per Gram of Dry Soil.

Investigator	Samples	Mn	Na	Sc	Co	Cs
Hiroshima						
[36]Kerr	2	0.53	14	0.005	0.0038	0.005
[35]Hashizume	16	0.9	18	0.006	0.02	0.01
[30]Arakawa		0.93	32			
[37]Borg	3	0.28	9			
Nagasaki						
[36]Kerr	2	1.3	7.7	0.02	0.022	0.004
[35]Hashizume	8	2.7	2.2			

cities were not exact, these studies are now of interest mostly for their methodology and for the soil compositions measured. The measured soil concentrations of the elements of interest for the two cities are shown in Table 7. The variability among the sets is considerable and indicates that calculated activations may not be broadly applicable.

The application of both measured and calculated exposure rates to estimating the cumulative exposures of survivors and others entering the area will depend very strongly on knowledge of the amount of time spent in a particular location by an individual. Fortunately, the half-life of most of the significant activation products is short enough that exposures of those entering the area after a few days are not important.

Estimates of Induced Radioactivity from Soil Activation

Samples of soils from Hiroshima and Nagasaki were irradiated with neutrons to see which radionuclides would be produced by activation.[30,35] Arakawa irradiated a series of soil and tile samples at Oak Ridge National Laboratory (ORNL) with a neutron fluence of 6 $\times 10^{12}$ cm^{-2} in a reactor. The activity was measured by gamma-ray spectrometry initially and after one year. These values were used to calculate radiation exposure at the hypocenter. Hashizume et al exposed a 60×60×60 cm box containing soil at 30% moisture to a neutron fluence of 10^{12} cm^{-2} from a Van de Graaff generator with a ^{9}Be target. They also analyzed small samples by activation with the generator and with a research reactor. These data were combined with field measurements of exposure rates from known sources of ^{24}Na, ^{60}Co, and ^{137}Cs to estimate exposure rates around the hypocenter.

In both experiments, the gamma-ray spectroscopy was performed with the low-resolution spectrometers available at the time and it is possible that other radionuclides were formed. This is not important in a practical sense, since the lack of resolution means that other nuclides were included with the major radionuclides and their dose contributions are not omitted.

Thermal neutron activation of soils was also carried out at ORNL (see Chapter 3). The radionuclide concentrations estimated in the three investigations are shown in Table 8. These numerical values cannot be compared directly since they involved different soil samples, neutron fluences, and irradiation conditions, but they do indicate the bases of later calculations by the authors.

Table 8. Radionuclides Formed in Experimental Irradiations of Hiroshima Soil; μCi Per Gram of Soil.

Radionuclide formed	Hashizume et al[35]	Arakawa[30]	ORNL[a]
Hiroshima			
^{56}Mn	3	0.6	5
^{24}Na	0.9	0.3	2
^{46}Sc	5×10^{-5}	7×10^{-5}	1×10^{-4}
^{60}Co	5×10^{-6}	7×10^{-6}	6×10^{-6}
^{134}Cs	2×10^{-7}		8×10^{-6}
Nagasaki			
^{56}Mn		2	4
^{24}Na		0.5	0.4
^{46}Sc		2×10^{-4}	2×10^{-4}
^{60}Co		1×10^{-5}	1×1^{-5}
^{134}Cs			2×10^{-5}

[a] This report, Chapter 3.

Table 9. Exposure Rate Estimates by Hashizume et al[35] for Hiroshima Soil at the Hypocenter for t=0 and the Cumulative Exposure for Complete Decay.

Radionuclide	Initial exposure rate (mR/h)	Cumulative exposure (mR)
^{56}Mn	4800	18000
^{24}Na	2950	64000
^{46}Sc	0.085	250
^{60}Co	0.011	730
^{134}Cs	4.8×10^{-6} [a]	0.1[b]

More recent calculations indicate these entries should be:

[a] 3×10^{-4} mR/h

[b] 7.8 mR

The relative dosimetric importance of the radionuclides considered is indicated in Table 9. The exposure rates at the hypocenter in Hiroshima were calculated by Hashizume et al[35] on the basis of thermal neutron fluences estimated as a function of distance from data on ^{60}Co activity induced in iron materials on the surface of buildings. Here, the estimated exposure rates have been integrated to give the cumulative exposures for complete decay. The exposure rate from ^{56}Mn disappears within a day and that from ^{24}Na within a week, while ^{46}Sc, ^{60}Co, and ^{134}Cs will contribute for many years. The major exposure comes from the short-lived emitters and is delivered over a few days.

Gritzner and Woolson (Appendix 6-2) calculated the radioactivity induced in Hiroshima and Nagasaki soil from estimated neutron fluences produced by the weapons. The soil compositions used in the calculations were those reported by Kerr et al.[36] The detailed soil compositions are tabulated in Chapter 3, while the most significant elements are listed in Table 7.

Chapter 3 also contains tabulations of calculated neutron fluences. The prompt neutron fluences at ground level near the hypocenters are given as 1×10^{13} for Nagasaki and 3×10^{13} for Hiroshima. Gritzner[38] states that delayed neutrons add about 40% at Nagasaki and 7% at Hiroshima. It may be noted that the lower fluence at Nagasaki is partially compensated for by the higher concentrations of sodium, scandium, and cobalt in the soil.

The Gritzner and Woolson results are given as gamma-ray kerma in tissue at 1 m above the ground in the absence of a person or structure. Graphs for the two cities (see Appendix 6-2) show the kerma rate as a function of time after burst and of distance from the hypocenter. It should be noted that, while the initial kerma rates are plotted for $t=1$ hour, the infinite exposure kerma is plotted starting at $t=0$. Thus, the rate curve does not include the contribution from ^{28}Al, while the kerma to infinity curve does. For added comparisons, Gritzner[38] calculated a number of exposure rates for use in the tables of this chapter.

Direct Measurements of Exposure from Induced Radioactivity

None of the measurements were made soon enough to include the short-lived ^{24}Na and ^{56}Mn. The decay of the long-lived induced activity depends on the relative amounts of the radionuclides formed. The earliest measurements reported were those of Kimura[39] who calculated an effective half-life of 57 days near the hypocenter at Hiroshima, based on measurements at H+11 (days) and H+53. Shinohara et al[40] measured the decay at the Nagasaki hypocenter from N+30 to N+396. While complex, the decay chiefly followed a 90-day half-life, corresponding to the ^{46}Sc half-life of 84 days. Miyasaki and Masuda[28] measured the decay at the Hiroshima hypocenter on H+71 and H+193. They found an effective half-life of 180 days.

Shinohara et al[40] measured the long-lived induced activity at Nagasaki as a function of distance from the hypocenter, while Miyasaki and Masuda[28] made similar measurements at Hiroshima on H+71 and H+193. The falloff with distance may be represented approximately as exponential with the exposure rates being halved for each 175 m distance at Nagasaki and 350 m at Hiroshima for both times. These values are in agreement with measurements made by NMRI,[17] but the falloff with distance is slower at Hiroshima than that calculated by Gritzner and Woolson (Appendix 6-2).

Measurements of bricks and tiles listed in Table 10 indicate that the activation was not markedly different from soil for most radionuclides.[30,35] Tile samples showed higher levels of ^{56}Mn by about a factor of 5. These could have contributed to the short-term exposures near the hypocenter but would not have been seen in the direct measurements, which were made after the ^{56}Mn had decayed away. In any case, the allocation of exposure to soil, bricks, tiles, and other materials would seem to be impossible at this time.

Several direct measurements of gamma radiation from the long-lived induced radioactivity were made near the hypocenter in the few months following the explosions. The instrumentation and calibration were the same as for the fallout measurements, and most measurements were made by the same people. Since the measurements were made at different times, it is difficult to compare results; but a comparison is attempted here by estimating the gamma-ray exposure at $t=0$ by using the calculated decay of the radionuclide composition shown in Table 8 (as found for Hiroshima by Hashizume et al[35]) and the methodology outlined below.

Table 10. Concentration of Radionuclides Produced in Various Materials from Hiroshima by Neutron Activation; μCi/g.

Investigator and Sample	^{56}Mn	^{24}Na	^{46}Sc	^{60}Co	^{134}Cs
[35] Hashizume et al[a]					
Soil	3	0.89	5×10^{-5}	0.5×10^{-5}	2×10^{-7}
Roof tile	16	0.84	17	1.3	5
Brick	12	1.3	11	1.1	2
[30] Arakawa[a]					
Soil	0.63	0.32	7×10^{-5}	$<1 \times 10^{-5}$	
Roof tile	3.0	0.11	12	0.7	

[a] Irradiations were not the same for the two investigations.

Table 11. Measured Exposure Rates Near the Hypocenters from Long-lived Induced Radioactivity; μR/h.

Investigator	Exposure rate μR/h	Days after bomb	Exposure rate at t=0, μR/h
Hiroshima			
[28] Miyasaki and Masuda	120	H+71	200
	75	H+193	260
[29] Fujiwara and Takeyama	80	H+45	110
NMRI[a]	69	H+87	130
MED[a]	100	H+60	160
Nagasaki			
[41] Masuda et al	53	N+140	140
[40] Shinohara et al	75	N+32	100
NMRI[a]	72	N+73	120
MED[a]	30	N+52	40

[a] Values for the Naval Medical Research Institute and the Manhattan Engineering District were taken from the maps in McRaney and McGahan.[16]

Table 11 indicates the range of the measured data and the extrapolated values for the long-lived radioactivity at t=0. The Hiroshima values may also be compared with the value of 100 μR/h calculated by Hashizume et al[35] for ^{46}Sc plus ^{60}Co at t=0.

The induced radioactivity near the hypocenter was detected in generally flat areas and the large amount of surface rubble and litter should have reduced any movement of radioactivity by weathering. In addition, the radioactivity was distributed throughout the upper few centimeters of soil and would be less mobile than fallout deposited on the surface. Thus the measurements should give a reasonable estimate of the amounts of long-lived radionuclides induced by the explosions.

Several investigators made estimates of the total radiation; either initial exposure rate, cumulative exposure, or both. These values are shown in Table 12. As another indicator of

Table 12. Estimates of Initial Exposure Rates and Cumulative Exposures from Total Induced Radioactivity Near the Hypocenter.

Investigator	Exposure rate at t=0 (μR/h)	Cumulative Exposure (R)
Hiroshima		
[42]Hashizume and Maruyama	8	80
[30]Arakawa	2[a]	24[a]
[5]Takeshita	5	98
[43]Shohno		130
Gritzner (Appendix 6-2)	8	100
This chapter	9	70
Nagasaki		
[42]Hashizume and Maruyama		30
[30]Arakawa	0.8[a]	4[a]
[5]Takeshita		39
[43]Shohno		55
Gitzner (Appendix 6-2)	12	35

[a]Indicates values stated by Arakawa[30] to be the best of the four models tested by him. They are based on neutron fluence estimates that are lower than those given in Chapter 3 of this report by a factor of 5 for Hiroshima and 2 for Nagasaki.

Table 13. Areas with Specified Exposure Rate Contours from Induced Radioactivity Around the Hypocenter in Nagasaki Compared with Values Calculated by Gritzner[38] from Neutron Fluences.

Group	Exposure rate contour (mR/h)	Days after bomb	Exposure rate contour at t=0		Area (ha)
			From measurement (R/h)	From calculation (1 rad)	
MED	0.03	N+50	3.5	5.8	13
	0.02		2.3	1.4	65
	0.005		0.6	0.14	180
NMRI	0.072	N+73	9.9	12	Point
	0.069		9.5	10	0.6
	0.032		4.4	5.5	15
	0.011		1.5	1.4	100

MED. Manhattan Engineering District.
NMRI. Naval Medical Research Institute (in McRaney and McGahan[17]).

the distribution of induced radioactivity around the hypocenter, the areas within the contours of equal exposure rate on the maps in McRaney and Mcgahan[17] were determined. The two sets of data for each city are compared in Tables 13 and 14. It would appear that there is reasonable agreement for each city when comparing equal areas and that the exposure rates in Hiroshima were higher than those in Nagasaki.

Table 14. Areas with Specified Exposure Rate Contours from Induced Radioactivity Around the Hypocenter in Hiroshima Compared with Values Calculated by Gritzner[38] from Neutron Fluences.

Group	Exposure rate contour (mR/h)	Days after bomb	Exposure rate contour at t=0		Area (ha)
			From measurement (R/h)	From calculation (rad/h)	
MED	0.1	H+60	13	4.3	15
	0.03		3.8	0.57	100
	0.02		2.5	0.002	500
	0.01		1.3	0.00011	(900)[a]
NMRI	0.069	H+87	10	6.9	1.3
	0.057		8.6	6.2	4
	0.045		6.8	4.3	15
	0.032		4.8	2.2	40
	0.019		2.8	0.85	80
	0.011		1.6	0.05	230

MED. Manhattan Engineering District.
NMRI. Naval Medical Research Institute (in McRaney and McGahan[17]).
[a] Indicates area was not well defined.

Calculation of Exposure from Measured Induced Activity in Soil

Measurement of the neutron-induced radioactivity on the ground near the hypocenter in Hiroshima and Nagasaki was made well after the most significant contributing radionuclides had completely decayed. The following information was used in an attempt to link the experimental measurements with the values that will be obtained by the modeling procedures in the present dose assessment effort:

1. The data of Hashizume et al[35] (Table 8) on the activation of Hiroshima soil were selected.
2. A composite decay curve was drawn for the mixture of long-lived induced radionuclides, ^{46}Sc, ^{60}Co, and ^{134}Cs.
3. As an example, a measured exposure rate was selected from the NMRI value for the highest isopleth in Hiroshima (69 μR/h at H+87, Table 11). This was within 100 m from the hypocenter.
4. The decay curve of step 2 was used to extrapolate the 69 μR/h back to zero time, which gave an initial exposure rate of 130 μR/h for these radionuclides.
5. It was assumed that the ^{56}Mn and ^{24}Na each gave roughly the same gamma-ray exposure for the same soil concentration in μCi/g as the ^{46}Sc, ^{60}Co, and ^{134}Cs. The energy releases per disintegration are reasonably similar.
6. The activity ratios in Table 8 were used to estimate the initial exposure rates from ^{56}Mn and ^{24}Na.

7. The cumulative exposures (from time zero to infinity) were calculated for the three major radionuclides as shown below. The ^{60}Co and ^{134}Cs contributions to cumulative exposure were negligible.

Radionuclide	Initial Exposure Rate (R/h)	Cumulative Exposure (R)
^{56}Mn	7	26
^{24}Na	2.1	45
^{26}Sc	0.00013	1
Rounded Total	9	70

Okajima and Hoshi[44] estimated the thermal neutron fluence for the two cities by measurement of ^{152}Eu. The activities of ^{152}Eu contained in rocks exposed to neutrons near the hypocenter in Hiroshima and Nagasaki were measured. They are expressed as Bq/μg of natural europium contained in the rocks, adjusted to the time of the bomb. For Hiroshima, an activity density of 0.116 Bq/μg of Eu yields a fluence estimate of 6.3×10^{12} cm^{-2}, while for Nagasaki, an activity density of 0.0396 yields a fluence of 2.1×10^{12}.

SUMMARY

In this chapter available data and calculations for assessing the exposure of survivors of the Hiroshima and Nagasaki bombs and persons who entered the cities after the bombings have been presented. It appears that it is possible to produce firm estimates only for external radiation and, while the internal contribution for long-lived fission products appears small, there is no way to evaluate potential exposures to the short-lived fission products.

The radiation exposure in the most highly contaminated fallout area of a few hectares at Nishiyama, Nagasaki, is estimated as 20 to 40 R when integrated from one hour to infinity using a decay exponent of −1.2. For the Hiroshima Koi-Takasu area, the corresponding exposure is estimated as 1 to 3 R. The falloff with distance for Nagasaki is not steep and an exposure of one-fifth of the maximum is spread over an area of perhaps 1000 ha.

With the assumptions stated above, the potential maximum exposures to external radiation from induced radioactivity at the hypocenter is estimated to be about 80 R for Hiroshima and 30 to 40 R for Nagasaki with the assumptions stated above. These exposures fall off with both time and distance. The cumulative exposure would be about one-third as large after a day and only a few percent after a week. The falloff with distance is less striking, but can be estimated from the areas listed in Tables 13 and 14 or from the curves shown in Gritzner and Woolson (Appendix 6-2). Unlike the fallout, which exposed individuals in their living areas, exposures to induced activity came from reentry of individuals into the area around the hypocenter.

As an example, an individual entering the Hiroshima hypocenter area after one day and working 10 or 20 hours a day for a week would have been exposed to about 10 R. If the person had been working at a distance of 500 m, the exposure would have been about 1 R and, at 1000 m, about 20 mR.

The exposures described apply to the specified areas in the two cities. Application of these values to individuals requires knowing the location of the person to within about 200 m from the time of the explosion to a few weeks afterwards. This is an effort that might be comparable to the present shielding study for survivors. The sizes of the four exposed groups are relatively small; however, the number has been estimated only for those exposed to fallout in the Nishiyama district of Nagasaki. Okajima[23] listed the population of Nishiyama as about 600 at the time of the bomb. No figures are available for the other three groups.

The individual exposures from residual radiation may not be significant compared with the direct radiation at the time of the bomb. On the other hand, individuals with potential exposure from these sources are dubious candidates for inclusion in a cohort that was presumably not exposed.

For comparison with organ doses estimated in other parts of this program, the exposure estimates are converted to absorbed dose in tissue. The first conversion of exposure to absorbed dose in air uses the factor rad in air = 0.87 × exposure in R. UNSCEAR[20] uses an average combined factor of 0.7 to convert absorbed dose in air to absorbed dose in tissue for the whole body. This factor accounts for the change in material (air to tissue) and for backscatter and the shielding afforded by other tissues of the body. No allowance for shielding by buildings has been included here.

The cumulative fallout exaposures given above become absorbed doses in tissue of 12 to 24 rad for Nagasaki and 0.6 to 2 rad for Hiroshima. The cumulative exposures from induced radioactivity become absorbed doses in tissue of 18 to 24 rad for Nagasaki and about 50 rad for Hiroshima.

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