DOSES FROM EXTERNAL IRRADIATION TO MARSHALL ISLANDERS FROM BIKINI AND ENEWETAK NUCLEAR WEAPONS TESTS

André Bouville,* Harold L. Beck,† and Steven L. Simon*

Abstract—**Annual doses from external irradiation resulting from exposure to fallout from the 65 atmospheric nuclear weapons tests conducted in the Marshall Islands at Bikini and Enewetak between 1946 and 1958 have been estimated for the first time for Marshallese living on all inhabited atolls. All tests that deposited fallout on any of the 23 inhabited atolls or separate reef islands have been considered. The methodology used to estimate the radiation doses at the inhabited atolls is based on test- and location-specific radiation survey data, deposition density estimates of ^{137}Cs, and fallout times-of-arrival provided in a companion paper (Beck et al.), combined with information on the radionuclide composition of the fallout at various times after each test. These estimates of doses from external irradiation have been combined with corresponding estimates of doses from internal irradiation, given in a companion paper (Simon et al.), to assess the cancer risks among the Marshallese population (Land et al.) resulting from exposure to radiation from the nuclear weapons tests.**
Health Phys. 99(2):143–156; 2010

Key words: ^{137}Cs; dose, external; fallout; Marshall Islands

INTRODUCTION

Despite numerous efforts to monitor the Marshall Islands for radioactivity during the United States Pacific nuclear testing program and afterwards, there has been relatively little effort towards estimating radiation doses to all Marshallese exposed to the fallout from the testing. The United States Atomic Energy Commission (USAEC) issued a report on radiological surveys following Operation Ivy of 1952 (Eisenbud 1953) and Operation Castle of 1954 (Breslin and Cassidy 1955). The latter report estimated cumulative exposures from the tests of the Castle series, all of which were high yield. The measurement data used for those estimates of exposure were collected by two methods: (1) stationary, ground-level continuous reading Geiger-Müller type instruments with paper strip chart recording mechanisms, and (2) aerial surveys using fixed wing aircraft that carried scintillometer instruments. Most of the atolls of the Marshall Islands, including all that had populations of significant size, were monitored in the aerial radiological surveys in 1954 (Breslin and Cassidy 1955). The range of estimated cumulative exposures from the Castle series reported by Breslin and Cassidy (1955) covered approximately five orders of magnitude, similar to the range of ^{137}Cs concentrations measured in the environment of the Marshall Islands by the Nationwide Radiological Study conducted approximately 40 y later (Simon and Graham 1994, 1997). The USAEC-placed instrument on Rongerik Atoll was responsible for alerting the U.S. military weather observers on Rongerik to high levels of early fallout, leading to their evacuation and to the evacuation of Marshallese from Rongelap, Ailinginae, and Utrik following the test Bravo in 1954 (Eisenbud 1987; Simon 2000).

Other than atoll-specific values for the external exposure (reported in Roentgens or R) published in the USAEC reports (Eisenbud 1953; Breslin and Cassidy 1955), and later estimates of external dose by Lessard et al. (1985) for Rongelap and Utrik, few, if any, external dose estimates have been reported for Marshallese. One significant source of information on nuclear testing in the Marshall Islands, a special issue of *Health Physics* (Simon and Vetter 1997), was largely concerned with land contamination, resettlement issues, and assessments of doses received decades after nuclear tests were conducted in the Marshall Islands. Until the publication of this paper, no systematic effort had been made to estimate the annual doses from external irradiation, received from 1948 to 1970, from all tests at all inhabited atolls.

* Division of Cancer Epidemiology and Genetics, National Cancer Institute, National Institutes of Health, Bethesda, MD 20892; † New York, NY 10014 (retired from U.S. DOE).

For correspondence contact: Steven L. Simon, National Cancer Institute, National Institutes of Health, 6120 Executive Blvd., Bethesda, MD 20892, or email at ssimon@mail.nih.gov.

(*Manuscript accepted* 5 *March* 2010)
0017-9078/10/0

DOI: 10.1097/HP.0b013e3181dc521d

The method of estimating external doses can be based on either historical data of ground-level exposure rates, or, alternatively, on data on the deposition density of particular radionuclides contained in the fallout, such as ^{137}Cs, combined with information on the ratio of the nuclide activity at the time of fallout to the exposure rate at that time. Crude exposure estimates can also be made from retrospective estimates of ^{137}Cs or ^{90}Sr inventories measured in soil samples, provided one can estimate the relative contributions from each of the tests to the total measured inventory. The reliability of dose estimates is dependent, however, on having reliable estimates of the time of transport of the fallout from the detonation point to the receptor point. Those data, called the fallout "time-of-arrival" (TOA, measured in h), can considerably affect the dose estimates for locations relatively close to the detonation point (i.e., within a few hours transit time for the fallout). In a separate paper, Beck et al. (2010) describe available post-test data on measured exposure rates and provide estimates of both TOA and ground deposition densities (Bq m^{-2}) of ^{137}Cs based on those and other types of data. ^{137}Cs deposition density estimates were developed for each of 32 atolls and separate reef islands of the Marshall Islands from each of the 20 tests that took place at Bikini or Enewetak that resulted in measurable fallout on the atolls.[‡] Estimates of fallout TOA were also developed for those tests and atolls so that estimates of dose from external irradiation could be reconstructed using either method. The names, dates, and yields of the 20 tests that deposited fallout on any of the inhabited atolls or separate reef islands, other than the test site atolls themselves, are provided in Simon et al. (2010a, Table 1).

In a companion paper (Simon et al. 2010b), the doses from internal irradiation also are estimated for all the tests and atoll populations that are considered in this paper. The risks of cancer resulting from the doses arising from exposure to radioactive fallout from regional nuclear testing in the Marshall Islands, taking into consideration age and atoll of residence at the time of the tests, are assessed in another companion paper (Land et al. 2010).

MATERIALS AND METHODS

The doses from external irradiation were estimated in three basic steps:

1. estimation of the outdoor exposure rates at 12 h at each atoll after each test and of the temporal variation of the exposure rate after each test;
2. estimation of the total external exposures from fallout from TOA to infinity, obtained by integrating the estimated exposure rates over time assuming continuous residence on the atoll (with corrections for relocated populations); and
3. estimation of whole-body and organ doses by applying conversion factors from outdoor exposure to tissue dose.

Estimation of the outdoor exposure rates

The outdoor exposures at each atoll following each test have been assessed in one of two ways depending on whether measured exposure rates were available for the times and locations of interest. If historical data on exposure rate were available, the data were assessed and a best estimate of the island- or atoll-average exposure rate at 12 h post detonation (termed $\dot{E}12$) was made. Because the quality of the exposure-rate measurements varied by test and location, expert judgments were often used to determine the appropriate weighting of measurements of varying quality. As discussed in Beck et al. (2010), many of the reported measurements were made before all the fallout from a test was deposited, while other measurements were obtained many weeks after the test when the exposure rate had been attenuated due to weathering of the fallout by rainfall or human activities. Of course, neither would have been as preferable as high-quality ground-level exposure-rate measurements made soon after deposition was complete.

If no reliable exposure-rate data were available to estimate $\dot{E}12$ directly, then the dose estimation method used was that developed by the Off-Site Radiation Exposure Review Project (ORERP) for estimating external whole-body and organ doses from fallout originating at the Nevada Test Site (NTS) (Hicks 1982). That method relates the ^{137}Cs deposition densities and fallout TOA values to $\dot{E}12$ using ratios of ^{137}Cs to $\dot{E}12$ for a range of times developed specifically for some of the tests considered in this paper (Hicks 1984). The types of data provided by Hicks (1981, 1982, 1984) are: (i) calculated exposure rates from all radionuclides in the fallout debris relative to a reference exposure rate of 1 mR h^{-1} at H+12 (12 h post detonation), at 31 times after detonation, ranging from 1 h to 50 y, and (ii) related radionuclide ground deposition densities, expressed in μCi m^{-2}, for more than 60 of the most important fission and activation products (the number varies from one test to another). Activities of fission products per unit of

[‡] The reader will note that this work does not attempt to quantify the deposition on the test site atolls (Bikini and Enewetak). Not only was the contamination on the islands of those atolls very heterogeneous, but they were monitored extensively for many years and those data are reported elsewhere. Moreover, those atolls were never inhabited during the testing years.

exposure rate were calculated from classified and declassified data available to Hicks on the amount of fissionable nuclides in the device and the measured fission neutron spectra. The "zero time" activation product values were the results of measurements made by aircraft surveillance within 1 to 4 h post detonation. Hicks made assumptions regarding fractionation effects from which he developed his tables for unfractionated debris (designated as $R/V = 1$, where R stands for refractory radionuclides and V for volatile radionuclides), as well as for debris with 50 and 90% of the refractory elements removed (designated as $R/V = 0.5$ and $R/V = 0.1$, respectively). As described in Beck et al. (2010), we modified Hicks' calculated activity ratios for unfractionated fallout ($R/V = 1$) to estimate the activity ratios for various degrees of fractionation. For all tests except the Bravo test, available data support our assumption of an R/V ratio of 0.5 at all atolls. In contrast, however, there were some significant variations in the degree of fractionation for Bravo fallout at some atolls: 0.7 for Likiep, 0.9 for Mejit Island, 1.3 for Ailinginae, 1.4 for Rongelap, 1.5 for Rongerik, and 0.5 at all other inhabited locations. The high fractionation conditions ($R/V > 1$) for test Bravo at atolls close to the Bikini Atoll test site reflect the preferential deposition of large particles at early times of arrival, in which the activity of refractory radionuclides is greater than that of volatile radionuclides.

Hicks calculated nuclide composition as a function of time for six thermonuclear tests in the 1954 Castle series (Mike, Bravo, Romeo, Yankee, Zuni, and Tewa); the data from the other 14 thermonuclear tests that deposited fallout in the Marshall Islands are still classified. As described below, Hicks' data were used in two different ways in our calculations according to the information that was available for each test and location:

1. If the exposure rate was measured or inferred at any time after the test, then only information on the temporal variation of the exposure rate was required to correct exposure-rate measurements made at different times to H+12, and, as described later in this paper, to integrate the estimated exposure rates to obtain total exposure. This is the method that was generally used for the atolls and tests where exposure rates were measured by airplane surveys or ground surveys conducted soon after the test. In our method, corrections were also made for the gradual decrease of radionuclide activities in the upper layers of soil resulting from environmental loss processes (termed "weathering effects" in this paper), which are not taken into account in Hicks' calculations. Those corrections, described later in this paper, are trivial for the first week or month after the test, but are substantial when calculations of exposure rate are made for years or decades after the test.
2. If the exposure rate had not been measured, but rather the ^{137}Cs deposition density was estimated for a given test i and at an atoll j, then $\dot{E}12(i, j)$ was estimated from Hicks' predicted ratios of ^{137}Cs to $\dot{E}12$, modified to account for our best estimate of fractionation. Eqn (1) presents the form of this calculation:

$$\dot{E}12(i, j) = \frac{A(i, j)}{ND(i, j)}, \quad (1)$$

where $A(i, j)$, in Bq m^{-2}, is the ^{137}Cs activity deposited per unit area of ground at atoll j after test i (Beck et al. 2010), and $ND(i, j)$ is the normalized ^{137}Cs deposition density, expressed in Bq m^{-2} per mR h^{-1} at H+12, and inferred from the work of Hicks (1981, 1984) for the selected value of R/V for test i at atoll j.

The method described above would be appropriate if the ^{137}Cs deposition density was measured within about one month after the test and if it could be unequivocally assumed to have been a result of fallout from that test. However, as a rule, ^{137}Cs was measured in soil many years later in the 1970's and the 1990's. In that case, we first decay-corrected the measurements of ^{137}Cs deposition back to the time of the testing in order to obtain a preliminary estimate of $\dot{E}12$ for further refinement.

In practice, as described by Beck et al. (2010), both methods were used to estimate both $\dot{E}12$ and ^{137}Cs deposition, often in an iterative manner in order to obtain: (1) credible fallout patterns over the territory of the Marshall Islands; (2) reasonable sets of $\dot{E}12$ and fallout TOA values; and (3) in some cases, estimates of fractionation.

As shown by Beck et al. (2010), the ratio of ^{137}Cs to $\dot{E}12$ decreases as the degree of fractionation increases, from 31.8 Bq m^{-2} per mR h^{-1} at H+12 for $R/V = 0.5$ to 7.8 Bq m^{-2} per mR h^{-1} at H+12 for $R/V = 1.5$. As previously indicated in this paper, the fallout from Bravo at some of the more northern atolls was enriched in refractory nuclides (i.e., $R/V > 1$) resulting in a reduced ratio of ^{137}Cs to $\dot{E}12$ relative to fallout deposited at further distances from the test site where typical values of R/V were 0.5. Although the dependence of the ^{137}Cs to $\dot{E}12$ ratio on fractionation is substantial, it had only a minor impact on the exposure-rate estimates made in this study since actual exposure-rate measurements were available for most of the atolls impacted by fractionated Bravo fallout. Thus, in practice, only the Hicks' data for $R/V = 0.5$, typical of fallout at distant sites from a detonation point (Hicks 1982), were used to estimate $\dot{E}12$

from ^{137}Cs deposition density estimates. However, as described in Beck et al. (2010), the assumed degree of fractionation was very important for estimating ^{137}Cs deposition density from exposure-rate measurements at some atolls heavily impacted by Bravo.

Estimation of the total exposure from fallout

In order to estimate the total exposure from fallout from an estimate of exposure rate at any specific time, we used the temporal variations of exposure rate given by Hicks (1981, 1984) in a manner described below.

First, we developed analytic expressions of the temporal variation of the normalized exposure rate for both Bravo and for a non-thermonuclear test (Tesla) that was conducted at the NTS for the purposes of deriving the exposure over any interval of time (post-detonation) from the data provided by Hicks (1981, 1984). The Hicks exposure-rate data, which are relative to an exposure rate of 1 mR h^{-1} at H+12, but do not take weathering effects into account, were fit to 10-component exponential functions such that a mathematical integration could be easily accomplished. The form for the fitted functions of the exposure rate was:

$$\dot{E}(t)/\dot{E}12 = \sum_{n=1}^{10} a_n e^{-\lambda_n t}, \qquad (2)$$

where

t = the time elapsed since the time of the detonation of the device (h);

$\dot{E}(t)/\dot{E}12$ = the ratio of the exposure rate at time t to the exposure rate 12 h after detonation, expressed in mR h^{-1};

a_n = the coefficient to the n^{th} exponential term; and

λ_n = the decay constant for the n^{th} exponential term (h^{-1}).

The fitted regression values for a_n and λ_n for Bravo and Tesla are given in Table 1 for $R/V = 0.5$. As shown in Fig. 1, exposure-rate data for six thermonuclear tests (Hicks 1984) are highly similar. For that reason, we concluded that the single set of regression parameters, shown in Table 1, would be suitable for all 16 thermonuclear tests listed in Simon et al. (2010a, Table 1). The regression parameters shown in Table 1 correspond to a degree of fractionation (R/V) of 0.5, typical of fallout at relatively large distances from the site of detonation where most of the deposited activity was associated with relatively small particles (<50 μm diameter). We also fit Hicks' data for Bravo for $R/V = 1.0$ and used those values for the higher fractionation ratios. As shown later, the difference in decay rates between the $R/V = 1.0$ and $R/V = 0.5$ curves is small. We used the $R/V = 1.0$ decay rate regression fit to calculate total exposure and $\dot{E}12$ values for close-in distances and short TOAs of fallout where we assumed R/V to be greater than 0.5. In the absence of similar data for any non-thermonuclear tests at Bikini or Enewetak, we concluded that the data derived by Hicks (1981) for the Tesla test conducted at the NTS would adequately reflect the decay rate and nuclide composition of the four non-thermonuclear tests (Simon et al. 2010a, Table 1) that deposited relatively low levels of fallout in the Marshall Islands. As shown in Fig. 1, the decay rate for Tesla is very similar to that for the six thermonuclear tests.

We subsequently took into account the influence of weathering on the temporal variation of the exposure

Table 1. Fitted parameter values of a_n and λ_n for use in eqn (2) to describe the variation of the exposure rate with time after detonation according to Hicks' (1981, 1984) data for fractionated debris (R/V = 0.5) for Bravo (thermonuclear tests) and Tesla (non-thermonuclear tests). The values of a_n are normalized to an exposure rate of 1 mR h^{-1} at H+12.

	Thermonuclear tests		Non-thermonuclear tests	
Component of exponential	a_n (mR h^{-1})	λ_n (h^{-1})	a_n (mR h^{-1})	λ_n (h^{-1})
1	9.30×10^{1}	2.25×10^{0}	1.02×10^{2}	1.86×10^{0}
2	3.35×10^{1}	8.30×10^{-1}	3.26×10^{1}	6.44×10^{-1}
3	1.65×10^{0}	8.30×10^{-1}	1.00×10^{-8}	6.44×10^{-1}
4	5.00×10^{0}	3.88×10^{-1}	1.68×10^{0}	1.34×10^{-1}
5	1.85×10^{0}	9.67×10^{-2}	9.57×10^{-1}	8.99×10^{-2}
6	3.50×10^{-1}	2.28×10^{-2}	3.04×10^{-1}	2.03×10^{-2}
7	9.58×10^{-2}	5.83×10^{-3}	8.08×10^{-2}	4.35×10^{-3}
8	1.38×10^{-2}	1.43×10^{-3}	8.75×10^{-3}	7.58×10^{-4}
9	1.40×10^{-3}	3.05×10^{-4}	9.28×10^{-6}	4.05×10^{-6}
10	7.37×10^{-6}	2.66×10^{-6}	2.38×10^{-6}	1.00×10^{-8}

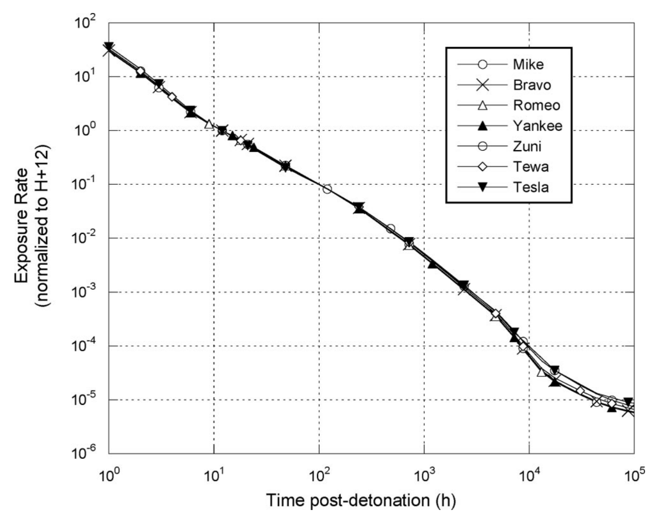

Fig. 1. Variation with time of the normalized exposure rates for six thermonuclear tests and a non-thermonuclear test (Tesla) for a fractionation level, R/V, of 0.5 (Hicks 1981, 1984).

rate. In Fig. 1 and Table 1, the gradual decrease of the exposure rate caused by the migration of the deposited activity into deeper layers of soil is not taken into consideration. Most radionuclides penetrate into the soil quite rapidly during the first year after deposition, but the vertical distribution of activity tends to stabilize after the first year. To properly account for the influence of weathering with time, we developed a time-dependent weathering correction factor, $W(t-TOA)$ (Fig. 2). We believe that this weathering correction, which is based on the analysis of actual depth profiles of ^{137}Cs and ^{90}Sr measured in the soil in the Marshall Islands in 1978 and 1991–1993, reasonably reflects the actual time variation in exposure rates from Bikini/Enewetak fallout in the years from 1948–1970. Mean values of observed relaxation lengths in the Marshall Islands in 1978 were about 5–7 cm and were only slightly greater in 1993–1994 (with of course wide variations). However, as discussed in Beck et al. (2010), ^{137}Cs was known to have been lost from the soil profile with an effective half life of about 12–20 y compared with a physical half life of 30 y. Thus, after about 5 y, when ^{137}Cs begins to account for most of the external exposure rate, the weathering loss of ^{137}Cs accounts for most of the reduction in exposure rate.

The weathering correction factor, $W(t - TOA)$, was analytically implemented in our calculations of exposure in one of two different ways, depending on the time after deposition: in the year of deposition, a weathering rate, λ_w, of 0.00018 h^{-1}, corresponding to a half-time of 5 mo and reflecting the initial weathering correction shown in Fig. 2, was added to each of the λ_n values; while for subsequent years, the exposure rates obtained using the values presented in Table 1 were multiplied by the time-dependent factors shown in Fig. 2, i.e., equal to 0.5 and 0.35 in years 1 and 2 following the test, respectively, and decreasing gradually to a value of 0.1 in the twentieth year after the test.

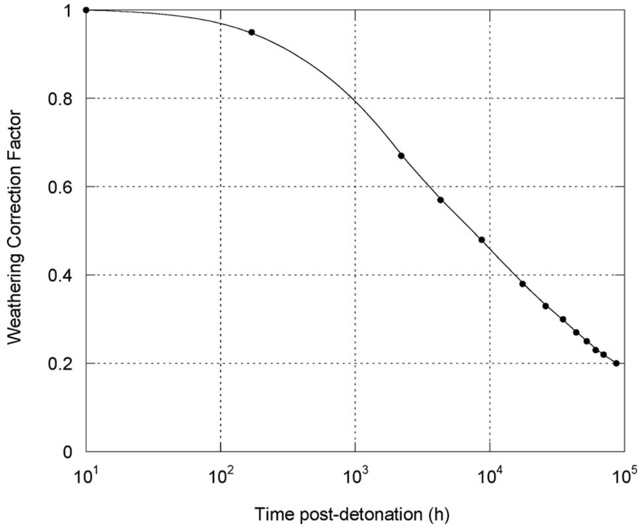

Fig. 2. Time-dependent correction factor used to take the weathering effect into account.

Our corrections for weathering impact the estimated exposure rates only after a few weeks and, because of the rapid decrease in fallout exposure rates with time shown in Fig. 1, have only a minor effect on an individual's integrated exposure as shown in Table 2. The effect on total exposure is greatest for large TOAs, corresponding in general to relatively low fallout. However, as discussed above, weathering does have a significant effect on the small annual doses from residual long-lived activity.

The variation with time of the exposure rate, relative to an exposure rate of 1 mR h^{-1} at H+12 h, is shown in Fig. 1 and illustrates that there is little difference in the rate of change of exposure from fallout from different tests. Fig. 3 and Table 2 illustrate that the degree of fractionation also has only a minor effect on the temporal variations of exposure rate and mainly at very long times after the detonation. At long times, the more volatile nuclides, such as ^{106}Ru and ^{137}Cs, contribute a greater fraction of the exposure compared to refractory nuclides. As shown in Fig. 3, weathering also has only a minor effect on exposure rate at early times, when the exposure rate is high and, thus, as shown in Table 2, has only a relatively small effect on the integrated exposure. However, as shown in Fig. 3, weathering does significantly reduce the exposure rate at long times after deposition.

Given the expressions for the decay rate as a function of time, modified for weathering, the exposure, E, between any two times of interest, t_1 and t_2, is determined by integrating the normalized exposure rate (either measured or calculated) using eqn (3):

$$E(t_1, t_2, i, j) = \int_{t_1}^{t_2} [\dot{E}12(i, j) \sum_{n=1}^{10} a_n e^{-\lambda_n t} W(t - TOA)]dt$$

$$= \frac{\dot{E}12(i, j) \times \sum_{n=1}^{10} a_n [e^{-(\lambda_n + \lambda_w)t_1} - e^{-(\lambda_n + \lambda_w)t_2}]}{(\lambda_n + \lambda_w)} \quad (3)$$

for the first year of exposure.

Estimation of the conversion factors from outdoor exposure to tissue dose

In order to estimate whole-body or organ dose from the integrated exposure, the following factors were considered.

First, the exposure rates estimated above correspond to outdoor conditions in the populated areas but do not

Table 2. Variation of the exposure (mR) with increasing TOA (h) and influence of the weathering effect. The exposure rate is normalized to 1 mR h^{-1} at H+12 and the relative degree of fractionation (*R*/*V*) is assumed to be 0.5.

Exposure (mR) from TOA to:	Weathering? (Y/N)	Exposure (mR) TOA = 0 h	TOA = 4 h	TOA = 6 h	TOA = 12 h	TOA = 22 h	TOA = 40 h	TOA = 68 h	TOA = 162 h
1 wk	Y	143.0	42.8	37.0	28.5	21.3	14.7	9.1	0.34
1 wk	N	143.3	43.0	37.3	28.8	21.5	14.8	9.1	0.34
1 mo	Y	154.0	53.3	47.4	39.0	31.8	25.2	19.7	11.1
1 mo	N	154.5	54.2	48.3	39.8	32.6	25.9	20.3	11.5
1 y	Y	158.0	58.2	52.3	43.9	36.7	30.1	24.6	16.1
1 y	N	162.1	61.4	55.5	47.0	39.7	33.0	27.4	18.6
10 y	Y	159.1	58.5	52.6	44.2	37.0	30.5	24.8	16.5
10 y	N	162.1	62.1	56.4	47.9	40.6	33.8	28.2	19.4
70 y	Y	159.1	58.5	52.7	44.2	37.1	30.5	25.0	16.5
70 y	N	165.2	62.6	56.8	48.3	41.1	34.4	28.8	20.0

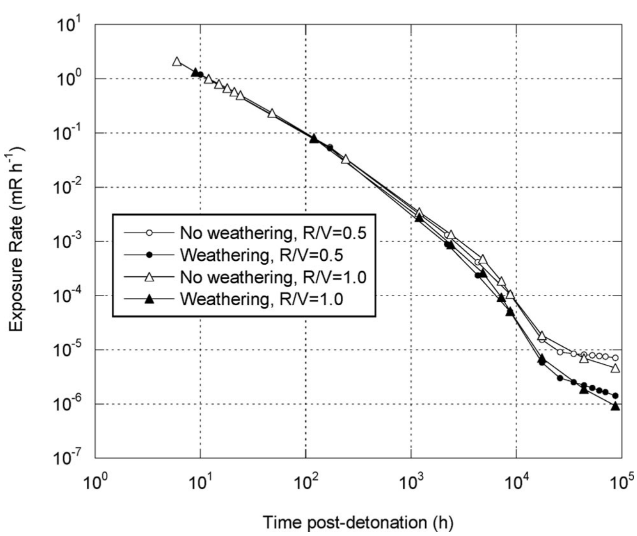

Fig. 3. Exposure rate as a function of time after detonation with and without a weathering correction at two fractionation levels, *R*/*V* = 0.5 and *R*/*V* = 1.0.

necessarily reflect the variation from one area of an island to another or to indoor conditions. The potential reduction of exposure due to shielding by building materials when inside traditional Marshallese houses would be small as suggested by measurements made after Bravo that indicated that native housing did not appear to substantially attenuate the fallout radiation (Sharp and Chapman 1957; Conard et al. 1975). Contemporary measurements of outdoor exposure rates (Fig. 4), however, show substantial variation from one area of any island to other areas. At downwind distances where most atolls were located, fallout debris clouds were, for the most part, larger than individual islands. For that reason, we believe that fallout deposition was usually relatively homogeneous over any given island. Therefore, during the first year after fallout, when over 97% of the lifetime exposure occurred (Table 2), there was little difference in the exposure rates from one area of any island to another. Over time, however, exposure rates in areas near the shore became lower compared to exposure rates in the center of islands as a consequence of weathering, human activity, and intermittent flooding from storms. The exposure rates were also much lower in subsequent years than during the first year after fallout. In this work, we have assumed that our estimated outdoor exposure rates, based on the original fallout levels, were representative of the average conditions under which people lived during the periods of maximum exposure, but we recognize that this assumption may have resulted in a very slight overestimation of the cumulative exposure as Marshallese spend much of their time in village areas that are typically near the lagoon shore.

In order to calculate the organ and tissue doses from the free-in-air exposure data, one must first convert exposure to dose in air using a factor of 8.75×10^{-3} Gy R^{-1}. Then, a factor of 0.75 Gy Gy^{-1} was used to convert from dose in air to dose in tissue or organ. This factor of course varies with the energy of the radiation and the orientation with respect to radiation incidence (NCRP 1999; Eckerman and Ryman 1993; ICRP 1996), as well as with the organ and tissue that is considered and with the anthropometric characteristics of the person. Because there is little difference between the values of this conversion factor for one organ to another for gamma-ray energies of a few hundreds of keV that are typical for fission products (Jacob et al. 1990; ICRP 1996), the same value was used for all organs and tissues that were considered in this study and also would be used if the effective doses were to be calculated. The conversion factor from dose in air to effective dose was taken as 0.75 Sv Gy^{-1} by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993) and by the National Council on Radiation Protection and Measurements (NCRP 1999) for adults exposed to fallout. The net conversion from exposure in air to tissue or

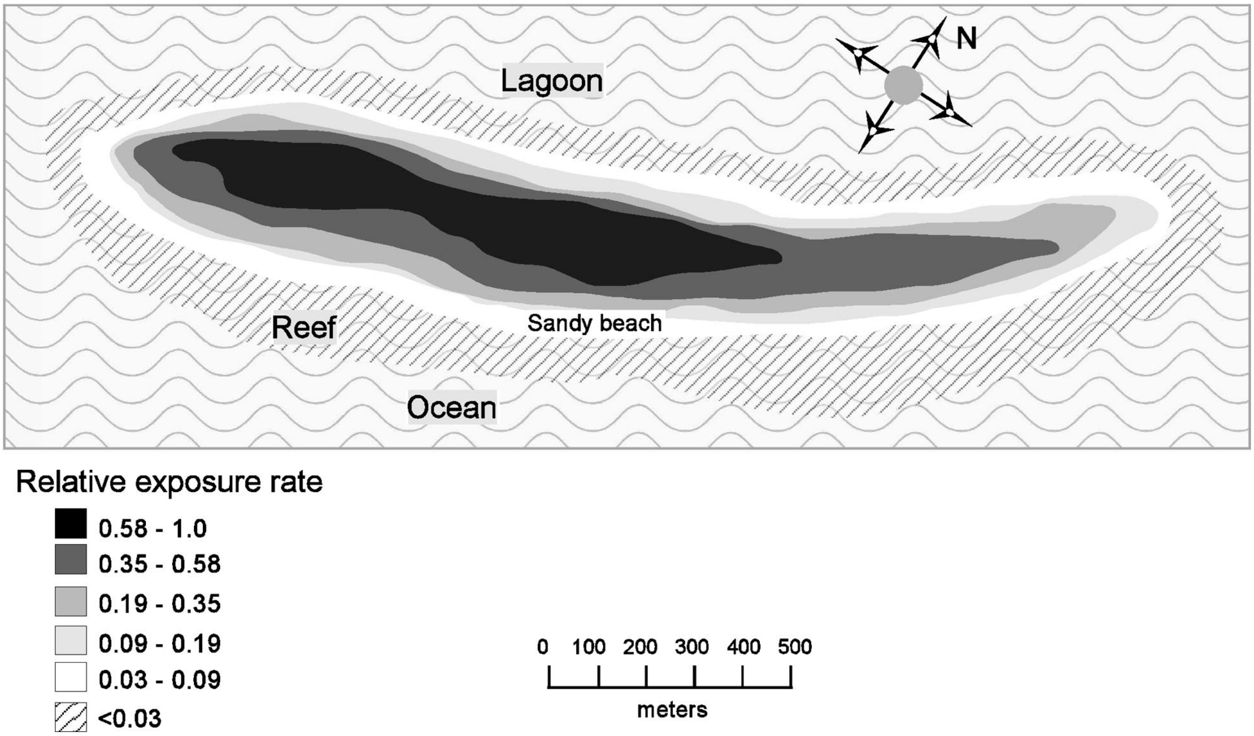

Fig. 4. Relative exposure rates (arbitrary units) across Eniwetak Island, Rongerik Atoll, in 1978. Data derived from the U.S. Department of Energy-sponsored aerial radiological survey of the Marshall Islands (Tipton and Miebaum 1981).

organ dose is thus about 8.75×10^{-3} (Gy R^{-1}) $\times$ 0.75 (Gy Gy^{-1}) = 6.6×10^{-3} (Gy R^{-1}) for adults.

While the dose conversion factor for an actual person depends on the age and sex of the person, or, more precisely, her or his anthropometric characteristics, doses in this study were estimated for representative persons, defined as hypothetical individuals with anthropometric characteristics that are typical of those of the people who lived in the Marshall Islands in the 1950's. Calculations using anthropomorphic phantoms of different ages (Jacob et al. 1990) indicate that body size, which is generally correlated with age, results in slightly higher doses for younger ages. Based on those calculations, we adjusted our estimated doses for representative adults to doses for younger (<3 y, including in utero) and older (3 through 14 y) children by multiplying the adult doses by 1.3 and 1.2, respectively.

RESULTS AND DISCUSSION

Doses from external irradiation were estimated for the entire population of the Marshall Islands and for each of the 20 tests that took place at Bikini or Enewetak that resulted in measurable fallout on inhabited atolls of the Marshall Islands (see Table 1 in Simon et al. 2010a). The population of the Marshall Islands was classified into 26 population groups consisting of the permanent residents of 23 atolls and islands, and of three population groups that were evacuated or relocated (see Table 2 in Simon et al. 2010a). With the exception of the populations of the atolls that were evacuated following the test Bravo of 1954 or were relocated before the testing began (see Simon et al. 2010a, Table 3), we have assumed that our estimated doses pertained to representative persons from each atoll, and that there was no movement of those people from one atoll to another.

Estimated exposures

As shown in Fig. 1, the ground-level exposure rate decreases very rapidly with time after detonation, by a factor of more than 1,000 during the first 1,000 h (about 40 d). For that reason, the lifetime exposure varies substantially with the fallout TOA, as was shown in Table 2. The example TOA values that were chosen for Table 2, with the exception of the extreme value of TOA = 0, correspond to the range of values estimated for the inhabited atolls after the various tests (Beck et al. 2010). As previously indicated, most of the external exposure occurs within the first year following the detonation. The influence of the weathering effect is barely noticeable during the first month after the detonation and only plays a substantial role after one year. It is, however, extremely important to take the weathering effect into account when the only measurement available is of ^{137}Cs activity in soil sampled decades after the test.

The estimated outdoor exposures, from TOA to infinity, are presented in Table 3 for each test and each atoll or island, whether it was inhabited or not. For most of the tests, exposures of less than 1 R were estimated at all atolls and islands. Much higher exposures, ranging from 5 to 500 R, were assessed for several atolls in the northern part of Marshall Islands and for several tests of the 1954 Castle series (Bravo, Romeo, Yankee, Koon, and Union). When exposures are summed over all atolls and islands, those five tests account for 99% of the total exposure, with Bravo alone contributing 84%.

Estimated tissue and organ doses

Annual doses from external irradiation have been estimated for representative persons of the 26 population groups classified into three different age categories (infants, children, and adults). The annual doses are reported for the time period from 1948 to 1970. By 1970, the doses had decreased to very low levels in comparison to the peak observed in 1954. Since the doses are estimated for representative persons who were assumed to have remained on each atoll with movements between atolls limited to the relocated and evacuated populations (Simon et al. 2010a, Table 3), the doses from external irradiation are proportional to the exposures calculated using eqn (3), which are based on the environmental radiation data (measurements or estimated values) available for each atoll and test. The doses reported for the relocated populations include, where appropriate, contributions from exposures received before evacuation, during the period of resettlement, and following return to the atoll of origin.

Estimated annual doses for adults, shown in Fig. 5, were highest in 1954 and then decreased to values that were, in 1970, less than one thousandth of the peak values observed in 1954. The annual doses shown in Fig. 5 are for representative adults of four population groups (Majuro residents, Kwajalein residents, Utrik community members, and Rongelap Island community members)[§] that represent a range of deposition densities, as well as a range of exposures in four distinct areas.

In Table 4, the doses through 1970 resulting from the Bravo test are compared, for each of the 26 population groups, to the corresponding doses from all the tests of the Castle series conducted in 1954 and from all tests listed in Simon et al. (2010a, Table 1). At every atoll in the Marshall Islands, the Castle series was the predominant contributor to the total external dose. While Bravo was responsible for most of the external dose for the northern atolls, it was not the case for the mid-latitude and southern atolls. For example, the proportions of the external dose contributed by Bravo for the Rongelap Island community, the Utrik community, Kwajalein residents, and Majuro residents were >99%, 84%, 4.6%, and 23%, respectively. In contrast, among the mid-latitude atolls (Kwajalein and others), Yankee was the most important test. The contributions from Yankee to the external dose for the Rongelap Island community, the Utrik community, Kwajalein residents, and Majuro residents were $\ll$1%, 4.5%, 39%, and 1.9%, respectively. Among the southern atolls, the Romeo and Koon tests were the most important contributors to external dose. The contributions to the external dose from the combination of Romeo and Koon fallout for the Rongelap Island community, the Utrik community, Kwajalein residents, and Majuro residents were 0.5%, 6.5%, 25%, and 61%, respectively.

The external doses we estimated for the adult populations of the Rongelap Island and Utrik communities from Bravo are very similar to those estimated previously by Lessard et al. (1985), but our estimated dose for the 18 persons from Rongelap Island who were exposed to Bravo fallout on Ailinginae is about one half the dose estimated by Lessard et al. The reason for the differing estimates for exposures on Ailinginae appears to be due to different estimates of TOA, 3 h for Lessard et al. (1985) compared to 4 h assumed in this study. As shown in Table 2, the integral dose over the first few days is very sensitive to TOA, particularly within the first day. The exact TOA for Bravo fallout at Ailinginae was not measured directly but was inferred from measurements at other atolls and, thus, is uncertain.

Estimates of external doses to representative adults from all tests are summarized in Table 5 according to region of residence. For reference, the populations of each atoll are given in Simon et al. 2010a (Table 2). As shown, the estimated total external doses from 1948 through 1970 to the adult populations of the southern atolls were all on the order of 5–22 mGy, and in the mid-latitude region, 22–59 mGy. The doses to the populations of Rongelap Island community, Ailinginae, and Utrik community were much higher, reflecting the heavy fallout from Bravo, even though the populations were relocated within a few days after the test (Simon et al. 2010a, Table 3). The dose shown for Rongerik in Table 4 (940 mGy) is the estimated dose from Bravo fallout

§ Note to reader: As indicated in Simon et al. (2010a), we make the distinction in this paper between "residents" of either Majuro and Kwajalein and "community members" of Rongelap or Utrik. In the former case, we are referring to anyone living on those atolls at the time of fallout. In the latter case, we are referring to the entire group of persons exposed on either Rongelap or Utrik and who were members of the group relocated from those atolls.

Table 3. Free-in-air exposure (mR), from TOA to infinity, by location and test.

Atoll	Yoke	Dog	Item	Mike	King	Bravo	Romeo	Koon	Union	Yankee	Nectar	Zuni	Flathead	Tewa	Cactus	Fir	Koa	Maple	Redwood	Cedar	Total
Ailinginae	290	120	0.0	61	0.0	120,000	11,000	6,700	180	2,000	24	40	3.9	0.0	0.0	35	0.0	0.0	75	0.0	140,000
Ailinglaplap	1.6	0.0	0.0	61	36	56	270	250	23	31	180	0.0	140	0.0	0.0	10	0.0	0.0	0.0	0.0	1,100
Ailuk	1.4	33	0.0	61	36	5,600	720	510	340	1,600	0.0	75	0.0	0.0	0.0	76	0.0	0.0	0.0	0.0	9,000
Arno	2.9	0.0	0.0	61	36	350	430	540	20	87	0.0	0.0	52	0.0	0.0	3.9	0.0	0.0	0.0	0.0	1,600
Aur	2.4	0.10	0.0	61	36	500	440	77	24	120	0.0	0.0	210	0.0	0.0	23	0.0	0.0	0.0	0.0	1,500
Bikar	2.6	14	0.0	61	0.0	93,000	5,300	5,000	1,700	8,500	0.0	0.0	1.9	0.0	0.0	43	0.0	0.0	0.0	0.0	110,000
Ebon	1.5	0.0	0.0	61	0.0	110	460	64	19	67	19	0.0	0.0	0.0	0.0	23	0.0	0.0	0.0	0.0	820
Erikub	2.1	8.6	0.0	61	34	750	450	370	53	120	0.0	0.0	26	0.0	0.0	37	0.0	0.0	0.0	0.0	1,900
Jabat	0.0	0.0	0.0	61	36	170	240	370	23	31	180	0.0	200	0.0	0.0	12	0.0	0.0	0.0	0.0	1,300
Jaluit	2.2	0.0	0.0	61	31	160	400	110	16	41	7.6	0.0	160	0.0	0.0	16	0.0	0.0	0.0	0.0	1,000
Jemo Island	0.80	35	0.0	61	71	4,500	740	290	62	710	0.0	75	0.0	0.0	0.0	73	0.0	0.0	0.0	0.0	6,600
Kili Island	0.77	0.0	0.0	25	0.0	160	390	120	16	20	57	0.0	100	0.0	0.0	8.2	0.0	0.0	0.0	0.0	900
Knox	2.0	0.0	0.0	62	32	290	350	320	38	20	0.0	0.0	0.0	0.0	0.0	0.94	0.0	0.0	0.0	0.0	1,100
Kwajalein	710	5.6	0.0	61	38	150	340	480	83	1,200	20	28	170	0.0	0.0	37	0.0	0.0	0.0	0.0	3,300
Lae	0.75	1.8	0.0	61	75	240	290	36	28	220	380	80	150	0.0	0.0	0.83	0.0	0.0	0.0	0.0	1,600
Lib Island	0.76	0.0	0.0	61	36	100	330	410	53	340	380	0.0	150	0.0	0.0	2.9	0.0	0.0	0.0	0.0	1,900
Likiep	1.4	0.0	0.0	61	71	3,700	900	180	69	710	0.0	110	0.0	0.0	0.0	36	0.0	0.0	0.0	0.0	5,900
Majuro	2.4	0.0	0.0	61	31	340	470	440	39	29	0.0	0.0	74	0.0	0.0	9.0	0.0	0.0	0.0	0.0	1,500
Maloelap	2.5	0.34	0.0	61	36	770	450	320	22	92	0.0	0.0	100	0.0	0.0	30	0.0	0.0	0.0	0.0	1,900
Mejit Island	1.9	23	0.0	61	34	4,200	700	440	390	1,500	0.0	0.0	7.5	0.0	0.0	91	0.0	0.0	0.0	0.0	7,500
Mili	2.0	0.0	0.0	61	31	280	330	310	36	20	0.0	0.0	0.0	0.0	0.0	0.90	0.0	0.0	0.0	0.0	1,100
Namorik	2.6	0.0	0.0	61	0.0	130	310	150	4.2	19	57	0.0	100	0.0	0.0	8.1	0.0	0.0	0.0	0.0	840
Namu	1.4	0.02	0.0	61	36	110	290	550	27	92	310	0.0	140	0.0	0.0	7.5	0.0	0.0	0.0	0.0	1,600
Rongelap Island	280	96	0.0	61	0.0	480,000	33,000	29,000	12,000	6,800	7.1	33	3.4	0.0	0.0	190	0.0	0.0	74	18	570,000
Rongerik	160	79	0.0	58	0.0	400,000	24,000	19,000	4,600	5,800	0.0	900	170	0.0	0.0	190	0.0	0.0	2.5	0.0	450,000
Taka	0.95	53	0.0	61	0.0	25,000	2,600	2,100	370	1,200	0.0	0.0	0.0	0.0	0.0	69	0.0	0.0	0.0	0.0	32,000
Taongi	14	1.2	0.0	61	0.0	390	130	31	29	36	1.8	0.0	0.0	0.0	0.0	490	160	0.0	2.5	7.4	1,400
Ujae	0.45	4.8	0.0	61	36	150	270	29	29	150	350	53	180	0.0	0.0	0.0	0.0	0.0	0.00	0.0	1,300
Ujelang	13	200	710	66	44	310	610	140	360	370	310	57	38	360	20	28	6.0	68	52	10	3,800
Utirik	1.7	53	0.0	57	0.0	35,000	2,400	2,400	940	1,200	0.0	45	8.6	0.0	0.0	170	0.0	0.0	0.0	0.0	42,000
Wotho	340	41	0.0	61	0.0	640	470	290	150	320	170	800	150	0.0	0.0	77	0.0	0.0	0.0	45	3,600
Wotje	2.1	3.4	0.0	61	34	2,600	730	430	28	710	0.0	0.0	7.5	0.0	0.0	50	0.0	0.0	0.0	0.0	4,600

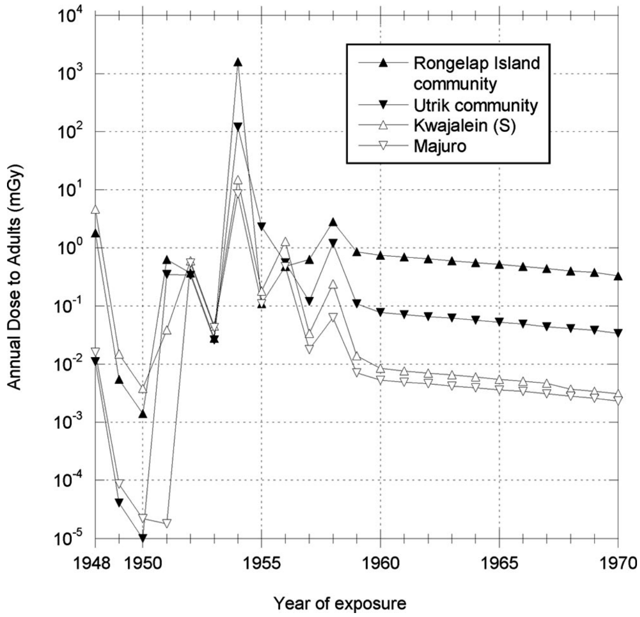

Fig. 5. Estimated annual doses, in mGy, to adults of four population groups.

Table 4. Estimates of external doses (mGy) received by adults from the Bravo test, the entire Castle (1954) test series, and from all tests (dose estimates rounded to two significant digits).

Atoll or population group	Bravo	Castle series	All tests
Ailinginae[a]	460	470	470
Ailinglaplap	0.37	5.3	6.9
Ailuk	37	57	59
Arno	2.3	9.3	10
Aur	3.3	7.7	9.9
Bikini community[b]	1.1	5.0	14
Ebon	0.71	4.8	5.3
Enewetak community[a]	2.1	14	25
Jaluit	1.1	4.8	6.6
Kwajalein	1.0	15	22
Lae	1.6	7.8	10
Lib Island	0.7	11	12
Likiep	25	37	39
Majuro	2.2	8.7	9.8
Maloelap	5.1	11	12
Mejit Island	27	47	49
Mili	1.8	6.4	7.0
Namorik	0.70	4.4	5.5
Namu	0.73	9.0	11
Rongelap control group[c]	8.4	17	22
Rongelap Island community[a]	1,600	1,600	1,600
Rongerik[d]	940	—	—
Ujae	1.0	6.4	8.6
Utrik community[a]	110	130	130
Wotho	4.3	13	23
Wotje	17	30	31

[a] Includes doses received while relocated (see Table 3 in Simon et al. 2010a).
[b] Includes doses while on Kwajalein and Kili (see Table 3 in Simon et al. 2010a).
[c] Includes doses while on Majuro and on Rongelap Island.
[d] Dose to U.S. military personnel on Rongerik prior to evacuation (see Table 3 in Simon et al. 2010a).

received by the U.S. military weather observers who were stationed there and evacuated within 2 d of the detonation. The Rongerik dose is based on only a few survey meter measurements made after the evacuation by a survey team but agrees very well with reported external exposure measured by film badges worn by the personnel (35–98 R) (Sharp and Chapman 1957), particularly considering the considerable uncertainty in both sets of measurements and the fact that some of the military personnel were indoors at least part of the time.

Whole-body absorbed doses (mGy) from external irradiation, cumulated over the time period from 1948 through 1970, for representative persons by birth year (1930 to 1958), are presented in Table 6 for the Majuro residents, the Kwajalein residents, the Utrik community, and the Rongelap Island community. As noted, doses for Utrik and Rongelap Island communities account for relocations. For a given population, the cumulative doses are greater for persons who were young at the beginning of the testing period.

The radionuclides that contributed most to the dose rate from external irradiation vary according to the time elapsed since the detonation. These contributions can readily be derived from the tables prepared by Hicks (1984), as the relative exposure rates are provided for all radionuclides for a range of times after detonation. As an example, the changing proportions of the external dose rate contributed by some of the most important contributing radionuclides to external exposure are shown in Fig. 6 for the Bravo test and an assumed relative degree of fractionation, R/V, of 0.5. In Fig. 6, ^{132}Te is the most important radionuclide within a few hours after the test, but is replaced successively by ^{140}Ba-^{140}La, ^{95}Zr, and finally by ^{137}Cs. Expressed in percentage of total exposure (averaged over a range of degrees of fractionation), ^{132}Te-^{132}I accounts for about 25–30%, ^{140}Ba-^{140}La about 20%, ^{131}I + ^{133}I + ^{135}I about 15–20%, and ^{95}Zr-^{95}Nb + ^{97}Zr-^{97}Nb about 10–15%. The exact percentages at any atoll and following any particular test also depend on fractionation with greater relative contributions from Zr-Nb isotopes for larger R/V values. Although ^{137}Cs and ^{106}Ru contribute little to the total integral dose from TOA to 1970, they contribute almost all the annual dose after 5 y.

All together, the deposition densities of 63 of the radionuclides listed in Simon et al. (2010a, Table 4) have been estimated at each inhabited atoll or reef island following each of the 20 tests. These radionuclides combined contribute more than 95% of the external dose. The proportions of the total exposure contributed from the individual radionuclides shown in Fig. 6 are actually

Table 5. Population-weighted average external dose to adults of four groups of atolls and/or communities. Grouping is based on similar levels of deposition of total ^{137}Cs (see Fig. 2 of Simon 2010a). Range in parentheses represents the minimum and maximum total external dose within the group of atolls or communities. All values rounded to two significant digits.

Atoll or population group	Atolls	Total external dose through 1970 from all tests (mGy)	Range of total external doses among atolls (mGy)
Southern latitude	Ailinglaplap, Arno, Aur, Ebon, Jaluit, Kili Island[a], Lae, Lib Island, Majuro[b], Maloelap, Mili, Namorik, Namu, Ujae	8.8	5.3–22
Mid-latitude	Ailuk, Kwajalein, Likiep, Mejit Island, Ujelang[c], Wotho, Wotje	34	22–59
Utrik community	Utrik and atoll of relocation[d]	130	—
Rongelap Island/Ailinginae/ Rongerik evacuees	Rongelap, Ailinginae, Rongerik, and atolls of relocation[d]	1,000	470–1,600
All	All	27	5.4–1,600

[a] Primary residence location of Bikini community during test years.
[b] Includes Majuro permanent residents and Rongelap control group.
[c] Primary residence location of Enewetak community during testing years.
[d] See Table 3 of Simon et al. (2010a) for atolls of relocation.

Table 6. Whole-body absorbed doses (mGy) from external irradiation cumulated from 1948 through 1970 for representative persons by birth year (1930 to 1958) (rounded to two significant digits). Doses for Utrik and Rongelap Island communities account for relocations.

	Whole-body dose from external irradiation (mGy)			
Birth year	Majuro residents	Kwajalein residents	Utrik community	Rongelap Island community
<1931	9.8	22	130	1,600
1931	9.8	22	130	1,600
1932	9.8	22	130	1,600
1933	9.8	22	130	1,600
1934	9.8	22	130	1,600
1935	9.8	23	130	1,600
1936	9.8	23	130	1,600
1937	9.8	23	130	1,600
1938	9.8	23	130	1,600
1939	10	23	130	1,600
1940	10	23	150	1,600
1941	12	26	150	1,900
1942	12	26	150	1,900
1943	12	26	150	1,900
1944	12	26	150	1,900
1945	12	26	150	1,900
1946	12	26	150	1,900
1947	12	27	150	1,900
1948	12	23	150	1,900
1949	12	20	150	1,900
1950	12	21	150	1,900
1951	12	21	150	1,900
1952	13	22	160	2,100
1953	12	21	160	2,100
1954	4.2	8.8	45	470
1955	0.78	2.1	3.1	13
1956	0.47	1.3	2.7	13
1957	0.14	0.41	2.3	12
1958	0.09	0.23	1.4	9.2

slight overestimates since the derived proportions are relative to only the 63 radionuclides considered.

External dose from $^{239+240}$Pu, the last radionuclide listed in Table 4 of Simon et al. (2010a), has not been

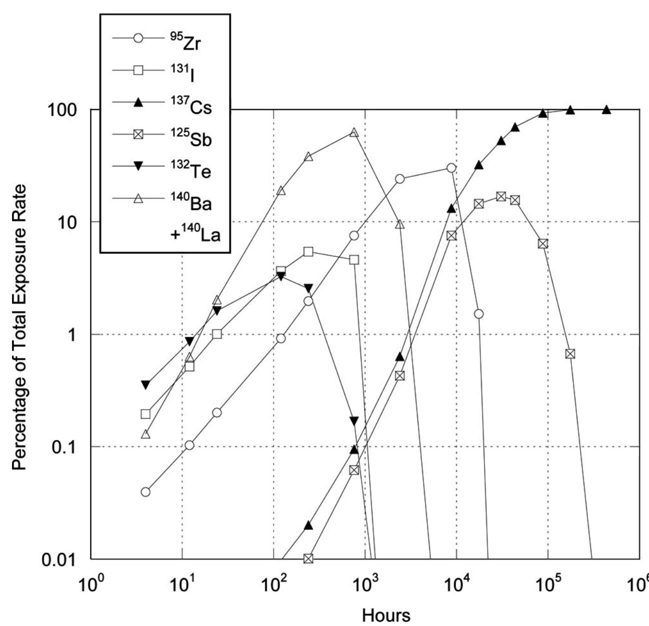

Fig. 6. Relative contribution (%) of selected radionuclides to the total exposure rate on the ground as a function of time (h) after the detonation.

calculated as deposition estimates for that radionuclide are not available for each test separately. More importantly, the corresponding external doses would have been trivial.

As a basis for evaluating the magnitude of the estimated external doses, the annual and total doses reported for adults in Tables 4 to 6 and in Fig. 5 can be compared with the external doses that Marshallese adults typically received from natural background radiation or with typical doses received by Americans who lived near the NTS. The average annual external dose received by Marshallese from natural sources is about 0.24 mGy, primarily from cosmic radiation, since the concentrations of ^{238}U, ^{40}K, and ^{232}Th in the coral soils is very low (Robison et al. 1997). This can be compared to the highest annual dose received in Majuro from fallout of 8 mGy in 1954 and annual doses on the order of 3–5 μGy after testing in the Marshall Islands ended (Fig. 5). External doses from atmospheric tests conducted at the NTS from 1951–1958 that were received by Americans (in this example, outdoor workers who lived in towns in Nevada and SW Utah) ranged from about 0.03 to 40 mGy (Henderson and Smale 1990). Because of shielding when indoors, the NTS doses were smaller for persons who spent much of their time indoors.

Uncertainty

Uncertainties in the total dose received by each population group in each year from all tests in that year were derived relying, primarily, on the uncertainty of available measurements of exposure rates and of deposition densities of long-lived radionuclides. For a given test i and a given atoll j, the external dose to permanent residents of age a, D_a in mGy, can be expressed as:

$$D_a(i, j) = \dot{E}12(i, j) \times \left[\frac{X(i, j)}{\dot{E}12(i, j)}\right] \times \left(\frac{D_{ad}}{X}\right) \times \left(\frac{D_a}{D_{ad}}\right), \quad (4)$$

where

$\dot{E}12(i, j)$ = the exposure rate at H+12 (mR h^{-1}) following test i at atoll j;

$X(i, j)$ = the lifetime exposure (mR) due to test i at atoll j; and

D_{ad}/X = the conversion factor from exposure to dose for adults (mGy mR^{-1}).

The uncertainties were assessed to be as follows:

- $\dot{E}12$: as discussed in Beck et al. (2010), an uncertainty estimate was assigned to each estimate of $\dot{E}12$ as inferred from the available measurement data. These uncertainties, expressed in terms of geometric standard deviations (GSDs), range from 1.3 to 3.0, depending on the availability, quality, and number of measurements of exposure rates and long-lived radionuclides at the atoll for the test under consideration; and
- $X/\dot{E}12$: because the exposure, X, is delivered over a number of years, at a rate that is relatively high during the year of the test and much smaller during the following years, the simplifying assumption was made, for the purposes of the evaluation of the uncertainties, that the exposure was delivered only during the year of the test. During that year:

$$X/\dot{E}12 = \sum_{n=1}^{10}\left[\frac{a_n}{\lambda_n}e^{-(\lambda_n \times TOA)}\right] - \sum_{n=1}^{10}\left[\frac{a_n}{\lambda_n}e^{-[\lambda_n(EOY - H)]}\right], \quad (5)$$

where a_n and λ_n, with n varying from 1 to 10, are the parameters of the fit to Hicks' calculated exposure rates vs. time (Hicks 1981, 1984), TOA, in hours, is the estimated time of arrival of fallout counted from the time of the test, H, and $(EOY-H)$ is the time elapsed between the time of the test and the end of the year (EOY).

As previously indicated, the exposure, X, is very sensitive to TOA (Table 2), while the uncertainty in the values of a_n and λ_n is assumed to be relatively minor compared to the uncertainty due to TOA. Also, as shown in Fig. 1, regression fit parameters vary little from one test to another. For that reason, we assumed that TOA is the parameter in eqn (5), which is uncertain to any significant degree. In our simulations, the uncertainty distribution for TOA for all atolls and all tests was taken to be uniform between 0.8 and 1.2 times the nominal values given in Table 6 of Beck et al. (2010):

- D_{ad}/X: its nominal value of 6.6×10^{-3} mGy mR^{-1} is based on the calculations of Jacob et al. (1990) and on the recommendations of ICRP (1996). The value of D_{ad}/X depends on the geometry of irradiation, on the energy spectrum of the incident γ-rays, and on the tissue or organ that is considered. In our analysis, the same nominal value is taken to apply to all organs and tissues of the body. The uncertainty distribution of D_{ad}/X is taken to be uniform between 0.9 and 1.1 times the nominal value and to mainly reflect differences between the doses to various organs and tissues of the body for exposures to γ-rays of a few hundred keV characteristic of fallout; and
- D_a/D_{ad} is the ratio of the external dose to children of age a to adults. Its nominal value is 1.3 for young children (less than 3 y of age) and 1.2 for older children. Here, the uncertainty distribution, which is assumed to be uniform between 0.9 and 1.1 times the nominal value, reflects the relatively large range of ages to which the nominal value applies.

The uncertainty estimates for individual tests were derived via Monte Carlo simulation to obtain an estimate of uncertainty for the total external dose received in each calendar year from all tests in that year. Results are presented in Table 7 in terms of GSD for representative persons (both adults and children) of four communities (Kwajalein residents, Majuro residents, the Rongelap Island

Table 7. Derived uncertainties, expressed in terms of the geometric standard deviation (GSD), in the annual doses from external irradiation for four representative communities of the Marshall Islands.

		Annual external whole-body dose (mGy) and uncertainty							
		Majuro residents		Kwajalein residents (south)		Utrik community		Rongelap Island community	
Year of exposure	Year of birth	Mean dose	GSD	Mean dose	GSD	Mean dose	GSD	Mean dose	GSD
1948	1929	0.016	2.8	4.6	2.0	0.011	2.8	1.8	2.8
	1947	0.021	2.8	6.0	2.0	0.014	2.8	2.4	2.8
1951	1929	—	—	0.039	2.8	0.35	2.9	0.62	2.7
	1947	—	—	0.047	2.8	0.42	2.9	0.75	2.7
1952	1929	0.55	1.6	0.60	1.9	0.34	1.8	0.37	1.8
	1947	0.67	1.6	0.72	1.9	0.41	1.8	0.45	1.8
1954	1929	8.5	1.2	15	1.3	120	1.3	1,600	1.3
	1953	11	1.2	19	1.3	160	1.3	2,000	1.3
1956	1929	0.48	2.9	1.3	1.7	0.56	1.4	0.48	2.8
	1953	0.57	2.9	1.5	1.7	0.67	1.4	0.58	2.8
1958	1929	0.063	2.8	0.24	1.9	1.2	1.3	2.7	1.5
	1953	0.076	2.8	0.29	2.0	1.4	1.3	3.3	1.5

community, and the Utrik community) that represent the range of exposures across the Marshall Islands. The table applies to all years when testing gave rise to measurable fallout in the Marshall Islands. The derived GSDs, which range from 1.2 to 2.9, vary among years and among atolls, essentially depending on the uncertainties assigned to $\dot{E}12$ for each test and location. There is, however, very little dependence with age as the uncertainties for adults and for children have the same numerical values within a few percent.

The external doses resulting from the tests detonated in 1954 were the largest of any year, regardless of the atoll or island. In contrast, the uncertainties of doses from tests in 1954 are the smallest because they are based on relatively good measurement data in comparison to other years when the doses were low and primarily based on ^{137}Cs deposition estimates derived from interpolation of measurement data at nearby atolls or, in some cases, meteorological modeling. As a simplification for the purposes of estimating the risks of radiation-induced cancers (see Land et al. 2010), the uncertainties assigned to the annual doses from external irradiation to members of each community were given the same value for all years when testing took place. The GSDs assigned were based on the derived GSD estimates in the years in which the doses were most significant. Overall, the GSDs were smallest in communities where the greatest dose resulted from the 1954 tests and highest in communities with the lowest doses from the 1954 tests. The derived GSDs were 1.2 for the Rongelap Island community, 1.5 for the Utrik community, and 1.8 for the Kwajalein and Majuro residents. Because the quality and availability of data were roughly the same for atolls and islands within each of four atoll groups (see Table 5), the GSDs were assumed to be the same for all communities within each group.

These selected uncertainties apply to the annual doses received during the years when testing with measurable fallout occurred. In later years, the uncertainty would be larger as weathering and estimated loss of ^{137}Cs from the soil profile, which can vary from one area of the island to another, could be substantial. However, the annual doses in the years without tests are lower by a factor of 100 or more than the doses received during the years of the tests; their GSDs have not been individually derived but assumed equal to those in the years assessed.

SUMMARY AND CONCLUSION

Annual doses from external irradiation resulting from fallout from regional nuclear weapons testing have been estimated, for the first time, for all tests that resulted in measurable fallout and for all Marshallese alive at the time of nuclear testing (1946–1958), and at all 25 inhabited atolls. The methodology used to estimate the doses is based on test- and location-specific radiation survey data coupled with estimates of fallout TOAs at the inhabited atolls or on deposition density estimates of ^{137}Cs coupled with fallout TOAs. Both types of data are discussed in a companion paper (Beck et al. 2010). For every test, the major part of the dose from external irradiation was received during the first year following the detonation. The most important tests with respect to external exposure were those of the Castle series conducted in 1954. Bravo was most important to the northern atolls, Yankee was more important to the mid-latitude atolls (Kwajalein and others), and Romeo and Koon were more important to the southern atolls (Majuro and others).

The total external doses to the populations of all the inhabited atolls from all tests at Bikini and Enewetak varied over two orders of magnitude with the adult residents of the southern atolls receiving relatively low total external doses ranging from 5–22 mGy on average, the adults at the mid-latitude atolls receiving external doses of 22–59 mGy, while the residents of the northern atolls most impacted by the Castle series and the Bravo test received external doses in the hundreds to over 1,000 mGy, even though the populations of the three most exposed communities (Rongelap Island, Ailinginae, and Utrik) were evacuated shortly after the test.

Our estimates of doses from external irradiation have been merged with corresponding estimates of doses from internal irradiation, given in a companion paper (Simon et al. 2010b), to assess the cancer risks (Land et al. 2010) among the Marshallese population as a consequence of exposure to radioactive fallout from the nuclear weapons tests.

Acknowledgments—This work was supported by the Intra-Agency agreement between the National Institute of Allergy and Infectious Diseases and the National Cancer Institute, NIAID agreement #Y2-Al-5077 and NCI agreement #Y3-CO-5117. The authors are indebted to several individuals whose analyses and research have made substantial contributions to this work. They include William Robison for various data and publications on measurements made in the Marshall Islands, Brian Moroz for meteorological analysis and graphic support, Robert Weinstock for computer programming support, Dunstana Melo for the review of the manuscript, as well as other scientists who have added to our understanding of the contamination and consequences in the Marshall Islands through their scientific publications, many of which are cited here.

REFERENCES

Beck HL, Bouville A, Moroz BE, Simon SL. Fallout deposition in the Marshall Islands from Bikini and Enewetak nuclear weapons tests. Health Phys 99:124–142; 2010.

Breslin AJ, Cassidy ME. Radioactive debris from Operation Castle, Islands of the Mid-Pacific. New York: United States Atomic Energy Commission, New York Operations Office; Health and Safety Division report NYO-4623; 1955. [Available from National Technical Information Service.]

Conard RA, Knudsen KD, Dobyns BM. A twenty-year review of medical findings in a Marshallese population accidentally exposed to radioactive fallout. Upton, NY: Brookhaven National Laboratory; Report BNL 50424; 1975.

Eckerman K, Ryman JC. Dose coefficients for external exposure to radionuclides distributed in air, water and soil. Washington, DC: U.S. EPA; Federal Guidance Report 12; 1993.

Eisenbud M. Radioactive debris from Operation Ivy. New York: United States Atomic Energy Commission, New York Operations Office; Health and Safety Division report NYO-4522; 1953. Available from National Technical Information Service.

Eisenbud M. Monitoring distant fallout: the role of the Atomic Energy Commission Health and Safety Laboratory during the Pacific tests, with special attention to the events following Bravo. Health Phys 73:21–27; 1987.

Henderson RW, Smale RF. External exposure estimates for individuals near the Nevada Test Site. Health Phys 69:715–721; 1990.

Hicks HG. Results of calculations of external gamma radiation exposure rates from fallout and the related radionuclide compositions. Livermore, CA: Lawrence Livermore National Laboratory; Report UCRL-53152, Parts 1–8; 1981.

Hicks HG. Calculation of the concentration of any radionuclide deposited on the ground by offsite fallout from a nuclear detonation. Health Phys 42:585–600; 1982.

Hicks HG. Results of calculations of external gamma radiation exposure rates from local fallout and the related radionuclide compositions of selected U.S. Pacific events. Livermore, CA: Lawrence Livermore National Laboratory; Report UCRL-53505; 1984.

International Commission on Radiological Protection. Conversion coefficients for use in radiological protection against external radiation. New York: Elsevier; ICRP Publication 74; Annals of the ICRP 26(3/4); 1996.

Jacob P, Rosenbaum H, Petoussi N, Zankl M. Calculation of organ doses from environmental gamma rays using human phantoms and Monte-Carlo methods. Part II: Radionuclides distributed in the air or deposited on the ground. Neuherberg: GSF-Institut für Strahlenschutz; Report GSF 12/90; 1990.

Land CE, Bouville A, Apostoaei I, Simon SL. Projected lifetime cancer risks from exposure to regional radioactive fallout in the Marshall Islands. Health Phys 99:201–215; 2010.

Lessard E, Miltenberger R, Conard R, Musolino S, Naidu J, Moorthy A, Schopfer C. Thyroid absorbed dose for people at Rongelap, Utrik and Sifo on March 1, 1954. Upton, NY: Brookhaven National Laboratory; Safety and Environmental Protection Division report No. 0061648; 1985.

National Council on Radiation Protection and Measurements. Recommended screening limits for contaminated surface soil and review of factors relevant to site-specific studies. Bethesda, MD: National Council on Radiation Protection and Measurements; NCRP Report No. 129; 1999.

Robison WL, Noshkin VE, Conrado CL, Eagle RJ, Brunk JL, Jokela TA, Mount ME, Phillips WA, Stoker AC, Smart ML, Wong KM. The northern Marshall Islands Radiological Survey: data and dose assessments. Health Phys 73:37–48; 1997.

Sharp R, Chapman WH. Exposure of Marshall Islanders and American military personnel to fallout. Bethesda, MD: Naval Medical Research Institute; Report WT-938; 1957.

Simon SL. The role of Merril Eisenbud and HASL in monitoring the Marshall Islands during the Castle nuclear testing series. Technology 7:145–156; 2000.

Simon SL, Graham JC. Findings of the nationwide radiological study: summary report. Report submitted to the Cabinet of the Government of the Republic of the Marshall Islands. Majuro, Marshall Islands: Ministry of Foreign Affairs, Government of the Republic of the Marshall Islands; 1994.

Simon SL, Graham JC. Findings of the first comprehensive radiological monitoring program of the Republic of the Marshall Islands. Health Phys 73:66–85; 1997.

Simon SL, Vetter RJ. Consequences of nuclear testing in the Marshall Islands. Health Phys 73:66–85; 1997.

Simon SL, Bouville A, Land CE, Beck HL. Radiation doses and cancer risks in the Marshall Islands associated with exposure to radioactive fallout from Bikini and Enewetak nuclear weapons tests: summary. Health Phys 99:105–123; 2010a.

Simon SL, Bouville A, Melo D, Beck HL, Weinstock RM. Acute and chronic intakes of fallout radionuclides by Marshallese from nuclear weapons testing at Bikini and Enewetak and related internal radiation doses. Health Phys 99:157–200; 2010b.

Tipton WJ, Miebaum RA. An aerial radiological and photographic survey of eleven atolls and two islands within the Northern Marshall Islands. Las Vegas, NV: EG&G; Report EGG-1183-1758; 1981.

United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of ionizing radiation. New York: United Nations; United Nations Scientific Committee on the Effects of Atomic Radiation 1993 report to the General Assembly with scientific annexes; Publication E 94:IX.2; 1993.