Estimation of the Baseline Number of Cancers Among Marshallese and the Number of Cancers Attributable to Exposure to Fallout from Nuclear Weapons Testing Conducted in the Marshall Islands

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I. INTRODUCTION

From 1946 through 1958, 66 nuclear weapons tests, in seven series, were carried out by the United States at Bikini and Enewetak Atolls in the Marshall Islands (Fig. 1). The total explosive yield of the tests was approximately 100 Mt (equivalent to 100 million tons of TNT) (USDOE 1994, Simon and Robison 1997). Radioactive debris dispersed through the atmosphere was generally blown by the predominantly easterly winds towards the open ocean west of the Marshall Islands, though various historical reports indicate that radioactive debris from a number of tests traveled in other directions including north, east, southeast and southwest directions (e.g., Breslin and Cassidy 1955, DNA 1979). The radioactive debris that eventually fell to the ground is termed *fallout*.

To ensure the safety of the populations of Bikini and Enewetak, those groups were relocated to other atolls before the testing began (Simon 1997). However, following the detonation of the 15 Mt Castle BRAVO test in 1954, fallout was unexpectedly deposited on Rongelap, Utrik, and other inhabited atolls to the east and southeast of Bikini Atoll (see Fig. 1) resulting in by far the greatest exposure from any of the tests conducted in the Marshall Islands. Within the first 3 days after the detonation, the resident populations of Rongelap (including some present on Ailinginae) and Utrik, as well as American weather service men on Rongerik, were evacuated to avert continued exposure and to provide immediate medical care (Cronkite et al. 1997).

Iodine-131, an important radionuclide in fallout, was measured in the urine of adults from Rongelap and Ailinginae collected about two weeks after their exposure to BRAVO fallout. Those data have proven to be of significant value for dose reconstruction for those groups. For example, Brookhaven National Laboratory (Lessard et al. 1985) used the urine measurements, and other data and assumptions, to estimate external whole-body dose and internal thyroid dose for persons living on Rongelap, Ailinginae, Rongerik and Utrik. Lessard et al. (1984) also used whole-body counting data collected years later from exposed individuals to estimate internal doses from long-lived radionuclides on Rongelap and Utrik.

In contrast, similar data do not exist for populations who were living on other atolls of the Marshall Islands and radiation doses to Marshallese living there have, consequently, been difficult to assess. Neither estimates of doses nor cancer risks to inhabitants of the other atolls have been made until now except for risk projections for populations who might return to live on the test site atolls. The present analysis provides necessarily crude estimates of dose to specific organs for inhabitants of all the atolls, based on the afore-mentioned urine measurements and whole-body counting data, environmental measurement data on radionuclide deposition provided for all atolls by the Marshall Islands-sponsored radiological survey completed in 1995 (Simon and Graham 1994, 1997) and other historical information, using mathematical models and a variety of reasonable assumptions.

The U.S. Government through Brookhaven National Laboratory and other institutions has provided decades of medical care, health surveillance, and documentation of health effects among the highly exposed Marshallese from Rongelap/Ailinginae and Utrik (see for example, Conard et al. 1970; BNL 1975; Cronkite et al. 1997), but only two epidemiologic studies have been conducted, one of benign thyroid disease only (Hamilton et al. 1987) and one of benign thyroid disease and thyroid cancer (Takahashi et al. 1997, Takahashi et al. 2001). To date, there has not been an epidemiologic study of the Marshallese to estimate the total numbers of cancers and other serious illnesses resulting from exposure to radioactive fallout. It is possible, however, to develop estimates of the number of baseline cancers and radiation related cancers based on estimated doses and the large body of published cancer risk data derived from studies of various other irradiated populations. Estimation of diseases other than cancer is more problematic, although such diseases would likely occur in the more heavily-exposed population subsets. However, baseline morbidity and mortality data, as well as radiation-related risk data, are less developed than those for cancer, and would require access to expertise and data not readily available at the National Cancer Institute.

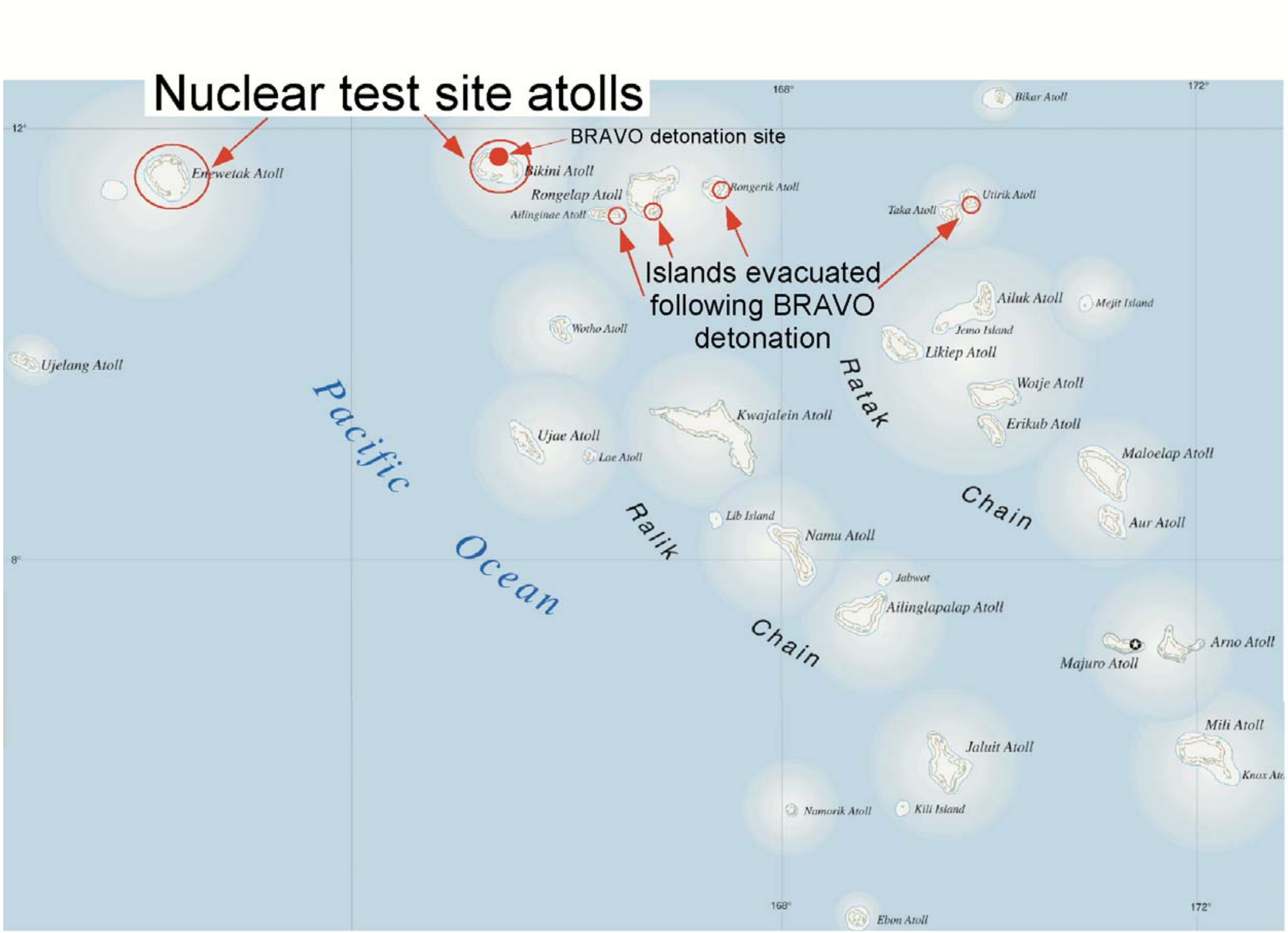

Fig. 1. Map of the Marshall Islands showing Bikini and Enewetak nuclear test sites and atolls evacuated following the BRAVO test.

II. OBJECTIVES

In this analysis, we provide preliminary estimates of (1) the baseline number of cancers expected to occur naturally among the population alive during the years of nuclear testing in the Marshall Islands, (2) organ-specific radiation doses to that population, and (3) the numbers of cancers (fatal plus non-fatal) likely to develop among those Marshallese as a result of exposures to fallout from the nuclear weapons tests. We also discuss the most important sources of uncertainty in the estimated doses and the numbers of predicted cancers.

III. DOSE ESTIMATION

The detonation of a nuclear fission device creates over 150 different radionuclides with half-lives varying from fractions of a second to many years. Immediately after the detonation, all of the debris and radioactive byproducts are in a hot, gaseous cloud, but as the cloud cools, the radionuclides condense in or onto small particles of debris depending on their individual chemical properties. The radioactive particles are initially swept upwards in the atmosphere by the explosion and are then dispersed in the atmosphere in the directions of the prevailing winds. The radioactive particles which eventually fall to the ground are termed *fallout*. The longer the particles stay aloft, the less of the short-lived radioactivity remains to expose people. Radioactive particles from tests with high explosive yields are swept to much higher altitudes than those from tests with low explosive yields and for the megaton and larger tests – which included many of those detonated at Bikini and Enewetak – much of the debris was sent to extremely high altitudes where it entered into the global circulation pattern. In that case, the particles were not deposited for long periods of time ranging up to several years after the detonation during which time the short-lived radionuclides decayed. In general, low-yield tests that do not disperse the particles to extremely high altitudes have the greatest potential to expose members of the public within a few hundred kilometers of the site of detonation.

The radiation released from the radioactive particles as the particles are descending to the ground can expose humans externally as well as internally if they are inhaled or ingested. If inhaled, only particles that are very small can effectively reach the deep lung and be absorbed by the body. Once the fallout is deposited onto the ground, it can continue to irradiate people though it gradually permeates into the soil which reduces its potential for external exposure. Because most of the activity decays in the first few weeks, most of the dose is delivered in the same time frame.

Radioactive materials also contaminated foods in the Marshall Islands but direct contamination from descending fallout debris would have been significant only at those northern atolls where fallout deposition has been shown to very high (see Simon and Graham 1997). Foods exposed to the open air and directly to the fallout would have been susceptible, in particular, to radioactive contamination by short-lived radionuclides. In contrast, certain long-lived radionuclides, e.g., cesium-137, were gradually released from the fallout particles in the soil as a result of natural weathering processes, were absorbed by plant roots, and made their way into edible fruits and plants.

Estimates of dose from fallout are almost always derived indirectly from various types of data, but the estimation process can vary depending on the type, quality, and amount of data available. Following the nuclear tests that took place some 50 years ago in the Marshall Islands; measurements were sparse and generally uncertain. The little data now available to reconstruct doses at many different locations present difficult challenges for dosimetrists. Consequently, we necessarily made numerous assumptions for our dose estimations. Our assumptions were intended to prevent an underestimation of the doses and of the number of cancers that might be attributed to the exposures.

We estimated radiation absorbed doses to the thyroid gland, stomach, colon, and bone marrow. These specific organs and tissues were selected because they are expected to give rise to the largest number of cancers for reasons noted below:

- The thyroid gland, more so than any other organ, concentrates radioiodine which is amply produced by detonations of nuclear weapons.

- Irradiation of the blood-forming cells in the red bone marrow, which is caused mainly by external exposure to gamma-emitting radionuclides and also by internal exposure to radiostrontiums, increases the risk of leukemia, which has shown an especially strong relationship with radiation exposure in many epidemiologic studies.

- The stomach and colon can be highly exposed after ingestion of fallout because many of the radionuclides produced by nuclear fission are highly insoluble, even in the gastro-intestinal tract, thereby irradiating the stomach and colon as they pass through it.

All other internal organs were judged to have been exposed mainly by radiation from external sources and, as a group, were assigned the same dose as that estimated for the red bone marrow.

The thirty-six radionuclides that were included in our calculations were chosen for their potential to produce the greatest radiation dose. The nuclides included isotopes of antimony, barium, cerium, cesium, cobalt, iodine, iron, lanthanum, molybdenum, neptunium, niobium, praseodymium, promethium, ruthenium, strontium, tellurium, tin, uranium, yttrium, zinc, and zirconium. Note that for some elements, e.g., iodine, there was more than one isotope created by the fission tests. All relevant isotopes of iodine and tellurium, important to estimating doses to the thyroid, were included in our dose estimations.

Three components of the radiation dose were considered and estimated separately as described in more detail below:

- doses received as a result of external radiation exposure from radionuclides in fallout during and after its deposition onto the ground;

- doses resulting from immediate ingestion of radionuclides in fallout at the time of its deposition;

- doses resulting from protracted ingestion of long-lived radionuclides, over months to years, after the deposition of fallout.

Doses were estimated for typical (average) persons on all atolls of the Marshall Islands inhabited during the years of nuclear testing. Doses from external radiation exposure do not vary greatly with age at exposure. However, doses from ingestion of many radionuclides vary substantially with age, in some cases being about ten times higher for infants than for adults. Also, for a given dose, radiation-related cancer risk may also vary by age at exposure. Accordingly, we estimated doses at 6 different ages (newborn, 1-year old, 5-year old, 10-year old, 15-year old, and adult) for which required dosimetric factors were available, and obtained dose values for intermediate ages by interpolation. This enabled us to estimate radiation-related risks for persons exposed at different ages.

External Radiation Dose

External dose is a consequence of radiation emitted from fallout in the air or on the ground, i.e., outside of the body. External gamma radiation, from fallout while it descends in the atmosphere and after it is deposited on the ground, tends to expose the body uniformly. While this is not necessarily true for external irradiation due to beta particles, beta radiation mainly exposes the skin and for reasons explained in Section V, skin dose and risk of skin cancer were not evaluated.

We derived external radiation doses from a combination of historical exposure rate measurements (Breslin and Cassidy 1954), contemporary measurements of ^{137}Cs deposited at each atoll (Simon and Graham 1997), and estimates of the exposure rate at the time of fallout deposition using test-specific decay-rate data and information on the mixture of radionuclides from Lawrence Livermore National Laboratory (LLNL) (Hicks 1984). We did not take into account the following factors that would have added complexity to the calculations, but probably would have resulted in some reduction in estimated doses:

- Any protection against external radiation afforded by Marshallese houses,
- Normal sweeping and cleaning around houses that was part of traditional island life and that might have removed or dispersed deposited fallout,
- The gradual weathering and dissolution of radioactive fallout particles over time that leads to the migration of the radionuclides into the ground and a consequent reduction in the external exposure rate.

Internal Radiation Dose from Immediate Intake of Fallout Radionuclides

Most exposure from internal radiation sources resulted from ingestion and inhalation of short-lived radionuclides at the time of fallout deposition or soon after. Depending on the metabolic properties of the radionuclide that is considered, doses from internal irradiation may vary considerably from one organ or tissue to another. This is, for example, the case for radioiodines, which irradiate mainly the thyroid, or for radiostrontiums, which irradiate mainly bone tissues. At Rongelap and Ailinginae, where urine samples were collected, our calculations were made under the assumption that all intakes were a result of ingestion of fallout as a result of its deposition on the face and hands, and to a lesser degree, on foods, in drinking water, and on eating utensils. That assumption, first proposed by Lessard et al. (1985), is reasonable because the fallout there was composed of particles too large to inhale to the deep lung. The average intake of Iodine-131 (^{131}I) for adults from fallout at Rongelap and Ailinginae was estimated on the basis of historical measurements made by Los Alamos Scientific Laboratory of ^{131}I in pooled samples of urine (Harris 1954) collected from adults sixteen days after they were exposed to BRAVO fallout on Rongelap and Ailinginae. We used a well-known and accepted quantitative description (a metabolic model) of the transfer of iodine in the body (ICRP 1989) to determine the intake of radioactive iodine by Marshallese adults from their exposure to BRAVO fallout. The average dose to adults was derived from the estimated intakes, under the simplifying assumption that the intake of ^{131}I occurred only at the time of fallout and was by ingestion. Thyroid doses corresponding to the intakes of ^{131}I were calculated using dose coefficients provided by the International Commission on Radiological Protection (ICRP 2001), an internationally recognized authority on radiation protection, with modifications to account for the characteristics of the Marshallese as compared to other populations. Other assumptions were then made to estimate the average ^{131}I intake, from which doses could be estimated, for other age groups at Rongelap and Ailinginae (newborn, 1-year old, 5-year old, 10-year old, and 15-year old). In order to calculate internal doses from radionuclides other than ^{131}I, the radionuclide mixture at the time of fallout on Rongelap was estimated on the basis of nuclide-specific data reported by LLNL for the BRAVO test (Hicks 1984). Estimates of the transit time for fallout to arrive at each atoll, necessary to correct for the rapid decay of short-lived radionuclides, were obtained for the BRAVO test from reported data for some atolls (Martin and Rowland 1982) or from a model to predict the transit time to atolls without data (Takahashi et al. 2001).

For all radionuclides and for all other atolls, our assumptions were similar to those for Rongelap: intakes occurred at the time of fallout from the BRAVO test and were due to ingestion only. The internal doses at all other atolls were estimated using contemporary measurements of the amounts of ^{137}Cs in the soil (Simon and Graham 1997) for purposes of rescaling the activity ingested at Rongelap. Those calculations included decay corrections for short-lived radionuclides based on the estimated transit time of the fallout to the specific atoll and adjustments to account for the preferential deposition of refractory radionuclides that are attached to larger, and generally more insoluble, fallout particles at close-in distances (a phenomenon called fractionation).

Internal Radiation Dose from Prolonged Intake of Fallout Radionuclides

The internal doses resulting from continual ingestion of radionuclides (primarily from consumption of locally grown foods) months and years after the deposition of fallout were based on measurements of activity of long-lived radionuclides in the body and in excreta reported in the scientific literature for the populations of Rongelap and Utrik (Lessard et al. 1984). The doses at all other atolls were estimated using contemporary measurements of the amounts of ^{137}Cs in the soil per unit area (Simon and Graham 1997) for purposes of rescaling the activity in the body to the amount of fallout activity deposited at each atoll. One simplifying assumption made was that the ^{137}Cs present in the soil today was deposited by the BRAVO test alone. It should be understood that this assumption does not result in any underestimation of intake of long-lived radionuclides since the measurements of ^{137}Cs represented the cumulative deposition from all tests (after correction for global fallout).

Accounting for Evacuations

The populations of Rongelap, Ailinginae, and Utrik were evacuated from their atolls at approximately 51, 58, and 66 hours, respectively, following the detonation of BRAVO. Our estimations of dose account for the time of evacuation. Our preliminary calculations do not account for the resettlement of those groups to their home atolls or to other locations; however, the specifics of those movements likely have little effect on the estimated doses or the number of cancers estimated since all movements were to less contaminated locations.

Estimated Doses

Dose estimates that we derived for the purposes of estimating the number of cancers that might be attributable to radiation exposure are summarized in Table 1. In that table, age-weighted average population doses in units of Gray (Gy; 1 Gy = 100 rad) to bone marrow, thyroid, stomach, and colon are presented by atolls or groups of atolls. As described earlier, radiation dose to individual organs from internal exposure typically varies with age, and the estimated doses to the youngest residents were several times higher than the age-weighted average, while the estimated doses to adults were several times lower than the average.

Table 1. Estimated age-weighted average absorbed dose (Gray) by organ/tissue for specific atolls or groups of atolls (see text for explanation).

				Southern atolls	
	Rongelap, Ailinginae	Utrik	Other northern atolls**	Low exposure atolls***	Very low exposure atolls****
Population size*	82	157	2005	3834	7862
			Age-weighted average dose (Gray)		
Bone marrow	2.7	0.32	0.13	0.015	0.0043
Thyroid	88†	13	2.9	0.27	0.075
Stomach	12	1	0.21	0.019	0.010
Colon	79†	8.9	1.2	0.11	0.022

*Estimated from 1958 census (except for evacuated populations).

**Ailuk, Mejit, Likiep, Wotho, Wotje, Ujelang

***Lae, Kwajalein, Maloelap, Namu, Arno, Mili

****Lib, Aur, Ailinglaplap, Majuro, Ujae, Kili, Jaluit, Namorik, Ebon

†These doses are far higher than those experienced by other study populations, on which conventional estimates of risk as a function of dose are based.

Three findings from the dose estimation are worthy of comment and are discussed further below:

- Doses at Rongelap and Ailinginae were very high and were in a range for which there is little experience in dose estimation or health risk assessment;
- There was considerable heterogeneity of dose by organ;
- There was considerable heterogeneity of dose by atoll.

Estimated doses at Rongelap and Ailinginae, as expected, were very high, particularly to children – in the range of tens to more than one hundred Gray depending on the age at exposure and the particular organ of interest (see Table 1). Doses of that magnitude from accident situations have rarely, if ever, been documented. The doses we estimated on Rongelap and Ailinginae from external radiation are similar to those estimated by others (Lessard et al. 1985), though the internal doses we estimated are considerably higher, primarily due to our interpretations of the ICRP model that describes iodine metabolism in the body (ICRP 1989), the urine sampling data (Harris 1954), and observations of iodine metabolism among Marshallese (Rall and Conard 1966; BNL 1975).

Note that the component of the dose from external radiation can be estimated fairly reliably because it can be derived from contemporary measurements of radioactivity in the soil and verified against limited historical measurements of exposure rate. Dose from external radiation represents about two-thirds of the age weighted bone marrow dose but only about 3% of the thyroid or colon dose and about 25% of the stomach dose. In contrast, the internal doses estimated at Rongelap and Ailinginae were derived exclusively from the urine sampling data of Los Alamos National Laboratory (Harris 1954) because internal doses to Marshallese cannot be reliably predicted by standard exposure models. Any weaknesses of the urine sampling data are reflected in the present dose estimates.

Estimated doses for certain organs, as expected, varied considerably. Thyroid doses tend to be high because the gland naturally accumulates iodine and does not distinguish between its radioactive and non-radioactive isotopes. High doses to the colon primarily reflect the relatively long transit time of ingested material in the lower part of the intestinal tract. While doses to the thyroid gland and colon were similar in magnitude, doses to the stomach were 15% to 50% of those received by the thyroid or colon, and doses to bone marrow were a few percent of those received by the thyroid or colon. The differences in estimated doses to the thyroid and colon were most pronounced for atolls at long distances from the Bikini test site because many of the short-lived radionuclides that could expose those organs were largely decayed by the time fallout was deposited at those locations.

Estimated doses at different atolls varied considerably as expected from contemporary measurements of ^{137}Cs in the soil (see Simon and Graham 1997). Several factors account for the general decrease in dose with increasing distance from the nuclear test site(s). In particular, greater distance is associated with greater dilution and dispersion of the nuclear debris clouds; also, as just mentioned, longer times of transit for the fallout to reach the distant atolls implies greater decay of the short-lived radionuclides. For illustration purposes (only), we have grouped the atolls roughly by their estimated age-weighted average thyroid doses, though the same grouping would follow using the estimated average dose to any other organ. Note that the assignment of atolls to the two groups most distant from the Bikini test site is uncertain, as are the estimated doses at any individual atoll. It is clear that the doses at Rongelap and Ailinginae were the highest and similar in magnitude, doses at Utrik were about 15% of those at Rongelap, and doses at other northern atolls (Ailuk, Mejit, Likiep, Wotho, Wotje, and with less confidence, Ujelang) were about one-third of those at Utrik. Estimated doses at all other atolls were lower by ten times or more. Though it is difficult at this time to separate the remaining atolls into groups having similar doses, our present dose estimations – which are acknowledged to have considerable limitations (see next section) – indicate that some of the mid- to more southerly-located atolls (Lae, Kwajalein, Maloelap, Namu, Arno, Mili) appeared to be nominally higher in dose than an another group of relatively close-by atolls (Lib, Aur, Ailinglaplap, Majuro, Ujae, Kili, Jaluit, Namorik, and Ebon). Note that the groupings, as shown here, do not affect the estimates of the numbers of cancers attributable to exposure to fallout.

Limitations of Dose Estimation

Doses have been estimated for typical individuals in six age groups at all inhabited atolls. Any specific person could have received a dose many times lower or higher than the estimated doses. Even though we made estimates for all inhabited atolls and all age groups, it is important to keep in mind that the dose estimates are uncertain, and in some cases, uncertain to a high degree. Particular assumptions we made are recognized to be only approximate. For example, at the more distant locations, e.g., Kwajalein, Majuro, etc., ingestion of fallout would probably play a much less important role than we assumed and inhalation of fallout would be more important. Those assumptions, in general, would likely have resulted in over-estimation of internal doses at distant atolls, though there may be other, yet unrecognized, compensating factors. Another simplifying assumption for this analysis was to ignore possible migration between atolls after the BRAVO test (with the exception of organized evacuations). Since this analysis pertains to typical and not specific persons, and because most of the dose was received within the first month after deposition, the assumption is adequate for the purposes of this analysis.

IV. ESTIMATION OF THE NUMBER OF CANCERS

Sources of Baseline Cancer Rates

Estimating cancer incidence in the various islands of the Pacific has been attempted by many but found to be difficult, largely because populations with variable ethnic backgrounds are scattered across a large number of islands having different levels of infrastructure for reporting health statistics. Most of the island populations are very small and cancer registry data, even if present, are subject to considerable inaccuracies and limitations. Such is the case for the various countries and territories of Micronesia, including the Marshall Islands (Henderson et al., 1985). Based on limited survey data, however, the island populations appear to share certain features, for example high lung and other smoking-related cancer rates, low colon cancer rates, high female cervical cancer rates, and most importantly for this analysis, high thyroid cancer rates. Some similarities of cancer patterns between the Micronesians and the Polynesians in Hawaii and New Zealand have also been noted in the literature. For projecting the magnitude of baseline cancer rates, one needs reliable estimates of cancer rates for major organs by age and gender. These cannot be estimated directly from published statistical data for the island populations in the Pacific Ocean region, but may be approximated by cancer incidence data for ethnic Hawaiians, collected by the Hawaii Cancer Registry and reported by NCI's SEER (Surveillance, Epidemiology, and End Results) registry.

Radiation Related Cancer Risks

Cancer risks related to radiation exposure have been well characterized by the large number of epidemiological studies of irradiated populations, which include Japanese atomic bomb survivors, persons irradiated for medical reasons, and populations occupationally exposed to radiation. It is widely recognized that the age-specific risk of radiation-related cancer depends not only on the dose received, but also on age at exposure, the age attained at the time of examination, time since exposure, and gender. The temporal pattern of the risk associated with age is especially important in projecting excess cancers in exposed populations. The most useful information for understanding radiation risk with advancing age comes from the long-term follow-up studies of the atomic bomb survivors. This population, like the exposed Marshall Islands population, includes men and women exposed to a wide range of radiation doses, at a wide range of ages. The results of the A-bomb survivor studies are supported by findings from other irradiated populations. Several findings are germane to this analysis. In particular, it has been learned that radiation-related leukemia risk increases shortly after exposure, reaching a peak within 5-10 years, and then declines gradually thereafter. In contrast, risks of most solid cancers increase gradually and continue to rise as the background cancer rates increase with age, and may remain elevated throughout life. At doses less than about 3 Gray, radiation related cancer risk generally increases roughly in proportion to radiation dose, i.e. the risk increases linearly with increasing dose and is largest for the highest doses in this range. However, the linear relationship may not extend to very high doses and the cancer risk may be diminished because high-dose irradiation causes a significant loss of viable cells (due to cell death) that might otherwise become cancerous.

Cancer Risk Estimation Methods

The National Cancer Institute (NCI) previously developed an algorithm for estimating the likelihood that a particular cancer, diagnosed following a given history of radiation exposure, could be attributed to that exposure (DHHS 2003). That algorithm is used by the Department of Veterans Affairs[1] and the Department of Labor[2] to adjudicate compensation claims against the government for cancers possibly associated with radiation exposures incurred during military service or employment by the Department of Energy or its contractors. The algorithm has been adapted by the NCI as an internal research tool to estimate organ-specific lifetime risks of cancer associated with any radiation exposure history. We judged this research tool to be sufficiently well developed to be used to estimate cancer risks among Marshallese exposed to

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[1]P.L. 101-426, Radiation Exposure Compensation Act (1990), http://www.usdoj.gov/civil/torts/const/reca/about.htm

[2]P.L. 106-398, Energy Employees Occupational Illness Compensation Program Act of 2000, http://www.usdoj.gov/civil/torts/const/reca/eeoicpa.htm

radioactive fallout from nuclear weapons tests during the 1950's, given estimates of average radiation dose by atoll, exposure age, and organ site.

As noted earlier, radiation related cancer risk is known to vary by gender, age at exposure, age at cancer diagnosis, and time following exposure, and such variation depends to some extent upon the type of cancer. In general, the radiation related lifetime cancer risk is greater for exposures at younger ages; the dependency on age at exposure is particularly strong for thyroid cancer for which the risk from exposure in early childhood is about ten times greater than that associated with exposure as an adult. In addition, the age-specific risk increases with increasing age at observation in rough proportion to age-specific baseline rates. The algorithm used here incorporates all these variations.

The primary assumptions we used to estimate the number of radiation related cancers in the Marshall Islands are as follows:

Date of exposure: All exposures were assumed to have occurred in 1954 and were assumed to have been prolonged over time.

Size of population at each atoll: For Rongelap, Ailinginae, and Utrik, the numbers of people exposed at each atoll were assumed equal to the number of evacuated residents as described in Brookhaven National Laboratory reports; for the remaining atolls, the population at each was assumed equal to the numbers reported from the 1958 census.

Age and sex distribution in 1954: For Rongelap and Ailinginae, the actual numbers of residents by gender and age were used; for the remaining atolls, the total numbers for Utrik (1954) and other atolls (using 1958 population numbers) were distributed by gender and age according to a tabulated distribution of the 1973 Marshall Islands population (since the 1958 population data were not specified by gender and age).

Organs and cancers considered: The numbers of radiation-related leukemias, thyroid cancers, stomach cancers, and colon cancers were estimated on the basis of the doses obtained for red marrow, thyroid, stomach and colon, respectively. All other cancers were treated as a group; their numbers were crudely estimated assuming that the dose to red bone marrow was representative of the dose to all organs and tissues other than thyroid, stomach, and colon.

Radiation related risk coefficients: For each sex and each possible exposure age, the radiation risk per person (lifetime from 1954, and future from January 1, 2004) associated with exposure, in 1954, was calculated for each of the 5 organs or cancers sites mentioned. Estimates of the past cancer risk (i.e., 1954-2003) were obtained by subtraction (past risk = lifetime risk – future risk). Lifetime and future lifetime risk coefficients were calculated by adapting an NCI computer algorithm ("IREP", for Interactive Radioepidemiological Program, see http://www.dceg.cancer.gov/radia-tools.html#Algorithms) developed in response to a Congressional mandate to update the 1985 NIH radioepidemiological tables report (see DHHS 2003).

Baseline cancer risk: NCI's SEER (Surveillance, Epidemiology, and End Results) website (see http://seer.cancer.gov/faststats/) provides organ-specific, sex-specific tables of the average probability that a person now of a given age will later develop cancer by a given, subsequent age. In the absence of tumor-registry-based baseline cancer rates for the Marshall Islands, these rates, adjusted to approximate those for native Hawaiians, were used as a surrogate.

V. LIMITATIONS OF OUR PROCEDURES TO ESTIMATE THE NUMBER OF CANCERS

Baseline cancer rates for the Marshall Islands are approximate: Robust and reliable baseline population cancer rates are lacking for the Marshall Islands and for Polynesia and Micronesia generally. Our estimated baseline and excess risks are based on all-race rates for NCI's SEER registry, adjusted to reflect age-standardized rates for ethnic Hawaiians as published by SEER from the Hawaii Tumor Registry.

Estimated doses are uncertain: The estimated radiation doses are approximate and likely to overestimate the true dose for locations distant from the test sites, as discussed in sections of this analysis dealing with dose estimation.

Estimated doses for some atolls are extremely high: For the most heavily exposed atolls, radiation doses to certain organs (thyroid, colon, stomach) were far higher than those estimated for the Hiroshima and Nagasaki A-bomb survivors and medically-irradiated populations which form the main observational basis for the NCI cancer risk algorithm.

Most of our understanding of the biological response to radiation exposure pertains to doses that are much lower than those of the more highly exposed Marshallese: Models for estimating radiation related cancer risk have been developed primarily from studies of populations exposed very briefly to radiation doses in the 0.1 Gray to 2.0 Gray range, and much attention has been paid to extrapolation of these findings to populations exposed to much lower doses and to populations with exposures that have been fractionated or protracted over time. To our knowledge, there are no epidemiologic data on populations, like those of Rongelap, Ailinginae, and Utrik, for which protracted exposures to stomach, colon, and thyroid were in tens of Gray. At such high doses, the risk (based on the assumption of a linear dose-response and calculated as the product of the age-specific dose-response coefficient times the age-specific protracted dose) was often greater than 100% and had to be truncated at 100%. In general, extrapolation to high dose levels is uncertain because radiation-related acute effects can involve destruction of affected cells and organ failure leading to death or, in the case of the thyroid, surgical removal of the organ. For this and other reasons, at very high doses proportionality between the doses received and the number of resulting cancers is unlikely to be maintained, and our projected cancer risks are likely to be exaggerated.

Treatment of life span leads to an overestimate of risk: A relatively minor consideration is that standard U.S. life tables were used for the calculations in the absence of life tables for the Marshallese population. Current estimates of the natural life span of that population (69.7 years for both sexes combined) are about 8 years shorter than those for the general U.S. population (77.4 years).[3] A possibly more serious inaccuracy is that no account was taken of the competing effect of mortality due to death from a fallout-related cancer, because that would have required a drastic overhaul of the basic algorithm which was designed for evaluation of low-level exposure effects. For most atolls, this was a trivial problem, but

[3]The World Fact Book 2004: http://www.cia.gov/cia/publications/factbook.

for the three heavily-exposed atolls, it has unquestionably resulted in some overestimation of the number of radiation related cancers expected.

Risk of skin cancer: The skin was also a tissue potentially exposed to fallout radiation. Marshallese who received significant amounts of fallout directly onto their body, e.g., at Rongelap where skin "burns" were documented, would have received high skin doses primarily from beta particles emitted during radioactive decay. In this analysis, we have not estimated the number of skin cancers that might be produced as a consequence of exposure to fallout because there are no baseline skin cancer data reported by the SEER and other U.S. registries. The baseline risks are an integral part of the calculation to estimate the number of cancers and calculations could not be completed without that important component. Moreover, examination of the number of personal injury claims awarded by the Marshall Islands Nuclear Claims Tribunal (NCT 2004) as of June 30, 2004 indicates that among the 2,046 personal injury awards, there have been 72 awards for skin burns, but only 1 award for skin cancer (in this case, of the non-melanoma type). It appears that despite high doses to the skin to, at least, a small subset of the Marshallese, there is little evidence that the risk of skin cancer is great.

VI. NUMBERS OF CANCERS EXPECTED

We used the 1958 census to estimate the size of the potentially exposed populations on each atoll except for Rongelap, Ailinginae, and Utrik where we used the actual number evacuated from those atolls at the time of the BRAVO test. Using that information, we assumed the population size at the time of the BRAVO test (1954) to be 13,940. Among the members of that group, the number of cancers expected to occur in the absence of exposure to radioactive fallout from tests conducted in the Marshall Islands (i.e., the baseline number of cancers) throughout their lifetime will be about 5,600, though about one-half of those cancers are yet to develop or be diagnosed. Within the lifetime of the cohort, we estimate an additional 530 cancers that might be attributable to exposure to fallout radiation. Similar to the case for the baseline cancers, about one-half of the radiation related cancers are yet to develop or be diagnosed. These findings indicate that we expect the exposure to fallout to result in about a 9% increase in the total number of cancers, giving an expected total number of cancers (fatal plus non-fatal) of about 6,130.

It is important to emphasize that the assumption of proportionality between radiation dose and radiation-related cancer risk, which has been shown to hold reasonably well at lower doses, cannot be assumed to hold at the extremely high radiation doses to the thyroid gland and the colon estimated for the populations of Rongelap and Ailinginae. Thus, the estimated excess numbers of these cancers tabulated in Table 2b, and their contributions to the summary values in Table 3, should not be taken at face value, but should be treated as a crude upper limit.

Numerical values from our calculations to estimate the number of baseline and excess (radiation related) cancers among Marshallese alive during the years 1946-1958 are presented in Tables 2a, 2b, and 3. We draw conclusions separately for the combined Rongelap and Ailinginae population and for all other atolls together. The following points summarize our findings, most which can be derived directly from the accompanying tables.

Leukemia

- Among members of the population exposed on Rongelap or Ailinginae, between 1 and 2 radiation-related leukemias are estimated during their lifetimes, compared to 1 baseline case. Thus, about 60% of all leukemia cases are expected to be radiation-related.
- Among people exposed on the other atolls, between 3 and 4 cases of radiation-related leukemia, and 122 baseline cases, are projected; i.e., about 3% of the projected total would be radiation-related.
- All leukemias related to exposure to fallout have likely occurred and been diagnosed, and no further radiation-related cases are projected for the future.

Thyroid cancer

- In the Rongelap/Ailinginae population, about 43 lifetime radiation-related thyroid cancer cases are estimated, compared to 1 baseline case. Thus, virtually all (98%) of all estimated cases would be radiation-related. As noted above, the estimated excess numbers should not be taken at face value but should be treated as crude upper limits. Also, the distribution of estimated excess cases by time period is also highly uncertain for reasons noted in Table 2b.
- For the other atolls, about 126 baseline thyroid cancers cases and 219 radiation-related excess cases (64% of the total) are projected.
- Roughly 38% of the radiation-related cases of thyroid cancer have yet to develop or to be diagnosed.

Stomach cancer

- For the Rongelap/Ailinginae population, about 8 radiation-related cases of stomach cancer are predicted, compared to 3 baseline cases; that is, 76% of all predicted cases would be radiation-related.
- About 7 excess and 320 baseline stomach cancer cases are projected for the other atolls; thus, 2% of the total would be radiation-related.
- About 13 radiation-related cases of stomach cancers, or 85% of the radiation-related total, have yet to develop or to be diagnosed.

Colon cancer

- About 64 radiation-related and only 4 baseline colon cancer cases are projected for the Rongelap/Ailinginae population, so that the vast majority (94%) would be radiation-related. Like the thyroid cancer estimates, these estimates of excess risk should not be taken at face value but should be treated as crude upper limits.
- About 93 excess and 470 baseline colon cancer cases are projected for the other atolls; thus, 17% of the total would be radiation-related.
- About 75% of the radiation-related colon cancers, have yet to develop or to be diagnosed.

Other cancers

- About 31 radiation-related and 36 baseline cases of other kinds of cancer are projected for the Rongelap and Ailinginae populations, so almost half (46%) would be radiation-related.
- For the other atolls, about 62 cancer cases of other types, compared to about 4500 baseline case, are projected. Thus, 1.4% of the projected total would be radiation-related.
- About 61 radiation-related cases of other types of cancer, or 66% of the radiation-related total, have yet to develop or to be diagnosed.

All cancers combined

- In all, about 148 radiation-related cancers of all types (more than the number of exposed persons, and likely too high) and 44 baseline cancer cases are projected for the Rongelap/Ailinginae population. To the extent that these totals reflect thyroid and colon cancers, they should be treated as upper limits.
- For the other atolls, the corresponding numbers are about 380 excess and 5600 baseline cancers, for a radiation-related proportion of 6.5%.
- About 56% of the total radiation-related cases have yet to develop or to be diagnosed, compared to about 50% of the baseline cancers. This temporal distribution reflects the generally young age structure of the exposed population and the greater sensitivity at younger ages to radiation carcinogenesis.

Age at exposure

- Of the exposed population, 35% were under 10, 25% between 10 and 20, 22% between 20 and 40, and 18% over 40 in 1954.
- Among members of the population exposed to BRAVO fallout at ages less than 10 years, about 2 leukemias, 200 thyroid cancers, 8 stomach cancers, 83 colon cancers, and 52 other cancers are projected to develop over their lifetimes. To the extent that these totals reflect thyroid and colon cancers among the residents of Rongelap and Ailinginae, they should be treated as upper limits.
- The cancers that will develop among those exposed under the age of 10 years represent about 38% of the radiation-related leukemias, and 77%, 54%, 53%, and 56% of the radiation-related cancers of the thyroid gland, stomach, colon, and other sites, respectively, that may develop within the entire cohort.

Location

- About 87% of all radiation related cancers are predicted from exposure on the northern atolls of Rongelap, Ailinginae, Ailuk, Mejit, Likiep, Wotho, Wotje, and Ujelang (84% of the radiation related leukemias, 95% of the radiation related thyroid cancers, 95% of the radiation related stomach cancers, 92% of the radiation related colon cancers, and 84% of the radiation related cancers of other types).

VII. CONCLUDING REMARKS

We estimate that the nuclear testing program in the Marshall Islands will cause about 500 additional cancer cases among Marshallese exposed during the years 1946-1958, about a 9% increase over the number of cancers expected in the absence of exposure to regional fallout. More than 85% of those radiation-related cases would likely occur among those exposed in 1954 on the atolls of Rongelap, Ailinginae, Ailuk, Mejit, Likiep, Wotho, Wotje, and possibly Ujelang.

Doses to the thyroid, colon and stomach of persons on Rongelap, Alinginae, and (to a lesser extent) Utrik at the time of the BRAVO test in 1954 were extremely high. Based on this analysis, a high proportion of cancers of those organs that develop among members of those population groups are likely to be radiation-related. About 40% of the thyroid cancers and more than one-half of cancers to the other organs (at all atolls) are yet to develop or to be diagnosed. Hence, most of the radiation excess is projected to occur in the coming years. The exception is radiation-related leukemia which is unlikely to develop in the future.

Estimated doses at the more distant atolls are more uncertain than those at atolls close to the test site, though the more distant atolls contribute only a small fraction of the total radiation-related cancers projected. Hence, while it may be possible to improve the estimation of average dose at the more distant locations, we believe such changes will make little difference to the number of excess cancers predicted.

Table 2a. Estimated number of cancers to occur in the absence of exposure to fallout from Marshall Islands tests (baseline) and those attributable to exposure to fallout from Marshall Islands tests (excess) among all Marshallese living in the Marshall Islands from 1946-1958 except those on Rongelap and Ailinginae at the time of the BRAVO test (population size assumed equal to 13,856). For presentation purposes, all estimated numbers of cancer are rounded to the nearest whole number.

Cancer type	Time period	Estimated baseline number of cancers	Estimated excess number of cancers	Estimated total number of cancers	Estimated percentage of total cancers attributable to fallout exposure
Leukemia	1946-2003	58	3	61	5.5
	2004+	64	Much less than 1	64	0.1
	Lifetime	122	3	125	2.7
Thyroid	1946-2003	97	123	220	56
	2004+	29	96	124	77
	Lifetime	126	219	345	64
Stomach	1946-2003	135	1	136	0.74
	2004+	189	6	195	3.0
	Lifetime	324	7	331	2.1
Colon	1946-2003	195	15	210	6.9
	2004+	271	78	350	22
	Lifetime	466	93	559	17
All Other Cancers	1946-2003	2225	21	2246	0.94
	2004+	2289	41	2330	1.8
	Lifetime	4514	62	4576	1.4
All Cancers Combined	1946-2003	2710	163	2873	5.7
	2004+	2842	221	3063	7.2
	Lifetime	5552	384	5936	6.5

Table 2b. Estimated number of cancers to occur in the absence of exposure to fallout from Marshall Islands tests (baseline) and those attributable to exposure to fallout from Marshall Islands tests (excess) among Marshallese on Rongelap and Ailinginae at the time of the BRAVO test (population size equal to 82). For presentation purposes, all numbers are rounded to two significant digits.

Cancer type	Time period	Estimated baseline number of cancers	Estimated excess number of cancers#	Estimated total number of cancers	Estimated percentage of total cancers attributable to fallout exposure
Leukemia	1946-2003	0.55	1.4	2.0	72
	2004+	0.43	0.05	0.48	25
	Lifetime	0.98	1.5	2.5	61
Thyroid	1946-2003	0.76	40†	41	98
	2004+	0.19	3†*	3	92
	Lifetime	0.96	43†	44	98
Stomach	1946-2003	1.4	1.4	2.8	51
	2004+	1.3	7.0	8.3	85
	Lifetime	2.7	8.4	11	76
Colon	1946-2003	2.0	26†	28	93
	2004+	1.8	38†*	40	95
	Lifetime	3.8	64†	68	94
All Other Cancers	1946-2003	20	11	31	35
	2004+	15	20	35	56
	Lifetime	36	31	67	46
All Cancers Combined	1946-2003	25	80	105	76
	2004+	19	68	87	78
	Lifetime	44	148††	192	77

†Based on linear-model estimates applied to doses far higher than those in other studied populations (see text).

††Estimated number of cancers exceeds number of exposed (see text).

#In this calculation, the possibility of more than one radiation-related cancer of the same organ, in the same person, was ignored. This made a difference only for cancers of the thyroid and, to a lesser extent, the colon.

*The estimated number of radiation-related cancers occurring in 2004 and later was constrained not to exceed the difference between the number estimated for lifetime and for 1946-2003. The total number could plausibly be distributed differently between the two time periods.

Table 3. Estimated excess (radiation related) cancers by atoll group and organ

	Rongelap, Ailinginae	Utrik	Other northern atolls**	Southern atolls: Low exposure atolls***	Southern atolls: Very low exposure atolls****	Totals (number of baseline cancers in parentheses)
Population size*	82	157	2005	3834	7862	13940
Leukemia	1.5	0.61	2.1	0.44	0.27	5 (123)
Thyroid	43†	46	132	26	15	262 (127)
Stomach	8.4	1.4	4.4	0.69	0.37	15 (326)
Colon	64†	31	49	9.2	4.0	157 (470)
Other cancers	31	8.5	39	8.6	5.9	93 (4550)
All Cancers combined (rounded totals)	148††	87	227	44	26	532 (5596)

*Estimated from 1958 census (except for evacuated populations) as described in text.

**Ailuk, Mejit, Likiep, Wotho, Wotje, Ujelang

***Lae, Kwajalein, Maloelap, Namu, Arno, Mili

****Lib, Aur, Ailinglaplap, Majuro, Ujae, Kili, Jaluit, Namorik, Ebon

†Based on linear-model estimates applied to doses far higher than those in other studied populations, and therefore the estimate of excess cases is likely to be a rough upper bound (see text). This caveat is less applicable to estimates for Utrik, and does not apply to the other atolls (see Table 1 for average doses by atoll).

††Estimated number of cancers exceeds number of exposed (see text)

REFERENCES

BNL. Brookhaven National Laboratory. A Twenty-year Review of Medical Findings in a Marshallese Population Accidentally Exposed to Radioactive Fallout. BNL-50424. Upton, NY: Brookhaven National Laboratory. 1975.

Breslin AJ, Cassidy, ME. Radioactive Debris from Operation Castle, Islands of the Mid-Pacific. NYO-4623. United States Atomic Energy Commission, New York Operations Office, Health and Safety Division. Available from Las Vegas: Coordination and Information Center. 1955.

Conard RA, Dobyns, BM, Sutow, WW. Thyroid neoplasia as a late effect of active exposure to radioactive iodine in fallout. JAMA 214: 316-324. 1970.

Cronkite EP, Conard RA, Bond VP. Historical events associated with fallout from BRAVO shot-Operation Castle and 25 y of medical findings. Health Physics 73(1):176-186. 1997.

DHHS. Department of Health and Human Services. Report of the NCI-CDC Working Group to Revise the 1985 NIH Radioepidemiological Tables. Bethesda, MD: U.S. Department of Health and Human Services, National Institutes of Health, National Cancer Institute. 2003.

DNA. Defense Nuclear Agency. Compilations of local fallout data from test detonations 1945-1962 extracted from DASA 1251, Volume II-Oceanic U.S. tests. Prepared by the General Electric Company-TEMPO. Washington, D.C.: Defense Nuclear Agency (DNA). 1979.

Hamilton TE, van Belle G, LoGerfo JP. Thyroid neoplasia in Marshall Islanders exposed to nuclear fallout. JAMA 258:629-636. 1987.

Harris P. A *Summary of the Results of Urine Analysis on Rongelap Natives, Americans and Japanese fisherman to Date*. Memo to Atomic Energy Commission. Los Alamos, NM: Los Alamos Scientific Laboratory. 1954.

Henderson BE, Kolonel LN, Divorsky R, Kenford D, Mori E, Singh K, Thevenot H. Cancer incidence in the islands of the Pacific. National Cancer Institute Monograph 69:73-81. 1985.

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. UCRL-53505. Livermore, CA: Lawrence Livermore National Laboratory. 1984.

ICRP. International Commission on Radiological Protection. Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 1. ICRP Publication 56. International Commission on Radiological Protection. Oxford. 1989.

ICRP. International Commission on Radiological Protection ICRP database of dose coefficients: workers and members of the public. Version 2.0.1 (available on CD-ROM). International Commission on Radiological Protection. Oxford. 2001.

Lessard ET, Miltenberger RP, Cohn SH, Musolino SV, Conard RA. Protracted exposure to fallout: the Rongelap and Utirik experience. Health Phys. 46(3): 511-527. 1984.

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, BNL 51882. Upton, NY: Brookhaven National Laboratory, Safety and Environmental Protection Division. 1985.

Martin EJ, Rowland, RH. CASTLE Series 1954. DNA-603F. Washington, DC: Defense Nuclear Agency. 1982.

NCT. Marshall Islands Nuclear Claims Tribunal. Analysis of NCT Personal Injury Awards Through June 30, 2004. Majuro, Marshall Islands. 2004.

Rall JE, Conard RA. Elevation of the serum protein-bound iodine level in inhabitants of the Marshall Islands. American Journal of Medicine 40(6):882-886. 1966.

Simon, SL. A Brief History of People and Events Related to Atomic Weapons Testing in the Marshall Islands. Health Physics 73(1):5-20. 1997.

Simon SL, Graham JC. Findings of the first comprehensive radiological monitoring program of the Republic of the Marshall Islands. Health Physics 73(1):66-85. 1997.

Simon SL, Robison WL. A compilation of atomic weapons' test detonation data for U.S. Pacific ocean tests. Health Physics 73(1):258-264. 1997.

Simon SL, Graham JC. Findings of the Nationwide Radiological Study: Summary Report, submitted to the Cabinet of the Government of the Republic of the Marshall Islands. December 1994. Available from Ministry of Foreign Affairs, Government of the Republic of the Marshall Islands, Majuro, Marshall Islands, 96960. 1994.

Takahashi T, Trott KR, Fujimori K, Simon SL, Ohtomo H; Nakashima N, Takaya K, Kimura N, Konno T, Satomi S, Shoemaker M. An investigation into the prevalence of thyroid nodules and thyroid cancer on Kwajalein Atoll, Marshall Islands. Health Physics 73(1):199-213. 1997.

Takahashi, T.; Trott, K.R.; Fujimori, K.; Nakashima, N.; Ohtomo, H.; Schoemaker, M.J.; Simon, S.L. Thyroid Disease In The Marshall Islands, Findings from 10 Years of Study. Tohoku University Press, Sendai, Japan. 2001.

USDOE. United States nuclear tests, July 1945 through September 1992. 1994. DOE/NV-209 (Rev. 14). Las Vegas, NV: U.S. Department of Energy.