Chapter 3
Estimation of Doses from Fallout

Contents: This chapter addresses external and internal radiation exposure from fallout originating at the Nevada Test Site and at other sites worldwide. The methods used to estimate doses and the principal findings are presented.

3.1 Introduction

This chapter presents dosimetric methods and results of calculations to estimate radiation doses that could have been received by Americans living in the contiguous United States as result of exposure to radioactive fallout originating at the Nevada Test Site and at other nuclear testing sites worldwide. It should be noted that these methods are based on data collected over more than four decades but primarily on the experience acquired in dose reconstruction during the past decade and a half. Crude methods of estimating doses have been used for this feasibility study. In some cases – particularly for the case of shorter-lived radionuclides (e.g., ^{131}I) in global fallout – the doses presented may be in error by as much as an order of magnitude. Future work could likely improve the precision of these calculations, however.

Because of the low precision of some of the dose estimates presented, the doses should not be used to make a claim of individual health effects or increases in health effects among subpopulations. The goal of these calculations was to show feasibility only, and in many cases the possible degree of error of the doses has not been evaluated. Thus, the usefulness of the doses presented here is limited only to very approximate evaluations of overall (that is, national) health detriment. Even though county-specific deposition densities and doses were computed and presented in a series of maps, those county-specific estimates are uncertain, and individual county values should not be used for definitive risk assessments until further refinements are made and the degree of possible error is evaluated in detail. The maps are provided only to show general spatial patterns of fallout and resulting exposure patterns across the United States.

The dose estimates in this report are: (1) based primarily on a review of the readily available open literature and supplemented with calculations of moderate complexity rather than on sophisticated computer models, (2) calculated on a county-by county basis as well as averaged over the contiguous United States, (3) calculated separately for the most important

radionuclides produced in nuclear weapons tests, (4) provided in terms of effective dose and absorbed dose to the thyroid gland and to the red bone marrow, and (5) calculated for tests conducted in individual years as well as summed over all years. The dose estimates and the methodology used for calculating them are summarized in this chapter. The details of the calculations and methodology are given in Appendices D through G of this report.

In this chapter, rudimentary estimates of radiation doses from fallout are presented for two groups of people that were assumed to have resided in the same county during their entire lives: (1) those who were adults in 1951, that is, at the time when substantial amounts of fallout from nuclear weapons tests began to occur in the United States and (2) those who were born on 1 January 1951, and are expected to be among the population group that received the highest doses from fallout. Thyroid and bone marrow absorbed doses accumulated through the year 2000 are presented for the two population groups. Exposure of the thyroid to ionizing radiation can, in some cases, give rise to the induction of thyroid cancer, especially among those exposed as very young children, while exposure of the red bone marrow can, in some cases, contribute to the induction of leukemia in the population.

In addition, absorbed doses are presented for selected other organs and tissues, and effective doses will be used to compare exposures from various radionuclides, types of nuclear tests, or exposure pathways, when appropriate.

Radiation doses are presented separately for the nuclear weapons tests conducted at the Nevada Test Site (NTS) and for those carried out at other sites outside of the United States. The main reason for this division is that the nuclear tests conducted in the United States and elsewhere resulted in different geographic deposition patterns of the fallout. In addition, the mixture of radionuclides deposited depended on the origin of the nuclear debris (fallout). Some of the primary considerations in making these estimates were:

- The tests conducted at the NTS had low yields, so that the radioactive clouds originating from the atmospheric explosions remained in the lower layers of the atmosphere and fallout deposition occurred within days. The level of fallout generally decreased with distance from the NTS, and consisted predominantly of short-lived radionuclides, like ^{131}I. The environmental measurements made after each test usually made it possible to relate the radioactive contamination to specific tests and thus to assess the radiation impact of each of those tests.
- In contrast, the radioactive contamination due to tests conducted far away from the United States was due primarily to high-yield tests, which resulted in radioactive clouds that reached high layers of the atmosphere. It took months to years for radionuclides to deposit on the ground from those altitudes. Within that time, relatively homogeneous mixing of the activity occurred in the high layers of the atmosphere within latitudinal bands all around the world, while the activity that gradually descended to lower atmospheric layers was preferentially removed from the atmosphere via precipitation. Consequently, the levels of global fallout were relatively constant throughout the United States, the differences being due to differences in precipitation levels. Fallout from those tests consisted predominantly of long-lived radionuclides, like Cesium-137 (^{137}Cs), as most of the short-lived radionuclides decayed before they deposited on the ground.

Thus, environmental measurements made at that time did not make it possible to relate the contamination to a specific test.

Following releases of radionuclides into the environment, human populations can be exposed to external or internal irradiation. In this report, the estimated radiation doses from external and from internal irradiation are presented separately.

Exposures via external irradiation occur when the radionuclides are outside the body (in the air, on the ground, building materials, vegetation, etc.). External irradiation usually arises from: (1) submersion in air contaminated with gamma-emitting radionuclides; and/or (2) the decay of gamma-emitting radionuclides deposited on the ground. In the case of radiation exposures from nuclear weapons tests, external irradiation from submersion in contaminated air plays a very minor role and will not be considered explicitly. Exposures via internal irradiation occur when radionuclides enter into the body, generally by inhalation or ingestion. Doses from internal irradiation may result from (1) the inhalation of radionuclide-contaminated air, and (2) the ingestion of radionuclides in water and foodstuffs. The estimation of doses from internal irradiation will focus on those from ingestion, as the doses from inhalation are usually much smaller than those from ingestion. Therefore, the doses that are presented in this report are those arising from the decay of gamma-emitting radionuclides deposited on the ground (external irradiation) and those incurred via the ingestion of radionuclides in water and foodstuffs (internal irradiation). Both types of dose are derived from the estimation of the amounts of radionuclides deposited per unit area of ground (often called 'deposition densities' in this report).

3.2 NTS Fallout

There were 100 officially reported nuclear events conducted in the atmosphere at the NTS (DOE 1994). These tests ranged in yield from extremely small explosions (<1 t equivalent TNT) to a maximum size of 74 kt (Shot Hood on 5 July 1957). In addition, there were "cratering" events that released significant amounts of radioactive debris; the most notable was the 104 kt Project Sedan detonated on 6 July 1962. Not all of these events produced fallout that was measured or measurable beyond the confines of the NTS; only the most significant events in terms of their releases to the offsite environment are considered. Deposition densities have been estimated for a total of 61 events: eight in 1951 (Ranger and Buster-Jangle series), eight in 1952 (Tumbler-Snapper series), 11 in 1953 (Upshot-Knothole series), 13 in 1955 (Teapot series), 19 in 1957 (Plumbbob series), and two in 1962 (Storax series). Some of these events were detonated so close together in time that it has been impossible to distinguish the debris. Thus, results for Bee and Ess (both fired on 22 March 1955); Apple and Wasp (both fired on 29 March 1955); Kepler (24 July 1957) and Owens (25 July 1957); and Wheeler (6 September 1957), Coulomb (6 September 1957), and Laplace (8 September 1957) were combined. The 61 tests that were included in this assessment accounted for over 95% of the total ^{131}I produced (NCI 1997); hence, they were the most important in terms of the exposure delivered to the American people. A complete list of these events with dates and yields is given in Table 3.1.

Table 3.1. Nuclear weapons tests conducted at NTS that are considered in the feasibility study (based on NCI 1997)

Operation (Series)	Test	Placement	Date	Yield (kt)
Ranger	BAKER	airdrop	28-Jan-51	8
	BAKER-2	airdrop	2-Feb-51	8
Buster	BAKER	airdrop	28-Oct-51	3.5
	CHARLIE	airdrop	30-Oct-51	14
	DOG	airdrop	1-Nov-51	21
	EASY	airdrop	5-Nov-51	31
Jangle	SUGAR	surface	19-Nov-51	1.2
	UNCLE	crater	29-Nov-51	1.2
Tumbler-	ABLE	airdrop	1-Apr-52	1
Snapper	BAKER	airdrop	15-Apr-52	1
	CHARLIE	airdrop	22-Apr-52	31
	DOG	airdrop	1-May-52	19
	EASY	tower	7-May-52	12
	FOX	tower	25-May-52	11
	GEORGE	tower	1-Jun-52	15
	HOW	tower	5-Jun-52	14
Upshot-	ANNIE	tower	17-Mar-53	16
Knothole	NANCY	tower	24-Mar-53	24
	RUTH	tower	31-Mar-53	0.2
	DIXIE	airdrop	6-Apr-53	11
	RAY	tower	11-Apr-53	0.2
	BADGER	tower	18-Apr-53	23
	SIMON	tower	25-Apr-53	43
	ENCORE	airdrop	8-May-53	27
	HARRY	tower	19-May-53	32
	GRABLE	airburst	25-May-53	15
	CLIMAX	airdrop	4-Jun-53	61
Teapot	WASP	airdrop	18-Feb-55	1
	MOTH	tower	22-Feb-55	2
	TESLA	tower	1-Mar-55	7
	TURK	tower	7-Mar-55	43
	HORNET	tower	12-Mar-55	4
	BEE/ESS			
	BEE	tower	22-Mar-55	8
	ESS	crater	23-Mar-55	1
	APPLE/WASP			
	APPLE-1	tower	29-Mar-55	14

Operation (Series)	Test	Placement	Date	Yield (kt)
	WASP	airdrop	29-Mar-55	3
	POST	tower	9-Apr-55	2
	MET	tower	15-Apr-55	22
	APPLE-2	tower	5-May-55	29
	ZUCCHINI	tower	15-May-55	28
Plumbbob	BOLTZMANN	tower	28-May-57	12
	WILSON	balloon	18-Jun-57	10
	PRISCILLA	balloon	24-Jun-57	37
	HOOD	balloon	5-Jul-57	74
	DIABLO	tower	15-Jul-57	17
	KEPLER/OWENS			
	KEPLER	tower	24-Jul-57	10
	OWENS	balloon	25-Jul-57	9.7
	SHASTA	tower	18-Aug-57	17
	DOPPLER	balloon	23-Aug-57	11
	SMOKY	tower	31-Aug-57	44
	GALILEO	tower	2-Sep-57	11
	WHEELER/C/L			
	WHEELER	balloon	6-Sep-57	0.197
	COULOMB-B	surface	6-Sep-57	0.3
	LAPLACE	balloon	8-Sep-57	1
	FIZEAU	tower	14-Sep-57	11
	NEWTON	balloon	16-Sep-57	12
	WHITNEY	tower	23-Sep-57	19
	CHARLESTON	balloon	28-Sep-57	12
	MORGAN	balloon	7-Oct-57	8
Storax	SEDAN	crater	6-Jul-62	104
	SMALL BOY	tower	14-Jul-62	Low

For the purposes of the feasibility study, three types of estimates were made: (1) deposition densities of a selected set of 43 radionuclides on the ground on a county-by-county basis for each test; (2) doses from external irradiation for the most important radionuclides as derived from data in Hicks (1981, 1982); and (3) doses from internal irradiation for the most important radionuclides contributing to internal dose (Table 3.2). The group of radionuclides selected for the internal dose calculations account for about 90% of the internal dose. If further work is conducted, ^{239}Np should be included in the internal dose calculations.

Table 3.2. Radionuclides in NTS fallout for which deposition densities (Bq m^{-2}) were explicitly calculated on a county-by-county basis.

Radionuclide	Half-Life	Used in External Dose Calculations	Used in Internal Dose Calculations
^{89}Sr	52 days		x
^{90}Sr ($^{90}Y^{*}$)	28.5 years (64 hours)		x
^{91}Sr	0.4 days	x	x
^{91m}Y	49.7 minutes	x	
^{91}Y	59 days	x	
^{93}Y	0.4 days	x	
^{95}Zr ($^{95}Nb^{*}$)	64 days (35 days)	x	
^{97}Zr ($^{97}Nb^{*}$)	0.7 days (72 minutes)	x	x
^{97m}Nb	53 seconds	x	
^{99}Mo	2.8 days	x	x
^{99m}Tc	6.0 hours	x	
^{99}Tc	213,700 years		
^{103}Ru ($^{103m}Rh^{*}$)	39 days (56 minutes)	x	x
^{105}Ru ($^{105m}Rh^{*}$)	0.2 days (45 seconds)	x	x
^{105}Rh	1.5 days	x	x
^{106}Ru ($^{106}Rh^{*}$)	368 days (30 seconds)	x	x
^{131}I (from NCI 1997)	8 days	x	x
$^{132}Te^{*}$	3.3 days	x	x
^{132}I	2.3 hours	x	
^{133}I	0.9 days	x	x
^{136}Cs	13 days		x
^{137}Cs (^{137m}Ba)	30 years	x	x
^{140}Ba ($^{140}La^{*}$)	13 days (1.7 days)	x	x
^{140}La	1.7 days	x	
^{141}Ce	32.5 days	x	
^{143}Ce	1.4 days	x	x
^{143}Pr	14 days		
^{144}Ce ($^{144}Pr^{*}$)	284 days	x	x
^{147}Nd	11 days	x	x
^{147}Pm	2.6 years		
^{239}Np	2.36 days	x	
$^{239+240}Pu$	24,131 years / 6,569 years		x
^{241}Pu	14.4 years		x
^{241}Am	430 years	x	

*Calculations for the progeny (in parentheses) are based on data for the precursor nuclide.

3.2.1 Deposition Densities

Fallout deposition density is the activity of each radionuclide per square meter that is accumulated on the ground as a result of settling of particles from clouds containing nuclear debris. The activity of each radionuclide deposited on the ground is important information for calculating both external and internal doses. Deposition of fallout can take place under both dry and wet weather conditions; however, when rainfall coincides with the passage of a cloud containing nuclear debris, the deposition of fallout is considerably increased.

The daily deposition density of each radionuclide listed in Table 3.2 was estimated from the daily ^{131}I deposition density estimates reported in the National Cancer Institute Study on ^{131}I exposure of the American people (NCI 1997). All calculations for this report were carried out separately for each county (and sub-county as defined in NCI (1997), Appendix 2), and then summed to provide estimates on a test-by-test, annual and cumulative basis. The deposition densities of nuclides other than ^{131}I were calculated from the NTS ^{131}I deposition density values by using the relationships calculated by Hicks (1981) for each NTS test. Further detail on these methods is provided in Appendix E.

Plutonium isotopes were also contained in the fallout from Nevada weapons tests. Because plutonium isotopes primarily emit alpha particles, they do not contribute to external dose and contribute only a small amount to ingestion (internal) dose. The primary hazard from plutonium comes about when it is inhaled. However, even inhalation has been shown not to be a significant contributor to population exposure from NTS testing (Church et al. 1990). Plutonium is primarily discussed here because of the high degree of interest by the public in plutonium contamination of man and the environment. Only crude estimates of plutonium deposition density can be made for individual tests partly because certain data – in particular, the ratios of plutonium to ^{137}Cs, ^{90}Sr, etc. – are still classified by the U.S. Government.

A reasonable set of assumptions has been made, however, from which rough estimates of plutonium deposition density can be developed. While possibly significantly in error for any specific given test, the estimates provide a reasonable total deposition value when summed over all tests. Using these methods, $^{239+240}$Pu and ^{241}Pu depositions in fallout were estimated for each test and test series. It should be noted that only about one-half the plutonium from tower and surface tests would be deposited outside the immediate vicinity of the NTS because it is associated with large particles that are deposited close-by to the detonation site. Accurate estimates of plutonium deposition from particular tests will only be possible if additional information on the cesium to plutonium ratios for particular tests is declassified. Thus, the plutonium results presented in this report should be treated as only crude estimates.

For the radionuclides considered in this report, deposition density estimates were developed for each of the approximately 3,000 counties within the contiguous United States. Nearby the NTS, where some of the larger counties experienced considerable gradations in deposition, counties were broken into subparts. In all, estimates were computed for 3094 geographic units (counties or subparts of counties). These estimates of radionuclide deposition density are based on the ^{131}I deposition densities reported in NCI (1997) (see

Appendix E) which in turn were based primarily on measurements made at the time of fallout and reported from the gummed-film network operated by the Department of Energy (DOE) Environmental Measurements Laboratory, which was then known as the Atomic Energy Commission (AEC) Health and Safety Laboratory. Because the measurement sites were few compared to the large number of counties, and because the deposition in each county is so highly influenced by the occurrence of rainfall, the measurements were extended to other nearby locations through the use of mathematical interpolation procedures (NCI 1997). Extrapolating data to locations without measurements is one of the inherent and unavoidable limitations of these calculations. For four tests (two in 1951 and two in 1962), the gummed-film network was not operational. For those tests, the deposition densities throughout the continental U.S. were estimated using an atmospheric dispersion and deposition model, based on estimates of fission yields of the four tests; the deposition densities obtained in this way are extremely uncertain. As discussed in Appendix F, there are reasons to believe that the results obtained for the test Sedan, detonated in 1962, are overestimated by a large factor.

The estimated total deposition of ^{137}Cs from all NTS tests considered in this report through 1962 is shown in Figure 3.1. As can be seen, the years of greatest deposition were 1957, 1953, and 1952. The geographic pattern of deposition of ^{137}Cs as shown in Figure 3.2 is similar to that for ^{131}I (see NCI 1997), although, due to the long half-life (30 years) of ^{137}Cs, the decrease in activity in the eastern United States is less than that for ^{131}I. The county estimates of ^{137}Cs deposition density range from well below 200 Bq m^{-2} to about 1300 Bq m^{-2}. The regional and local variations of deposition density are primarily due to variations in precipitation. The well-known elevated area in northern New York State was due to heavy thunderstorm activity during passage of the cloud from test SIMON in April 1953 (NCI 1997; Beck et al. 1990).

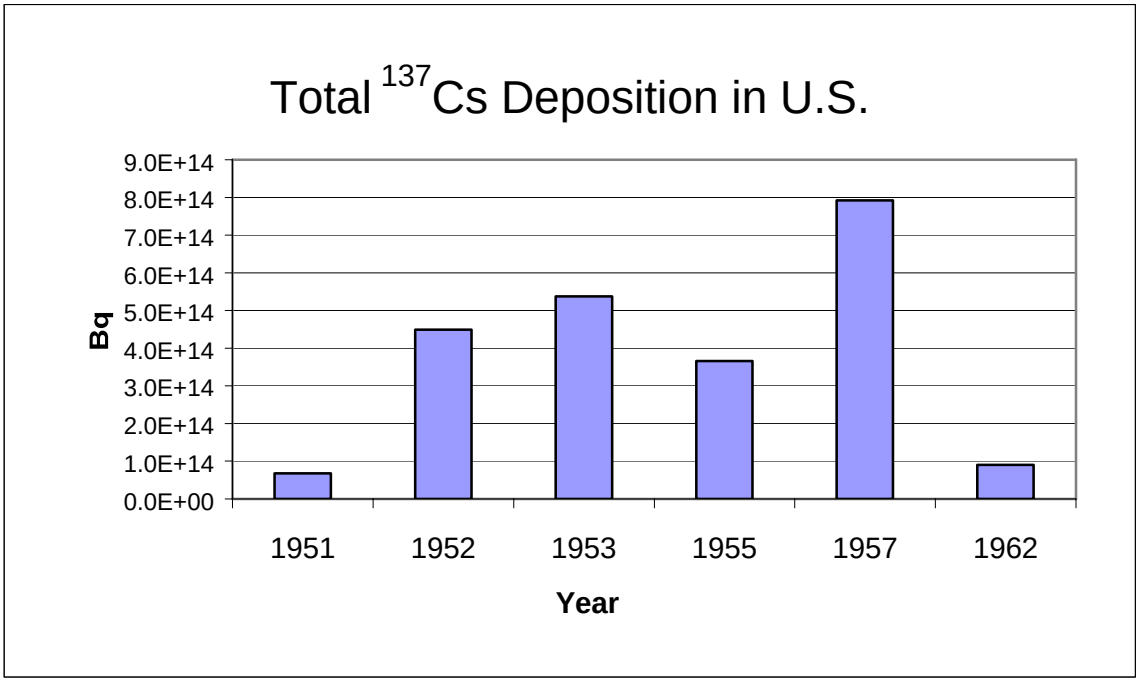

Figure 3.1. Total ^{137}Cs (Bq) deposited in the United States from NTS tests as a function of year of tests

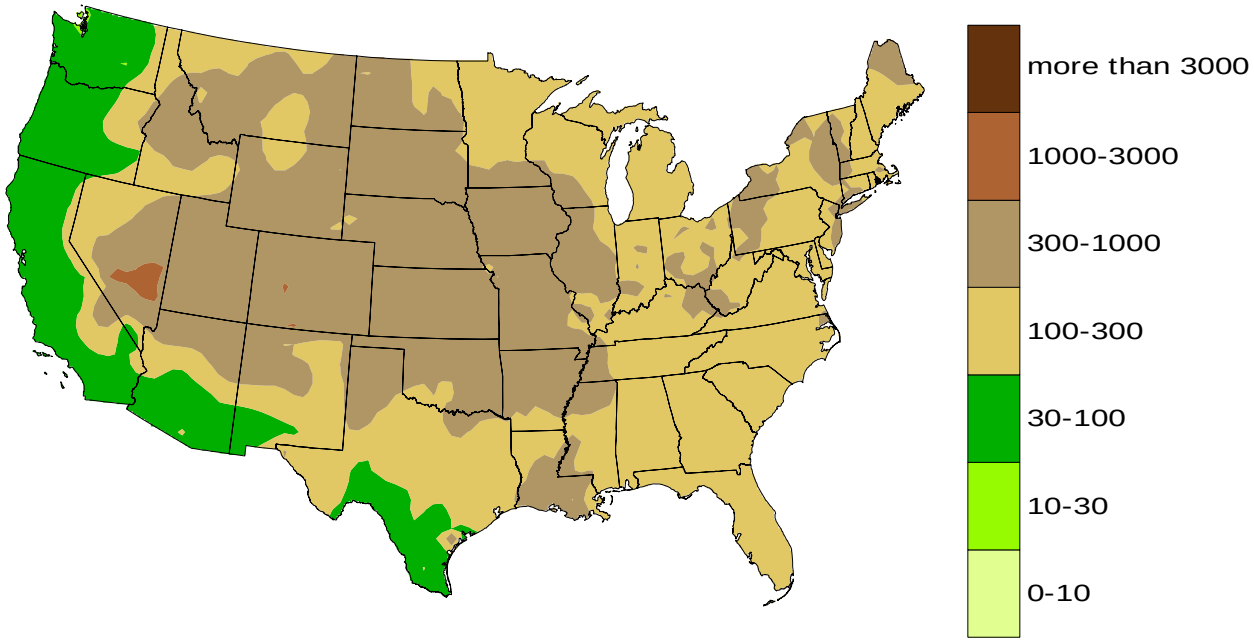

Figure 3.2. Cesium-137 deposition density (Bq/m^2) due to all NTS tests.

The geographic patterns of the overall deposition density due to all NTS tests for certain fallout radionuclides like ^{90}Sr (Figure 3.3) and $^{239+240}$Pu (Figure 3.4) vary somewhat

from those for ^{137}Cs and ^{131}I primarily due to the differences in the nuclear fuel used in different tests, the size of the particles associated with the radionuclides, and the directions of travel of the clouds of radioactive particles from each test. The overall deposition of ^{90}Sr was very similar to that of ^{137}Cs. The highest overall plutonium deposition density was in counties near the NTS because of the association of plutonium with larger particles, though other moderately high deposition densities can be seen in a few Midwest counties. For most of the country, the activity of ^{137}Cs was 10 to 20 times the activity of $^{239+240}$Pu deposited. As discussed previously, the plutonium estimates in this report for any particular county are very uncertain, and the data provided should be viewed only as illustrative of the variations across the country due to the varying paths of fallout clouds.

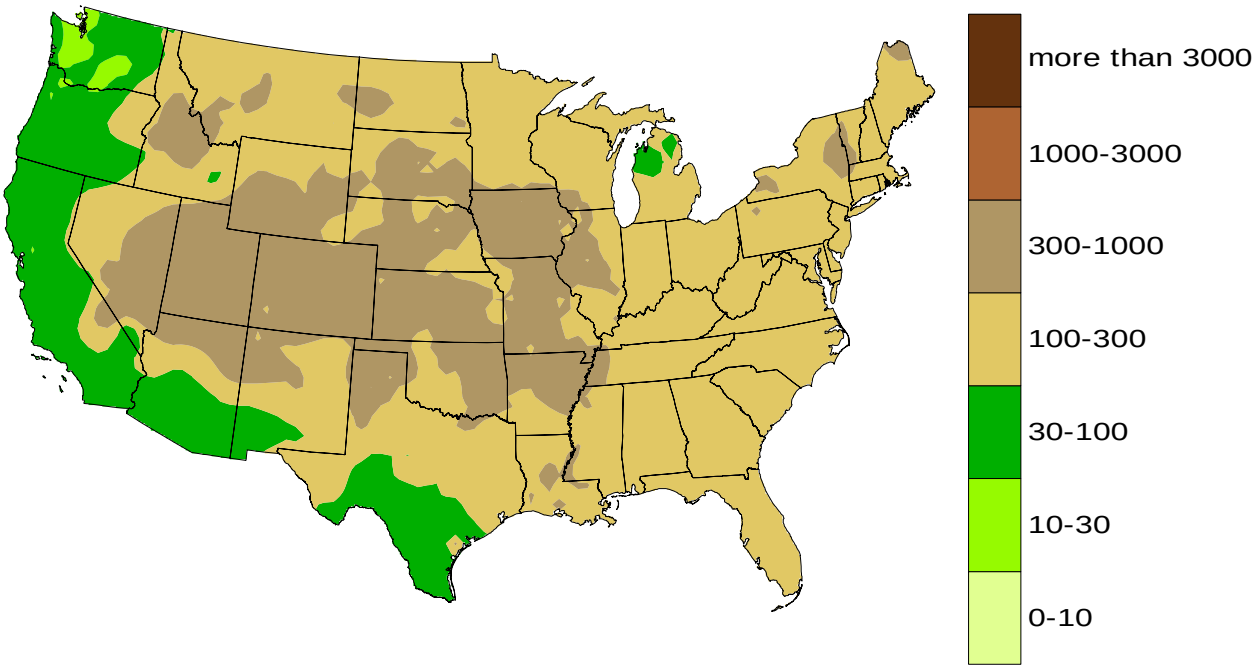

Figure 3.3. Strontium-90 deposition density (Bq/m^2) due to all NTS tests.

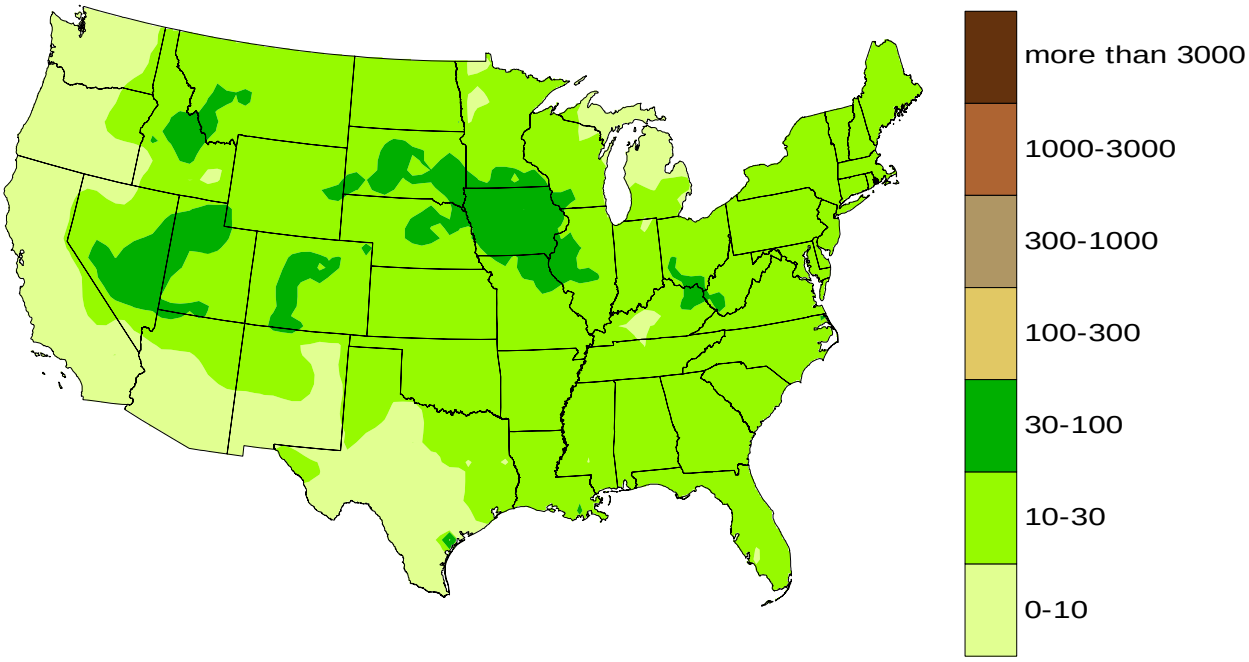

Figure 3.4. Plutonium (239+240) deposition density (Bq/m^2) due to all NTS tests.

The six test main series which took place in 1951, 1952, 1953, 1955, 1957, and 1962, deposited different amounts of fallout within the United States. For example, the 1957 Plumbbob series deposited 35% of the total cesium followed by the 1953 Upshot-Knothole series that contributed 23%. These proportions are shown in Figure 3.5.

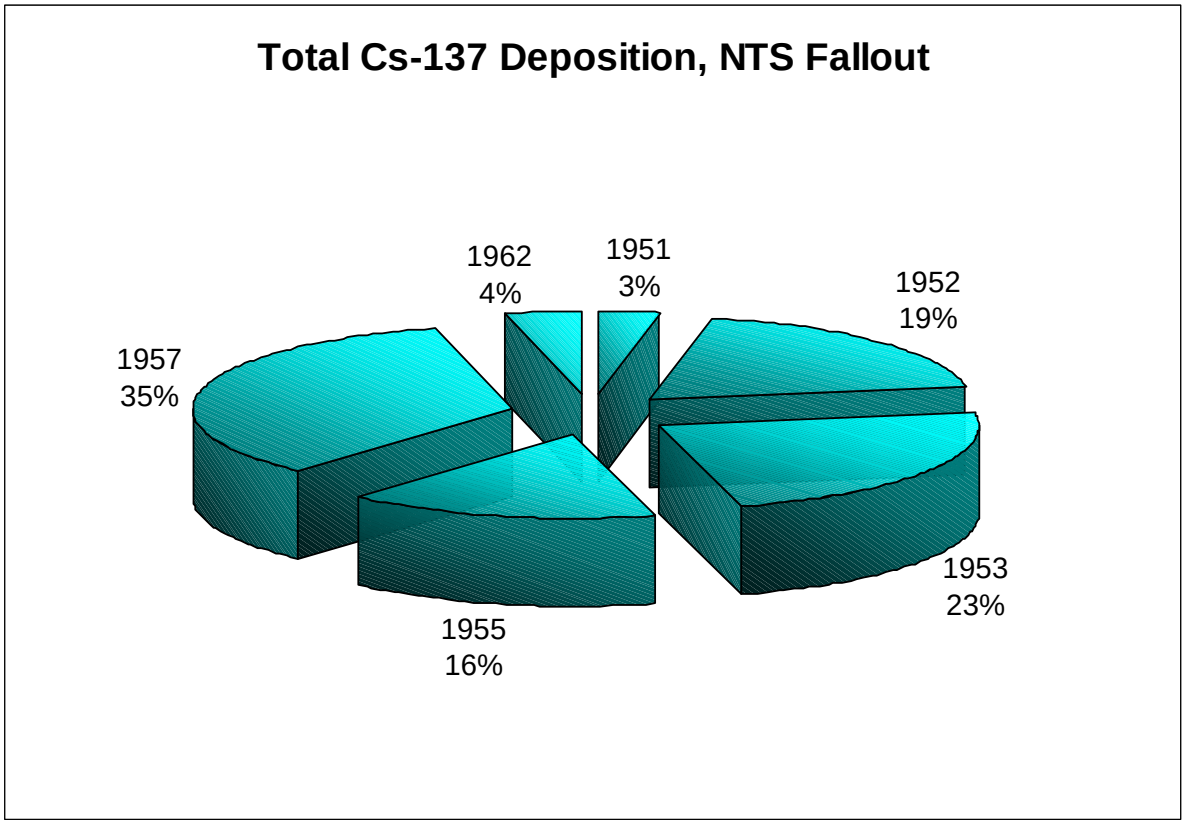

Figure 3.5. Estimated fractions of total ^{137}Cs deposited in the United States from NTS by year of test.

The total activity of ^{137}Cs deposited in the contiguous United States from all tests was estimated to be 2.3 PBq. The total deposition for a number of other selected radionuclides is shown in Table 3.3. The population-weighted deposition densities, i.e., the overall deposition densities estimated by weighting each county's value by the proportion of the country's population in that county, are also presented in Table 3.3. Because of the sharp gradations in deposition density from west to east, and the higher populations in the eastern United States, the population-weighted deposition densities are slightly less than the actual deposition densities. However, the population-weighted values give a better indication of the relative health impacts that might be expected. From all NTS tests, 34% of the ^{137}Cs produced was deposited in the contiguous United States and the remainder was deposited elsewhere; presumably, a large fraction was deposited in the oceans. Similar proportions would apply to other radionuclides with similar half-lives and physical and chemical properties.

Table 3.3. Total deposition and population-weighted mean deposition density for selected radionuclides for NTS fallout.

Nuclide	Total Deposition (PBq)*	Population weighted deposition density (Bq m^{-2})
^{137}Cs	2.3	260
^{90}Sr	1.8	200
^{95}Zr	220	2.5×10^4
^{103}Ru	430	4.6×10^4
^{140}Ba	1400	1.4×10^5
^{141}Ce	500	5.4×10^4
^{144}Ce	40	4.6×10^3
^{106}Ru	24	2.6×10^3
^{89}Sr	330	3.6×10^4
^{131}I	1500	1.9×10^5
$^{239+240}Pu$	0.13	~16
^{241}Pu	0.54	~59

*PBq = 10^{15} Bq

3.1.1 NTS External Exposure and Dose

Radiation received externally to the body from fallout is primarily a result of the gamma radiation emitted by radionuclides deposited on the ground. External exposure generally results in a radiation dose to the entire body and is usually considered to be uniform over the body, particularly when fallout is widespread in the environment. The calculation of radiation dose is often made through intermediate calculations of the amount of ionization of a volume of air, formally called exposure and measured in Roentgens (R). The absorbed dose in specific organs or tissues of the body is expressed in units of Gray (Gy). The effective dose, expressed in Sievert (Sv), is a weighted whole-body dose, in which the differences in damage caused by different types of radiation and radiosensitivity of the different tissues or organs of the body are taken into account. The calculation steps from deposition density (Bq m^{-2}) to exposure (R) to absorbed dose in tissues or organs (Gy), and to effective dose (Sv) are described in Appendix E.

The doses presented in this report are primarily based on measurements or estimates of radionuclide deposition densities, isotopic ratios calculated for each test by Hicks (1981), and various conversion factors. Very few actual measurements of exposure were made outside the immediate vicinity of the NTS. However, the external dose resulting from emitted gamma rays from individual radionuclides in surface soil is well understood. Hence, theory and available data can be used to predict the exposure or the dose that the public might have received across the United States. It should be understood, however, that

in those cases where little data are available, particularly concerning the lifestyles of individuals and the rate of penetration of radionuclides into the soil at any particular location, doses can only be estimated with very limited precision.

For states immediately downwind from the NTS, available data, including actual exposure rate measurements where available, were used to estimate deposition densities (Beck and Anspaugh 1991; Beck 1996). NCI (1997) used these data and data from gummed-film measurements to estimate ^{131}I deposition densities for each county of the contiguous United States. The NTS deposition densities in this report are based directly on the estimates of ^{131}I deposition density reported in NCI (1997). The conversion factors relating deposition density to exposure rate in air, while specifically applicable to idealized flat surfaces, have been validated in many studies and are believed to be accurate to within 5% (NCRP 1999) for those surface conditions.

A large number of fission products are produced in a nuclear explosion. However, only a few account for most of the external exposure. Different radionuclides contribute significantly to the exposure rate at different times and thus the relative importance of the various radionuclides with respect to total exposure varies according to the length of time for the fallout to arrive at the location where exposure took place. At early arrival times after each test (within a few hours), the short-lived iodine isotopes contribute substantially to the exposure while after a few days, ^{132}Te, ^{132}I, ^{140}Ba, ^{95}Zr-^{95}Nb and ^{103}Ru are more important.

The dose, whether external or internal, is often expressed by what is called effective dose (ICRP 1991), a quantity that is likely to correlate well with the occurrence of cancer (total of all types) arising as a result of the exposure of the whole body. Specifically, the effective dose is the sum of organ doses weighted by two factors, one to account for the quality and type of radiation and one to account for the relative radiosensitivity of specific organs or tissues such that:

$$E(i) = \sum_T w_T \sum_R w_R D_{T,R}(i)$$

Equation **Error! No text of**

where:

E(i) = effective dose from radionuclide *i* (Sv),

w_R = radiation weighting factor for radiation type R,

w_T = weighting factor for body tissue T, and

$D_{T,R}(i)$ = absorbed dose in tissue T from radiation emitted by radionuclide *i* (Gy).

Values of the radiation weighting factor are taken to be 1.0 for electrons, x-rays and gamma rays, between 5 and 20 for neutrons of various energies, and 20 for alpha particles (ICRP 1991). The radiation weighting factor adjusts the absorbed dose (simply the energy absorbed per mass of tissue) to better reflect the probability of damage by the type of radiation exposing the body. The fission products emit electrons, x-rays, and gamma rays,

so that their radiation weighting factors are equal to 1.0. The plutonium isotopes emit alpha particles; therefore, their radiation-weighting factors are equal to 20 in the case of internal irradiation when the alpha particles are immersed in the organ or body tissues. In the case of external irradiation, the alpha particles do not penetrate the clothes or the surface dead layer of the skin and, therefore, do not deliver a dose. The small external dose delivered by the plutonium isotopes is only due to the accompanying gamma and x-rays, for which the radiation weighting factor is taken to be equal to 1.0.

The tissue weighting factors reflect the radiosensitivity of different organs, and are chosen so that a uniform dose over the whole body gives an effective dose numerically equal to the uniform whole-body dose. The International Commission on Radiological Protection has recommended values for the radiation- and tissue-weighting factors (ICRP 1991). The conversion from exposure to effective dose is about 0.0066 Sv R^{-1} for the range of gamma energies usually encountered in fallout and for adults. Calculations using computer models of the human body indicate that the effective dose to young children is about 10-30% higher (NCRP 1999) than for adults. In order to simplify the feasibility calculations, two assumptions were made in the estimates presented here: (1) the external dose to organs like the thyroid and bone marrow were taken to be numerically equal to the effective dose, and (2) external doses were assumed to be age-independent. The first of these assumptions results from the fact that the external doses to most tissues and organs are about the same, primarily because the gamma rays emitted from many radionuclides are energetic enough to completely penetrate the body. Hence, it is justified to make an approximation that the effective dose (Sv) is numerically equal to the absorbed dose (Gy) for most organs.

Radionuclides deposited on the ground penetrate into the soil with passing time, a process usually accelerated by rainfall. Hence, after a few months, measurements have shown that external exposure decreases because of the radionuclide's penetration into the ground, as well as the fact that radionuclides decay with the passage of time, leaving less and less activity to expose people.

The dose received by individuals depends on the time they spent outdoors while the fallout was on the ground. Because most people spend most of their time indoors, their exposure is reduced greatly due to the inability of the radiation to effectively penetrate building materials. The amount of shielding provided by a building depends on the materials and design of the building. In general, heavily constructed buildings made of brick or concrete will allow only about 20% of the radiation to penetrate, while lightly constructed buildings will allow 40% or more. Assuming that most persons spend about 80% of their time indoors (UNSCEAR 1993; NCRP 1999) in a building that transmits about 30% of the radiation from the outside, their effective dose would be about 44% (0.8 x 0.3 + 0.2 = 0.44) of that that would be received outdoors. Using similar assumptions, the dose to persons of various occupations and lifestyles can be estimated.

The doses from external irradiation were calculated for each radionuclide listed in Table 3.2, for each county of the contiguous United States, and for each test listed in Table 3.1. The total doses from external irradiation for the population of a given county was then obtained by summing over all radionuclides and all tests. Details of the calculations are provided in Appendix E. A number of maps provided show the geographic distribution of

external dose. Figure 3.6 shows the external dose from all NTS tests, and applies equally to red bone marrow and the thyroid gland, both in adults and children. The most exposed individuals likely lived in states immediately downwind from the NTS. However, smaller areas of higher and lower exposures occurred throughout the United States as a result of the uneven deposition of fallout over the United States and the variation in directions taken by the clouds containing the radioactive fallout. Residents of some counties near the NTS received doses in excess of 3 mSv (300 mrem) while residents of the extreme western and northwestern states and some midwestern counties received average doses less than 0.25 mSv (25 mrem).

The actual dose to a person who lived in the United States during the years of fallout would generally lie within a range from about one-quarter as large as the estimates provided here to several times larger than these estimates. In some cases, the range of possible doses at a single location might even be larger. This wide range is a result of the variations in the amount of time people spent outdoors and the types of structures individuals lived and worked in.

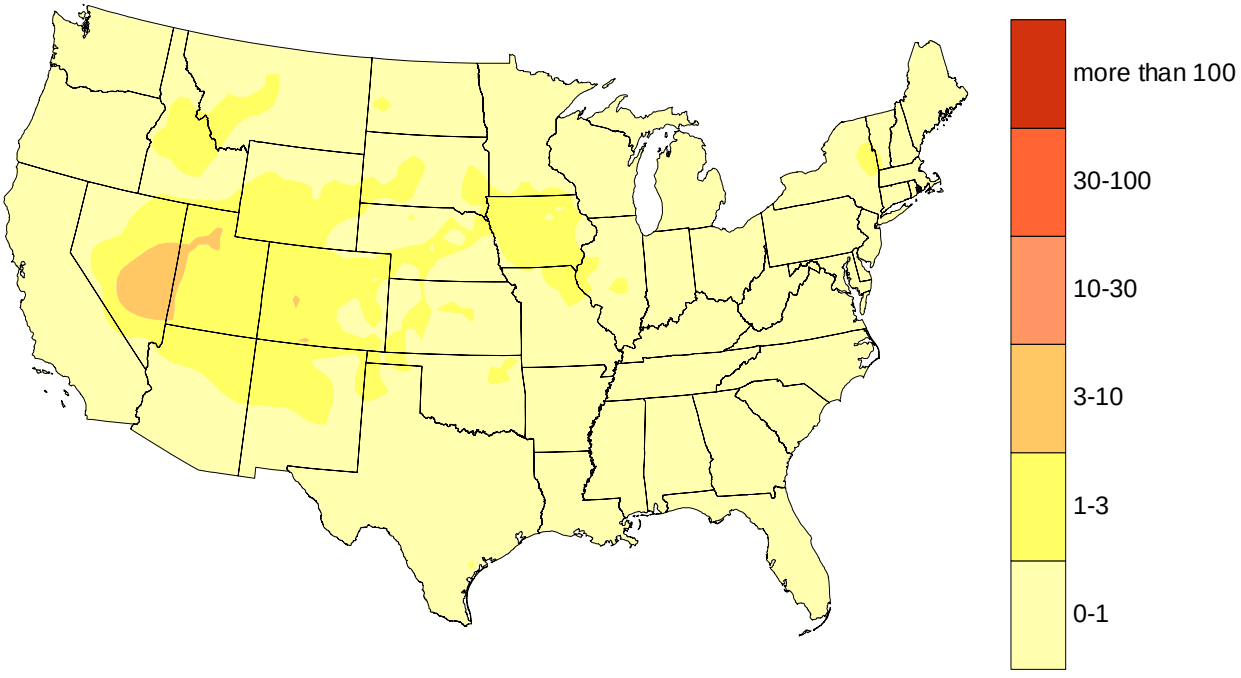

Figure 3.6. External dose (mGy) to the red bone marrow and the thyroid gland for both children and adults resulting from all NTS tests.

It should be clearly understood that the numerical values of dose provided in Figure 3.6 and in the remainder of this chapter are estimates for a typical individual living in the specified county. How close the doses provided here are to the actual dose received by a person living there depends on many factors; primarily, how similar the assumptions in the calculations are to an individual's lifestyle over the time the exposure was received. There are many factors about each individual member of the public – such as age and lifestyle for external exposure and diet for internal exposure – that might result in his or her exposure being different than the estimates provided in this report. Though there are statistical and mathematical methods available that can be used to estimate the range of doses in each county, applying these methods requires a great deal of literature review, expert judgment, and mathematical calculations. Assessment of the range of possible doses that might have been received in each county and/or the assessment of the precision of dose estimates for typical individuals are subject areas that will require additional work in future assessments of fallout-related doses.

The calculation of the collective doses from external irradiation resulting from each year when test series were conducted allows for an estimate of the relative contribution of each year of testing to the total dose. Results are presented in Table 3.4. Because most of the external dose is due to short-lived radionuclides, the external dose from each year of testing at the NTS was essentially received during the same year. The most important years of testing were 1957 (Plumbbob series) and 1953 (Upshot-Knothole series). The population-weighted exposure corresponds to an average effective dose of about 0.5 mSv during the years of testing, about what a person would receive annually from natural gamma radiation emitted from the minerals in the soil (UNSCEAR 2000).

Beta radiation from fission products in the surface soil resulted in an additional dose to the skin when outdoors. However, this contribution was not large enough to be considered an important component of total fallout radiation exposure except perhaps for children who played in the soil for very long lengths of time.

Table 3.4. Collective external dose and country-average dose from NTS fallout as a function of year of testing

Year	Test Series	Cumulative Collective Dose (10^3 Person-Gy)	Country-Average Dose (mGy)
1951	Ranger and Buster-Jangle	6.8	0.039
1952	Tumbler-Snapper	16	0.093
1953	Upshot-Knothole	20	0.12
1955	Teapot	13	0.072
1957	Plumbbob	23	0.12
1962	Storax	5.0	0.029
Total NTS		~84	~0.5

3.1.2 NTS Internal Dose

The method of calculation for internal dose was derived from that used for the Off-Site Radiation Exposure and Review Project (ORERP), which was performed during the time period of approximately 1979 through 1987 (Church et al. 1990). The ORERP study was designed to calculate external and internal doses from the tests of nuclear weapons at the NTS, but the focus was on populations living in the near downwind regions. Originally, the assessment area consisted of several counties in Nevada and one county in Utah that were known to have received higher deposition densities. Eventually, the assessment domain was expanded to include the entire states of Nevada, Utah, Arizona, and New Mexico, and portions of several additional states (western Colorado, southwestern Wyoming, southern Idaho, southeastern Oregon, and nearby areas of California, including Los Angeles).

The general ORERP method is described here because its models and findings were used for these feasibility calculations. Further detail on these methods is provided in Appendix F. That method includes:

- Estimating the total amount of an individual radionuclide that might be ingested by persons of differing ages. This simple statement covers a very complex undertaking of estimating the dynamics of radionuclide contamination of foods and age-dependent human-consumption rates of food (Whicker and Kirchner 1987).

- Estimating the dose at each age that would be received by a person from the ingestion of a single unit of activity of a particular radionuclide.

The formulation developed by the ORERP project, in simple form, can be expressed by the following equation:

$$D = P \times I \times F_g$$

Equation **Error! No text of specified style in**

where

D = Absorbed dose, Gy, or effective dose, Sv;

P = Deposition density of the radionuclide of interest at time of fallout arrival, Bq m^{-2};

I = Integrated intake by ingestion of the radionuclide per unit deposition density, Bq per Bq m^{-2}; and

F_g = Ingestion dose coefficient for the radionuclide, Gy Bq^{-1} or Sv Bq^{-1}.

Doses from internal irradiation resulting from ingestion of contaminated foodstuffs were derived from the deposition density estimates obtained for 61 tests, 43 radionuclides, and within each county of the contiguous United States (see Table 3.2). In a first step of the feasibility calculations, the radionuclide concentrations in important foodstuffs (milk, meat, leafy vegetables, root vegetables, and grain products) were estimated by means of

mathematically based environmental transfer models. Age-dependent consumption rates of foodstuffs (see Table 3.5) were used with estimates of the average value of the fraction of foods produced locally (see Figures 3.7 and 3.8) to estimate the radionuclide activities ingested with the contaminated foodstuffs. Finally, mathematical models simulating the behavior of radionuclides in the gastrointestinal tract, uptake of radionuclides by the gastrointestinal tract, and the subsequent absorption and retention of radionuclides in the various organs and tissues of the body were used to estimate the thyroid and bone marrow doses received by persons who were adults in 1951 and for persons who were born in 1951.

Table 3.5. Food-consumption rates used in the PATHWAY code (Whicker and Kirchner 1987). Estimates are based primarily on data summarized by Rupp (1980) for rural families.

Food Type	Food Consumption Rates By Age Group, Fresh kg day^{-1}			
	<1 y	1–11 y	12–18 y	>19 y
Milk	0.800	0.623	0.635	0.360
Milk products	0.144	0.074	0.143	0.062
Beef	0.044	0.113	0.210	0.277
Poultry	0.003	0.017	0.028	0.030
Eggs	0.017	0.026	0.036	0.053
Leafy vegetables	0.002	0.021	0.036	0.062
Stored fruits and vegetables	0.207	0.266	0.356	0.360
Grains	0.025	0.025	0.151	0.137

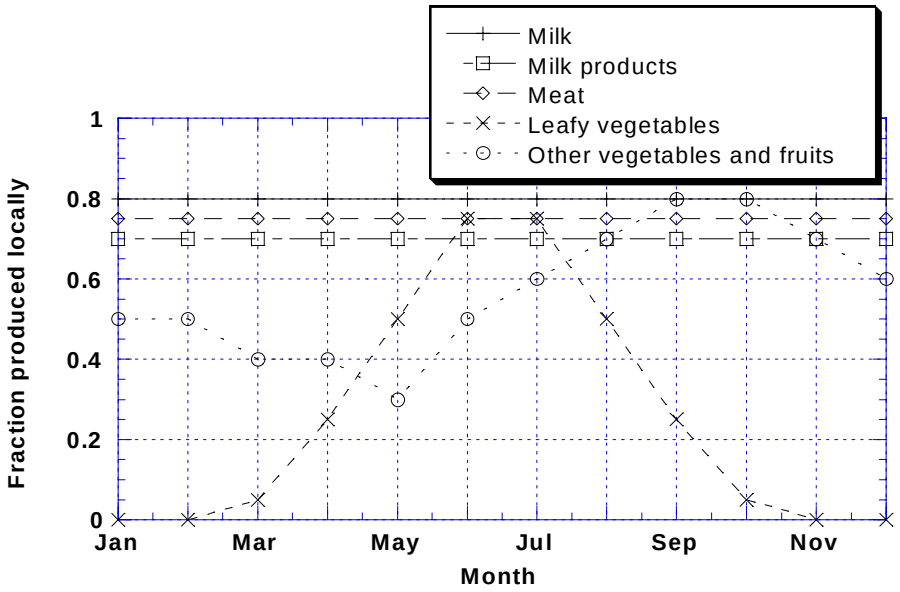

Figure 3.7. Fraction of food that is assumed to be locally produced for several different food categories. Values for eggs are the same as those for milk. From Whicker and Kirchner (1987).

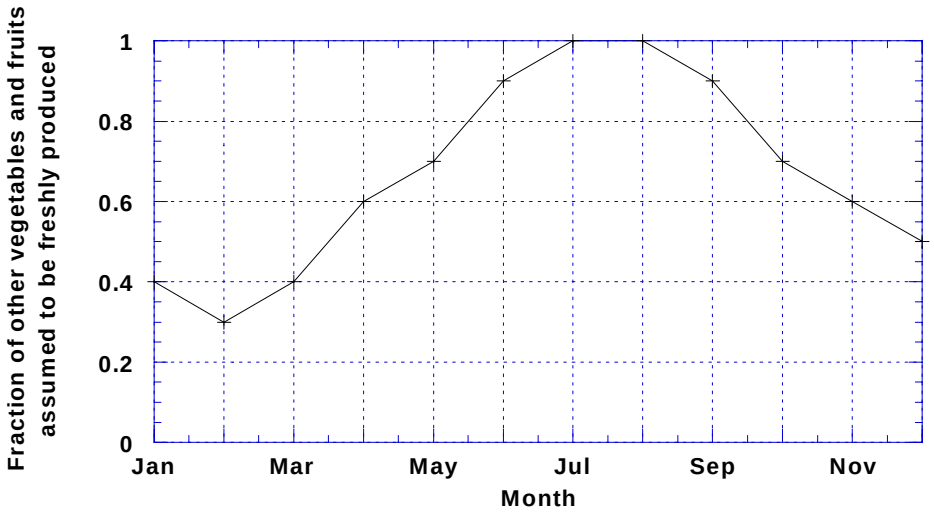

Figure 3.8. Consumed fraction of non-leafy vegetables and fruits assumed to be freshly produced. From Whicker and Kirchner (1987).

Radionuclides of Interest. Ingestion doses were calculated from nineteen of the most important radionuclides contributing to internal dose: ^{89}Sr, ^{90}Sr, ^{91}Sr, ^{97}Zr, ^{99}Mo, ^{103}Ru, ^{105}Ru, ^{106}Ru, ^{131}I, ^{132}Te, ^{133}I, ^{136}Cs, ^{137}Cs, ^{140}Ba, ^{143}Ce, ^{144}Ce, ^{147}Nd, $^{239+240}$Pu, and ^{241}Pu (see Table 3.2). The ORERP findings indicated that this group of radionuclides accounts for over 90% of the internal dose in the vicinity of the NTS as a result of ingestion of contaminated foods.

In addition to the list of parent radionuclides listed above, doses from decay products were also included in the calculation to the extent that the decay product arises from the decay of the parent radionuclide after it has entered the body. For example, the decay product of ^{132}Te is ^{132}I, which has a half-life of 2.30 h (ICRP 1983). Any ^{132}I that originates in the body from the decay of ^{132}Te is included in the dose calculation. Other parent-progeny pairs are ^{90}Sr (^{90}Y), ^{97}Zr (^{97}Nb), ^{103}Ru (^{103m}Rh), ^{106}Ru (^{106}Rh), ^{137}Cs (^{137m}Ba), ^{140}Ba (^{140}La), and ^{144}Ce (^{144}Pr).

Age Groups Considered. The detailed calculations of dose were performed only for adults in this feasibility study. This choice was necessitated by the limited time resources available for this study and because adults constitute by far the largest segment of the population. Doses to children born in 1951 were roughly estimated on the basis of the computed doses for adults. In the case of thyroid doses (such as from exposure to ^{131}I), age differences result in dramatically different doses with children receiving larger doses. This age-dependence has been treated extensively by the NCI (1997).

Estimates of Cumulative Intake. For the radionuclides listed above, seasonally dependent values of the intake of each radionuclide were estimated from output of the computer code, PATHWAY, developed as part of the ORERP project. That program

mathematically accounts for the ecological behavior of radionuclides by considering the initial retention of fallout by vegetation, the loss of radionuclides from vegetation, dilution of radionuclide concentration in fresh vegetation by plant growth, uptake of radionuclides through the soil-root system, and recontamination of plant surfaces by resuspension, redeposition, and rain splash. As expected, the intake of many radionuclides by the public would have occurred in the early summer months when garden and farm food production would have been highest. In Figures 3.9 to 3.11, the annual pattern of intake over the course of a year is shown for three radionuclides (^{90}Sr, ^{131}I, and ^{137}Cs) and four age categories (<1 y, 1-11y, 12-18y, and adults).

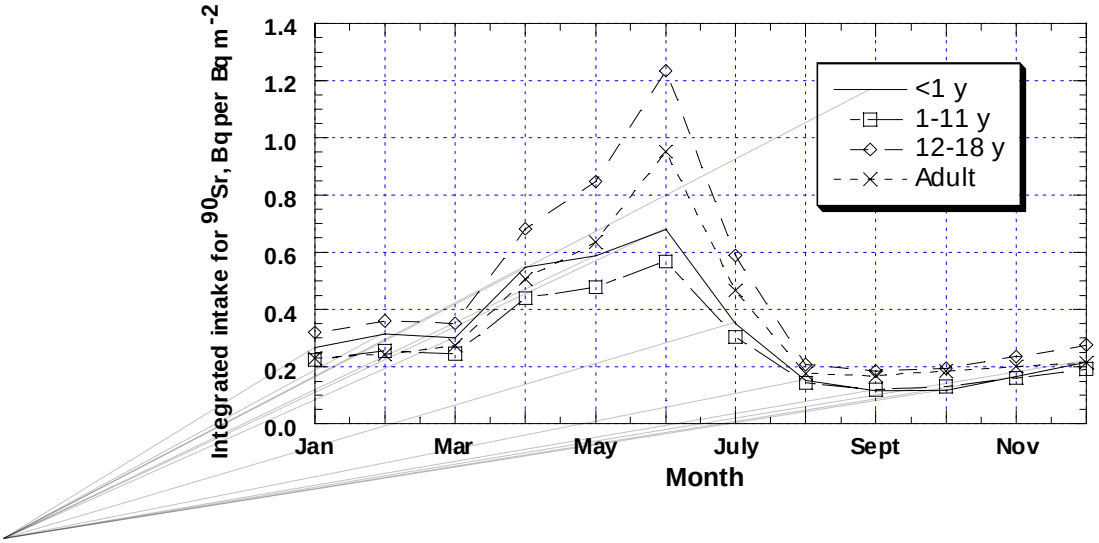

Figure 3.9. Monthly values of integrated intake for four age groups for ^{90}Sr. Data were derived from Whicker and Kirchner (1987).

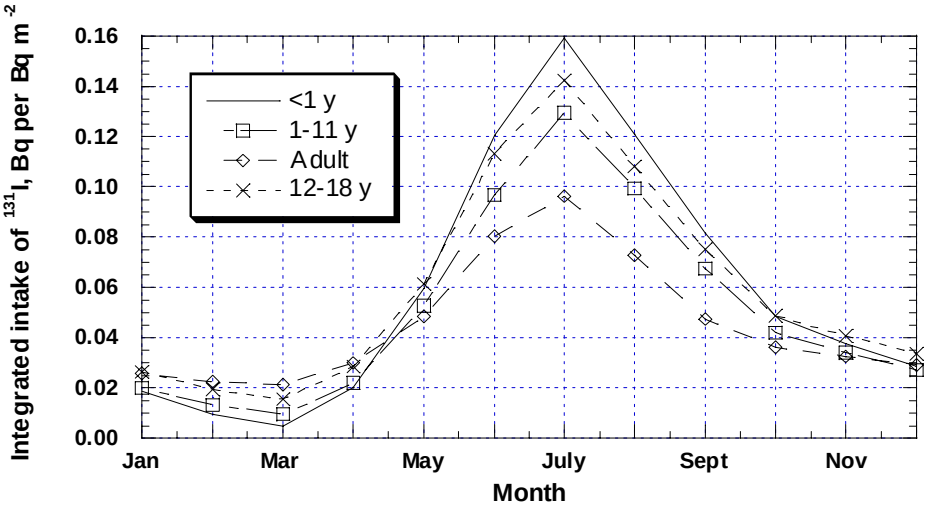

Figure 3.10. Monthly values of integrated intake for four age groups for ^{131}I. Data were derived from Whicker and Kirchner (1987).

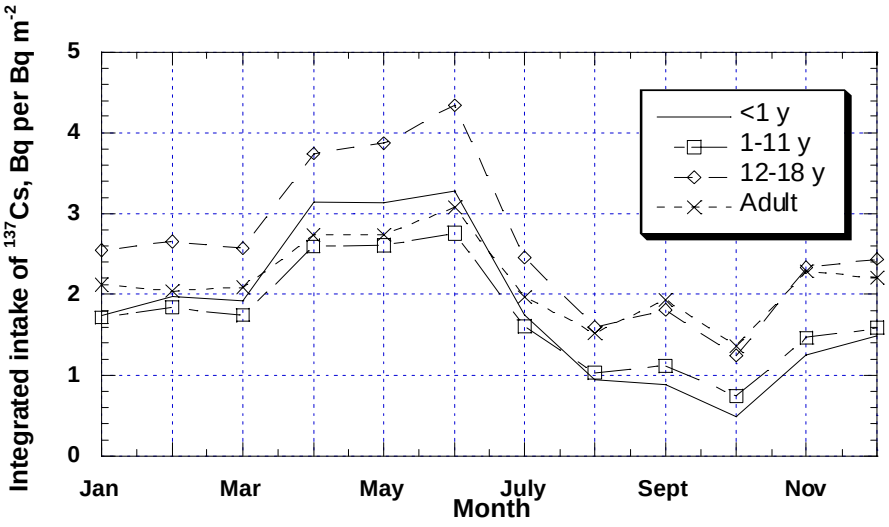

Figure 3.11. Monthly values of integrated intake for four age groups for ^{137}Cs. Data were derived from Whicker and Kirchner (1987).

It should be noted that the model PATHWAY used to derive the integrated intakes (Figures 3.9 through 3.11) was developed to simulate the transfer of radionuclides to foodstuffs in areas close to the Nevada Test Site. The model was used in this feasibility report primarily for illustrative purposes, as it is recognized that parameter values used by the program are not strictly applicable to other regions of the United States where precipitation patterns and agricultural practices differ substantially from those encountered in areas close to the NTS.

One of the critical factors that is known to vary substantially at different locations is the initial retention of fallout by fresh vegetation, particularly when deposition occurs with precipitation. Some increase in the precision of predicted doses might be achieved if county-by-county estimates of rainfall for each day following each shot were retrieved from National Weather Service records and used to adjust the calculated retention of fallout on plants, as was done in NCI (1997) for the dose from ^{131}I. That effort was beyond the scope of the present feasibility study, though could be a part of any future work.

Dose Coefficients. The ICRP-tabulated values are the source of dose coefficients used for these dose calculations. Recently, the ICRP (1998) has made available a system that allows the calculation of absorbed and effective doses for all organs for the six age groups considered by the ICRP (<3 months, 1 year, 5 year, 10 year, 15 year, adult). The dose coefficients provided by the ICRP represent the dose from a given intake that will occur over the next 50 years for adults, or until age 70 y for the younger age groups. In this feasibility report, doses are calculated through the year 2000, corresponding roughly to the period 50 years following the intake. The ICRP dose coefficients are applicable to that situation with very little approximation because the doses from most radionuclides taken into the body are delivered within the first year after the intake.

Organs of Interest. In principle, doses can be calculated for the 22 organs considered by the ICRP and for which dose coefficients are available (ICRP 1998). However, experience from ORERP (Ng et al. 1990) is that only the thyroid gland would likely receive a higher dose from the ingestion of NTS fallout compared to the dose received from external exposure to the same fallout. Hence, doses (and risks described in a later chapter) to two organs are emphasized: (1) red bone marrow, because of its role as a blood forming organ in which leukemia can arise, and (2) the thyroid, in which thyroid cancer and other diseases can be induced.

Periods of Exposure. For each county (or part of a county) and for each radionuclide, the cumulative dose was calculated through the year 2000 for the depositions resulting from tests that took place in the years of 1951, 1952, 1953, 1955, 1957, or 1962 (see Table 3.1).

NTS Internal Dose. In addition to absorbed doses to thyroid and red bone marrow, effective doses have also been calculated. The calculated internal doses from the 19 radionuclides considered are summarized for each county by year of test (1951, 1952, 1953, 1955, 1957, and 1962) and for all NTS tests together. Multiplying the average dose for each county by the estimated 1954 population and summing over all counties in the country calculated estimates of collective dose to the entire contiguous United States. Some internal dose was estimated to have been received in every county considered.

The highest estimate of cumulative internal effective dose from NTS fallout (1.8 mSv) was for Nye County, Nevada, and the lowest (0.010 mSv) in Wahkiakum County, Washington. The counties receiving greatest internal dose from NTS fallout were in general in Nevada and in Utah due to their close proximity to the NTS and because they were generally downwind from the test site, while the counties receiving the lowest internal dose were in the Pacific Northwest, primarily Washington and Oregon. Though the 3,000+ counties could be ranked according to the magnitude of the estimated dose, the precision of the feasibility calculations is not great enough to make quantitative distinctions about differences in dose among counties. The maps provided are only an indicator of the general geographic distribution of dose over the United States. Figure 3.12 presents estimated internal dose to red bone marrow for persons born 1 January 1951 while Figure 3.13 presents estimated internal dose to the thyroid for persons born 1 January 1951. County-specific thyroid dose estimates for persons born 1 January 1951 range from <0.1 mGy in less than 10 counties to as high as 300 mGy over 550 counties. Those estimates assume average milk consumption. In general, thyroid doses for persons who were adults in 1951 are a factor of about five times lower.

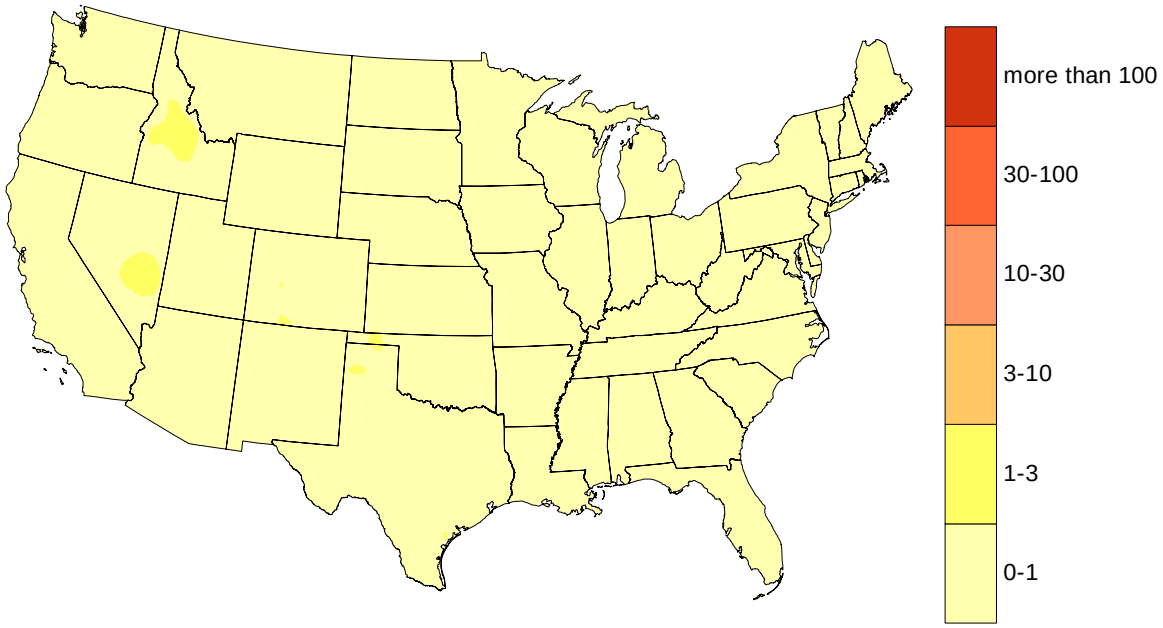

Figure 3.12. Internal dose (mGy) to red bone marrow of persons born 1 January 1951 from all NTS tests.

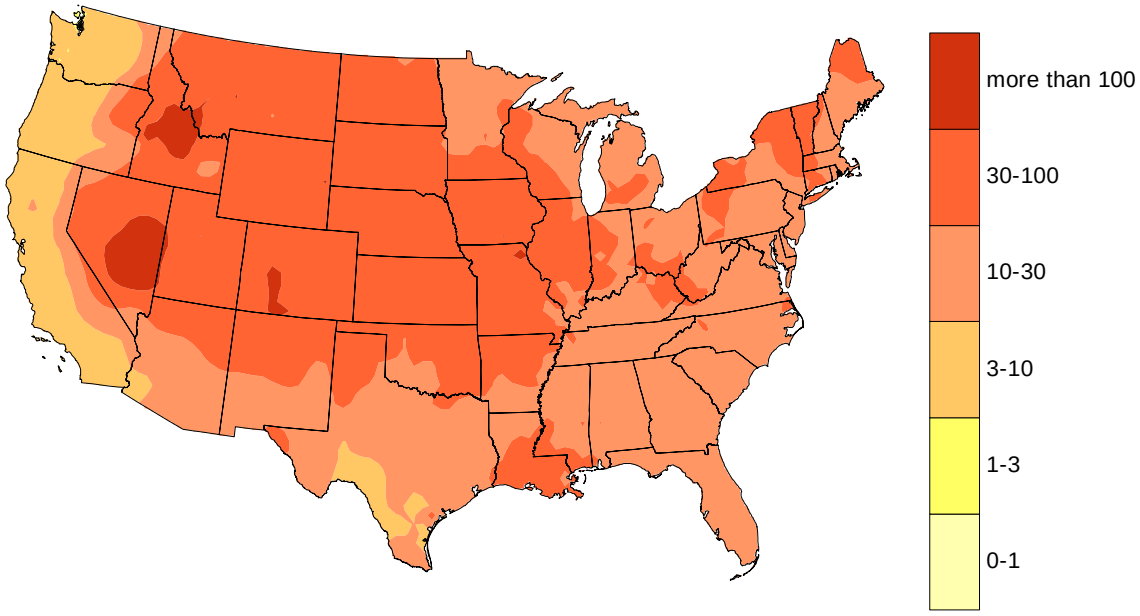

Figure 3.13. Internal dose (mGy) to the thyroid of persons born 1 January 1951 from all NTS tests.

The population-weighted bone marrow and thyroid doses from all NTS tests are summarized in Table 3.6. It should be noted that the values of thyroid dose in Table 3.6 are dominated by the dose from ^{131}I.

Table 3.6. Population-weighted red marrow and thyroid doses from all NTS tests (mGy).

Population subgroup	Organ Dose (mGy)	
	Red marrow	Thyroid
Persons born in 1951	0.12	30
Adults in 1951	0.1	5

Population-Weighted Effective Dose by Year of Testing. The population-weighted (adult) internal effective doses by year of testing are shown in Table 3.7. The highest contribution occurred in 1957 from the 16 explosions of Operation Plumbbob. The second and third larger yearly contributions were 1952, as a result of the eight events of Operation Tumbler-Snapper, and 1953, as a result of the 11 events of Operation Upshot-Knothole. A surprisingly large contribution is attributed to the two explosions that occurred in 1962 during Operation Storax; almost all of the latter was due to Project SEDAN, a large cratering experiment. As noted earlier, the intake of radionuclides through foodstuffs varies by time of year (see Figures 3.9 through 3.11). Because a large number of tests in 1957 took place in high food production months June through August (see Table 3.1), that year contributed more than twice the ingestion dose of any other year.

Table 3.7. Population-weighted (adult) effective dose from ingestion, calculated through year 2000, specified by year of testing.

Year of Testing	Effective Dose from Ingestion (mSv)
1951	0.012
1952	0.063
1953	0.049
1955	0.037
1957	0.13
1962	0.041
Total	0.33

Population-Weighted Effective Dose by Nuclear Test. The population-weighted (adult) effective doses (through the year 2000) for the 16 tests contributing the largest doses are presented in Table 3.8. Project SEDAN surprisingly heads this list. However, it should be noted that the precision on the doses from Project SEDAN is low and the values could be overestimated by one or more orders of magnitude. A careful re-evaluation of the data used by NCI (1997) to estimate the fallout from this test will be necessary in any follow-up study. The unknown fission yield is one reason for the low precision, though the use of the meteorological model also added considerable uncertainty to the dose estimates. The reason that this test appears to be such a large contributor to the collective effective dose is that this event took place during a time of year when the intake function was at a maximum. The

other events listed in Table 3.8 are generally known to have been major contributors to off-site dose, and they also occurred primarily during the time of year when environmental transfer would have been high. Together, these 16 events account for 73% of the effective dose (to adults at time of exposure).

Table 3.8. Population-weighted (adult) effective dose from ingestion for the 16 nuclear explosions giving largest predicted doses.

Event (series, test)	Date	Effective Dose (mSv)
Storax SEDAN	6 July 1962	0.038*
Tumbler-Snapper GEORGE	1 June 1952	0.027
Plumbbob DIABLO	15 July 1957	0.025
Upshot-Knothole HARRY	19 May 1953	0.017
Plumbbob KEPLER-OWENS	24–25 July 1957	0.016
Plumbbob HOOD	5 July 1957	0.016
Tumbler-Snapper HOW	5 June 1952	0.013
Upshot-Knothole SIMON	25 April 1953	0.012
Plumbbob PRISCILLA	24 June 1957	0.012
Teapot ZUCCHINI	15 May 1955	0.010
Plumbbob GALILEO	2 September 1957	0.010
Teapot APPLE 2	5 May 1955	0.010
Tumbler-Snapper FOX	25 May 1952	0.0086
Plumbbob DOPPLER	23 August 1957	0.0086
Plumbbob WILSON	18 June 1957	0.0080
Buster CHARLIE	30 October 1951	0.0067

*Values for SEDAN have very low precision and should be re-evaluated in future work.

Population-Weighted (Adult) Effective Dose by Radionuclide. External and internal absorbed doses calculated in this report are listed in Table 3.9. The fifteen radionuclides listed in this table contributed more than 98% of the estimated effective dose. Iodine-131 alone accounts for 76% of the population-weighted (adult) effective dose. Of the ten most important radionuclides, only ^{90}Sr and ^{137}Cs are long-lived. Plutonium radionuclides, though long-lived, accounted for only 0.4% of the estimated total effective dose.

Table 3.9. Comparison of population-weighted (adult) external dose, internal red bone marrow and thyroid dose from all tests at the NTS according to radionuclide, calculated through the year 2000.

Radionuclide*	Half-Life	External Dose (mGy)*	Internal Dose to Thyroid (mGy)	Internal Dose to Red Bone Marrow (mGy)
^{89}Sr	50.5 days	-	0.001	0.03
^{90}Sr	28.8 years	-	-	0.02
^{95}Zr-^{95}Nb	64.0 days	0.08	-	-
^{97}Zr-^{97}Nb	16.7 hours	0.02	-	-
^{103}Ru	39.3 days	0.03	-	-
^{106}Ru	374 days	<<0.005	0.001	0.002
^{132}Te-^{132}I	3.2 days	0.1	0.06	0.001
^{131}I	8.02 days	0.02	5	0.001
^{133}I	0.9 days	0.02	0.04	-
^{135}I	20.8 hours	<0.01	-	-
^{136}Cs	13.2 days	-	0.002	0.002
^{137}Cs	30.1 years	0.01	0.009	0.009
^{140}Ba-^{140}La	12.8 days	0.2	-	0.006
^{144}Ce	285 days	<0.005	-	-
^{239}Np	2.36 days	0.02	-	-
Sum (rounded)		~0.5	5	~0.1

*These fifteen radionuclides account for more than 98% of the total dose from ingestion and external exposure.

Population-Weighted (Adult) Dose by Organ. Population-weighted (adult) doses from each radionuclide were calculated for each organ that had a dose coefficient more than twice that of the dose coefficient for effective dose. The population-weighted organ doses were calculated by using the organ doses whenever they were available; otherwise the effective dose for that radionuclide was added to the sum. This procedure is only approximate, but was used for this feasibility study in order to derive some estimate of the organs receiving the more significant doses.

Table 3.10 gives the population-weighted (adult) doses by organ and indicates that many organs, except for thyroid, had doses of similar magnitude. In terms of population health risk, those organs listed in Table 3.10 would be of greatest potential interest and concern.

Table 3.10. Estimates of population-weighted (adult) organ dose and effective dose from ingestion through the year 2000 from all NTS tests.

Organ	Organ Dose (mGy)	Fractional Contribution to Effective Dose
Liver	0.086	0.01
Red marrow	0.1	0.04
Bone surface	0.19	0.01
Colon	0.34	0.12
Thyroid	5.0	0.76
Remainder of soft tissues	0.032	0.06
Effective (mSv)	0.33	

About two thirds of the population-weighted cumulative dose to the bone surface was contributed by three radionuclides: ^{90}Sr, $^{239+240}$Pu, and ^{89}Sr in that order. For the colon, about three fourths of the dose was contributed by four radionuclides: ^{89}Sr, ^{140}Ba, ^{106}Ru, and ^{144}Ce in that order. It is also useful to note that these population-weighted organ doses have about the same magnitude as the dose received from external radiation, as inferred from Table 3.4.

The only organ that has received a substantially higher population-weighted dose from NTS fallout due to the ingestion of contaminated foods as compared to the dose from external exposure is the thyroid, which is estimated to have received a county-average dose about 10 times higher than that due to external exposure from NTS fallout.

Dose from Inhalation. For this feasibility study, doses from inhalation of radioactive particles and gases have not been estimated. The primary difficulty in making such estimates is that values of integrated air concentrations are not presently available. When the gummed-film network was being operated in the 1950s, substantial numbers of measurements were made of concentrations of radionuclides in air. If these measurements should be used in the future for calculations of dose from inhalation, it would be necessary to go through a similar process of interpolating the data between measurement stations, as well as considering rainfall, to produce estimates on a county-by-county basis.

Past experience indicates that dose from inhalation is much less important than the dose received from external exposure or the ingestion of contaminated foods. In general, dose due to inhalation only becomes of some importance for those radionuclides that have an extremely low rate of absorption across the gut wall, but remain in the lung for a long time when inhaled, e.g., $^{239+240}$Pu.

Equations and theory exist to calculate inhalation dose, however, little data are available. Hence, inhalation doses will always remain imprecise.

Comparison of Results with Those from NCI (1997). The National Cancer Institute report on exposure of the American people to ^{131}I (NCI 1997) presents the results of

a very detailed multi-year study of the dose to the thyroid for U.S. residents. A primary finding from that study was that the collective thyroid dose was 4,000,000 person-Gy, whereas this report estimated 2,000,000 person-Gy. This difference is primarily due to differences in modeling assumptions; nevertheless, such a level of agreement is considered to be good for retrospective dose estimates.

The doses estimated by NCI (1997) appear to be higher in Idaho, Montana, and the Midwest than from this feasibility study. Those differences most likely result from the different assumptions for the important factor describing the amount of fallout retained by vegetation. For this study a constant value was used, where NCI (1997) used a value that varied depending upon the amount of rainfall. This and related issues should be examined in more detail in any future assessment.

Sum of External and Internal Dose from NTS Fallout. The sum of the external and internal dose components is shown in a series of maps. Figures 3.14 and 3.15 show the sum of external and internal dose to the red bone marrow for adults and children, respectively. The geographic distribution of doses received is very similar for the two age categories. Figures 3.16 and 3.17 shows the sum of external and internal dose to the thyroid for adults and children, respectively. A comparison of these two maps shows that, in general, thyroid doses were much greater for children than for adults. Geographic areas where the highest thyroid doses were received included the counties nearby the NTS, a group in the northern Rocky Mountains, and a few isolated counties in Colorado and the Midwest. For both red bone marrow and thyroid, populations living in the vicinity of the NTS received the highest doses from NTS fallout, while populations living along the western and eastern coasts received the lowest doses.

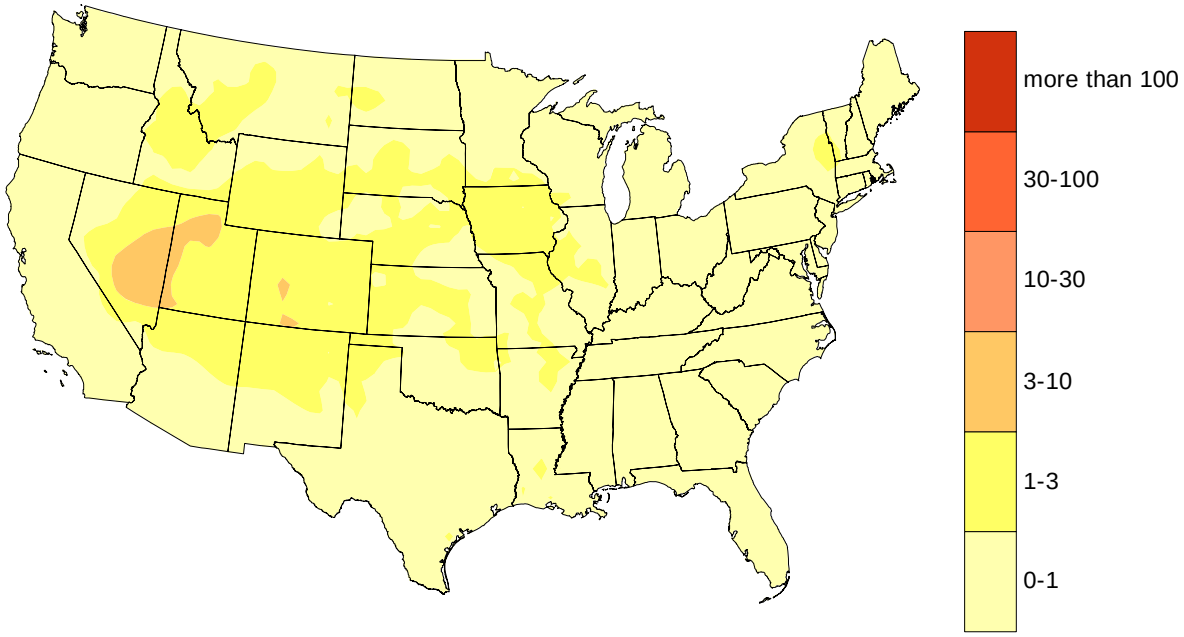

Figure 3.14. Total (external + internal) dose (mGy) to the red bone marrow of adults in 1951 from all NTS tests.

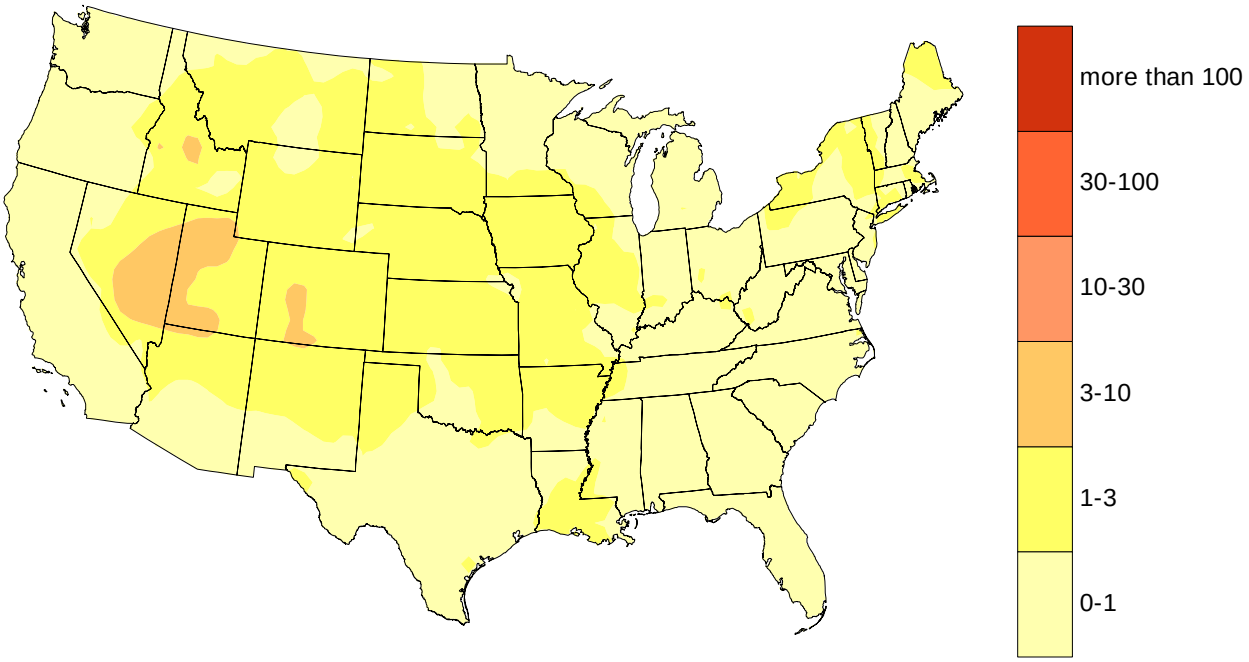

Figure 3.15. Total (external + internal) dose (mGy) to the red bone marrow of persons born on 1 January 1951 from all NTS tests.

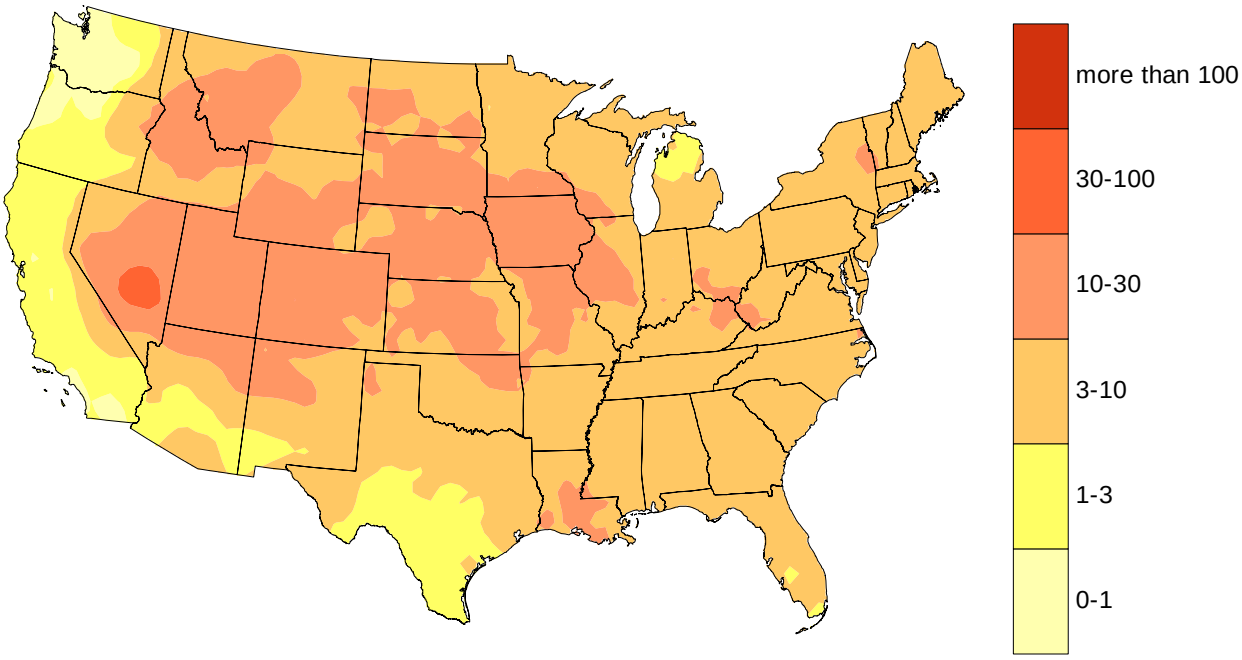

Figure 3.16. Total (external + internal) dose (mGy) to the thyroid of adults in 1951 from all NTS tests.

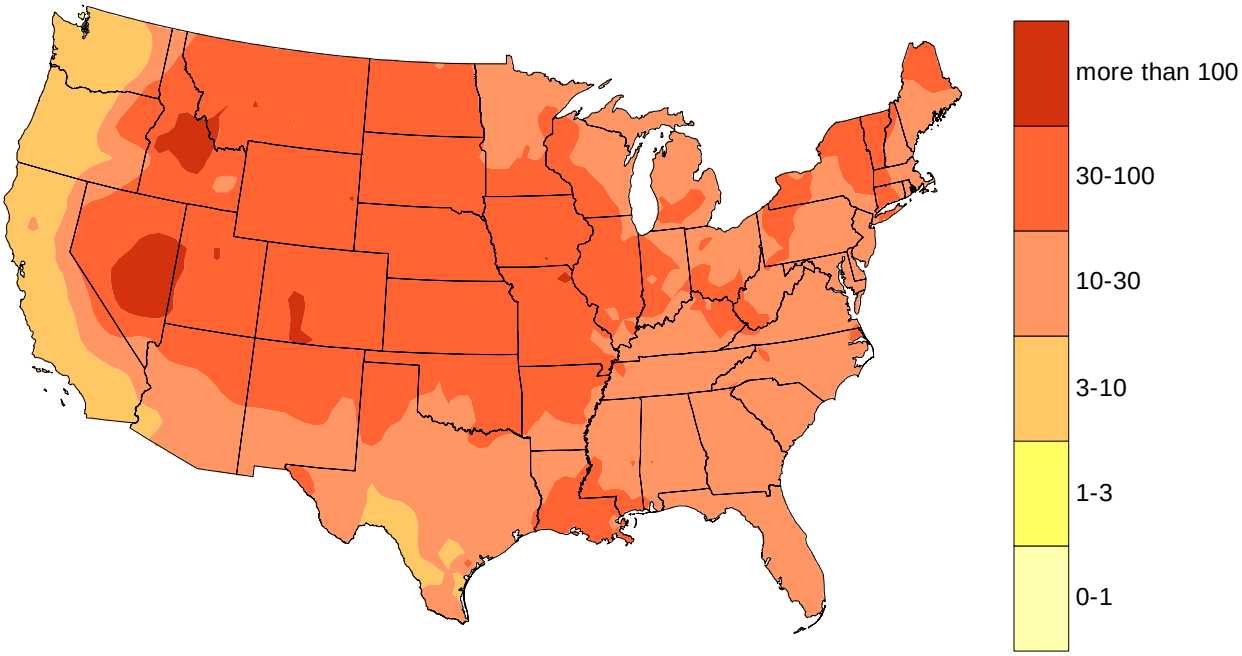

Figure 3.17. Total (external + internal) dose (mGy) to the thyroid of persons born on 1 January 1951 from all NTS tests.

3.1 Global Fallout

In the previous section, calculations of the external and internal dose to the population of the contiguous United States from NTS weapons tests were described. Other tests were conducted at a number of locations throughout the world and are referred to in this report as global nuclear tests that produced global fallout. As noted earlier, the mostly low-yield (<100 kt) weapons tests conducted at the NTS injected almost all of their debris into the lower atmosphere (troposphere) where it was deposited mostly within the contiguous United States. In contrast, the mostly high-yield (i.e., thermonuclear tests with yields greater than 1 Mt accounted for over 90% of the fission products produced) tests carried out by the United States, U.K. and U.S.S.R. in the Pacific and at various sites in the U.S.S.R. injected most of their debris into the stratosphere (UNSCEAR 1982, 1993). The total fission yield (see Table 3.11) of these tests, excluding the tests conducted by China and France, was about 170 Mt of which only about 1 Mt was from NTS tests. However, because of the long residence times for the transfer of air between the stratosphere and troposphere (on the order of 1 year), the fallout from these high-yield tests was relatively depleted of short-lived radionuclides. Thus the total deposition in the contiguous United States of short-lived radionuclides such as ^{131}I was considerably lower than that from NTS tests.

The estimated fission and fusion yields of nuclear weapons tests that were detonated in the northern hemisphere are indicated in Table 3.11 on a yearly basis. These values were derived from total yield values reported in UNSCEAR (1993), DOE (1994), and Mikhailov

et al. (1996). Explosions very close to the equator are conservatively considered to have taken place in the northern hemisphere.

Table 3.11. Estimates of Fission and Fusion Yields (Mt) by Year

Year	Fission Yield* (Mt)	Fusion Yield (Mt)
1952	6	5
1953	0.04	0.36
1954	31.1	17
1955	1	0.88
1956	9.6	13
1957	4.9	3.9
1958	27	31
1959	0	0
1960	0	0
1961	18	69
1962	72	99
Total	170	240

*For most tests, fission yields are estimated because some data remain classified. Assumptions are: tests smaller than 0.1 Mt total yield were assumed as 100% fission, tests in the range 0.5-5 Mt, fission were assumed to be 50% fission, tests in the range 0.1-0.5 Mt were assumed to be 67% fission.

The debris from the large tests conducted in the Pacific and in Russia was dispersed throughout the atmosphere, resulting in global fallout. This fallout was deposited in a relatively uniform pattern across the United States. The amounts of the longer-lived radionuclides, such as ^{137}Cs and ^{90}Sr were about 10-15 times those from NTS fallout. However, in this feasibility study, it was not possible to estimate the deposition density of ^{131}I from global fallout in individual counties with a reasonable degree of confidence.

While much of the fallout from NTS tests, particularly in areas close to the NTS, fell to the ground without any accompanying rainfall, most of the debris from global fallout was deposited by precipitation, which tended to effectively wash the debris from the lower altitudes after the material fell from high altitudes where it was originally transferred by the explosion. Thus, the deposition density of fallout in each county was closely related to the frequency and intensity of rain, particularly during the months when fission products were at their peak concentration in the lower atmosphere.

Though a huge body of literature exists regarding fallout from nuclear weapons tests, the only widespread continuous monitoring of fallout deposition was the global networks of gummed-film samplers and later precipitation collectors (stainless-steel pots and ion exchange columns) operated by the AEC's Health and Safety Laboratory (HASL) and the network of air sampling stations along the 80th meridian operated prior to 1963 by the Naval

Research Laboratory and after 1963 by HASL (Harley 1976; Lockhart et al. 1965). The Public Health Service monitored radioactivity in milk at a number of U.S. cities beginning in 1958 and also total beta-activity in air and precipitation at a number of U.S. sites beginning in 1957 (Rad. Health Data 1958; PHS 1958). A large amount of other scattered sources of data are available in reports by investigators at national laboratories, universities, and state and local agencies. The HASL, in conjunction with the Department of Agriculture, also carried out extensive soil sample surveys in 1956, 1958 and 1964-66 (Alexander et al. 1961; Meyer et al. 1968; Hardy et al. 1968). These soil data provide estimates of the geographical variation in the cumulative deposition density of long-lived radionuclides such as ^{137}Cs and ^{90}Sr. The HASL also carried out nationwide surveys of external exposure rate in 1962-64, using *in situ* gamma-ray spectrometry to identify the contribution of fallout to the total exposure rate in air (Beck et al. 1964, 1966; Lowder et al. 1964). These exposure rate measurements provide confirmation of the dose estimates in this report.

Due to widespread concern about global fallout and its effects beginning in the 1950s, scientists from many countries have been involved in numerous fallout-related studies. For example, concern about global fallout was one of the main reasons that led to the formation of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). That committee has studied global fallout over many years and has issued a number of assessments of the dose from global fallout with primary interest on calculating global averages of dose. The dose estimates provided by UNSCEAR (1993) will be compared to those estimated in this report.

3.1.1 Global Fallout Deposition Density

Global fallout, in general, originated from weapons that derive much of their yield from fusion reactions. These explosions, conducted by the United States and the U.S.S.R., but entirely outside the contiguous United States, produced large amounts of ^{3}H and the intense neutron flux also produced large amounts of ^{14}C through the irradiation of nitrogen in the atmosphere with high-energy neutrons. Though these two radionuclides are created and/or released mainly by fusion explosions, they are also created in the atmosphere by some naturally occurring processes. Because ^{3}H and ^{14}C enter their respective environmental pools and cycle in the environment according to their own chemical properties, they do not deposit in the same manner as do radionuclides associated with more insoluble fallout particles. Hence, the usual methods of calculating deposition density are not appropriate. In order to calculate the dose from ^{3}H and ^{14}C, it is necessary to estimate the amount of activity created per unit of fusion energy and to estimate the fusion yields as a function of time. Based on the combination of naturally occurring rates and measurements of the concentrations in components of the environment (including man), it has been possible to estimate the dose per unit release of ^{3}H or ^{14}C using the specific activity approach (UNSCEAR 1993).

When considering the transport of the radioactive debris around the world, it is known that there is little movement of radionuclides across the hemispherical boundary, so the fusion yield (see Table 3.11) in the northern hemisphere is of primary importance for this assessment. Most of the fusion tests took place in the northern hemisphere, but with a substantial number near the equator. The assumption is made here that the radioactivity

created by northern hemisphere fusion tests remained in the northern hemisphere. For global fallout, the mix of radionuclides of concern differs from that of NTS fallout for several reasons. The main reason is that global fallout by definition consists of radioactive debris that is globally dispersed due to its injection into the high atmosphere by the force of large explosions. Due to its high-altitude dispersion, over half of the global fallout typically does not return to earth for one or more years. During this time the short-lived fission products decay to very low levels and, except for unusual occurrences, the short-lived radionuclides of concern for NTS fallout are not of concern in the case of global fallout. Two radionuclides, ^{90}Sr and ^{137}Cs, however, have long half-lives (about 30 y each) and do not decay appreciably before they return to earth. These two radionuclides were studied extensively due to their widespread presence in global fallout.

On the basis of data provided by UNSCEAR (1993) on relative doses from individual radionuclides produced in the large nuclear devices, a set of radionuclides was selected for external and internal dose calculations in this study (see Table 3.12). The inclusion of ^{131}I on the list for internal dose may be surprising, as its half-life is only eight days. The appearance of ^{131}I in global fallout has tended to be sporadic, but contamination of milk in the United States from global fallout has been observed on a number of occasions (e.g., Dahl et al. 1963; Terrill et al. 1963). Possible mechanisms for these sporadic occurrences have been suggested by Machta (1963) and include the subsidence of large air masses contaminated with debris from U.S.S.R. tests at its Novaya Zemlya site near the Arctic Circle, and the penetration of large thunderstorms into the upper troposphere and stratosphere that resulted in the scavenging of debris from the United States tests in the Pacific.

Monthly deposition densities were estimated for the radionuclides listed in Table 3.12. Plutonium deposition was only crudely estimated and relied on the fact that it is generally proportional to ^{90}Sr deposition (UNSCEAR 1993). The methods used to estimate the deposition density of the fallout radionuclides from global fallout used records of the average precipitation for each month in each county of the contiguous United States as well as available radionuclide deposition density data and results of soil analyses. Details of the procedures that were followed are found in Appendix G.

Monthly precipitation has been measured at over 8,000 National Weather Service cooperative monitoring sites, and data are available for most sites beginning about the year 1900. For the feasibility study, an estimate of monthly precipitation was obtained for each county for each month from 1953-1972 by averaging the available reported monthly data for that county. There are many possible errors in estimating a monthly precipitation value, including whether the average data at the monitoring stations are representative of the entire county or where most of the people resided.

Table 3.12. Radionuclides deposited in global fallout for which deposition densities and doses were calculated.

Radionuclide	Half-Life	Used in External Global Fallout Dose Calculations	Used in Internal Global Fallout Dose Calculations
^{3}H	12.3 y		x
^{14}C	5700 y		x
^{54}Mn	312 d	x	
^{90}Sr,^{90}Y[a]	28.8 y	x	x
^{95}Zr	64.0 d	x	
^{95}Nb	35.0 d	x	
^{103}Ru, ^{103m}Rh[a]	39.3 d	x	
^{106}Ru, ^{106}Rh[a]	374 d	x	
^{125}Sb	2.76 y	x	
^{131}I	8.02 d	x	x[b]
^{137}Cs	30.1 y	x	x
^{140}Ba, ^{140}La[a]	12.8 d	x	
^{141}Ce	32.5 d	x	
^{144}Ce, ^{144}Pr[a]	285 d	x	
$^{239+240}Pu$	24,100y/ 6560 y		

[a]In equilibrium with parent radionuclide
[b]Population weighted dose only (not county-specific)

The most important radionuclide deposition density data that are available for global fallout are the monthly ^{90}Sr deposition density measurements reported by the HASL for about 30 sites across the United States (HASL 1958-72, USERDA 1977). The number of monitoring sites varied from year to year with the maximum number in operation during 1962-1965. Little or no data exist for years prior to 1958. In a separate program, the HASL monitored total deposition of beta-emitters at about 50 sites from 1952 through 1960 using gummed film (see Beck 1999, Beck et al. 1990). However, only the data for limited periods of time following the NTS tests have been reevaluated, and thus the data useful for estimating global fallout were unavailable for use in this analysis.

In order to estimate the deposition density of ^{90}Sr in each county of the contiguous United States on a monthly basis, it was assumed that the deposition density in any particular county was proportional to the precipitation that occurred in that county during that month. Since the deposition density per cm of precipitation has been shown to vary significantly with latitude and longitude (see Appendix G), it was necessary to develop a model describing this variation.

It should be noted that this crude model for deposition density of global fallout does not account for deposition under dry weather conditions. This is generally not a large error, as the fallout under such conditions was probably less than 10% of the total deposition. The impact of not accounting for dry deposition is most significant for the more arid regions of the United States. This model as well as other details could be improved in future efforts. Although the model used to estimate the ^{90}Sr deposition density is fairly crude, a comparison with the available data for a number of sites where sufficient data are available indicates that the agreement is fairly good (see Appendix G).

As for NTS fallout, all calculations for global fallout were carried out separately for each county in the contiguous United States, though estimates have not been made for the states of Hawaii and Alaska. Specifics of those two states, e.g., geography, location relative to test sites, limited measurement data, etc., put calculations for them beyond the limits of the feasibility study, though doses for these states could be addressed in future work.

Only two radionuclides were monitored fairly continuously for global fallout, ^{90}Sr, and for fewer sites and times, ^{89}Sr. The reason for this was that ^{90}Sr at that time was considered to be the most significant health hazard from global fallout due to its incorporation in bone following ingestion of contaminated foodstuffs and because of its long physical and biological half-life. Thus, other radionuclides were monitored infrequently and only at a few sites in the United States. Because short-lived nuclides such as ^{95}Zr-^{95}Nb and others listed in Table 3.12 contributed significantly to external exposure rates, it is necessary to estimate the deposition density of these nuclides as well in order to estimate the exposure of the United States population to external gamma radiation.

Because of the sparseness of available environmental measurement data on deposition of global fallout, a mathematical model which describes the global circulation patterns that control the dispersion of fallout was used to estimate the activity ratios of various nuclides to ^{90}Sr deposition for periods when no data were available (Bennett 1978). The model predicts quite well the variation of ^{90}Sr deposition over time (UNSCEAR 1982). However, the estimates of the deposition density of the shorter-lived nuclides such as ^{131}I are much less precise because of the very small number of environmental measurement data that could be used to calibrate the model. The deposition density of each of the radionuclides listed in Table 3.12 was estimated for each county and month by multiplying the estimated ^{90}Sr deposition density for that county and month by the ratios of isotopes estimated for each month. The estimates for the more important contributors to external dose, ^{95}Zr-^{95}Nb and ^{137}Cs are probably quite reasonable since (1) ^{95}Zr was measured in precipitation or air at several sites in 1958 and 1961-62 and ^{89}Sr was measured at a relatively large number of sites (HASL 1958-72), and (2) the activity ratio of ^{137}Cs to ^{90}Sr in fallout is relatively constant.

The monthly results for individual nuclides deposited from global fallout were summed to provide annual and cumulative estimates of deposition density for each county as well as used to derive population-weighted estimates for the contiguous United States. The total deposition of ^{137}Cs from global fallout during the years 1953 through 1972 is shown in Figure 3.18. In general, the lowest values of deposition density occur in the western, more arid United States. The area of the country from the Mississippi River to the eastern seaboard was relatively uniform in the amount of ^{137}Cs deposited by global fallout. Table

3.13 gives the calculated total deposition of each radionuclide and the population-weighted deposition density from global fallout (1953-1972), and compares these with the estimates for NTS fallout and estimates for the Northern Hemisphere from UNSCEAR (1993).

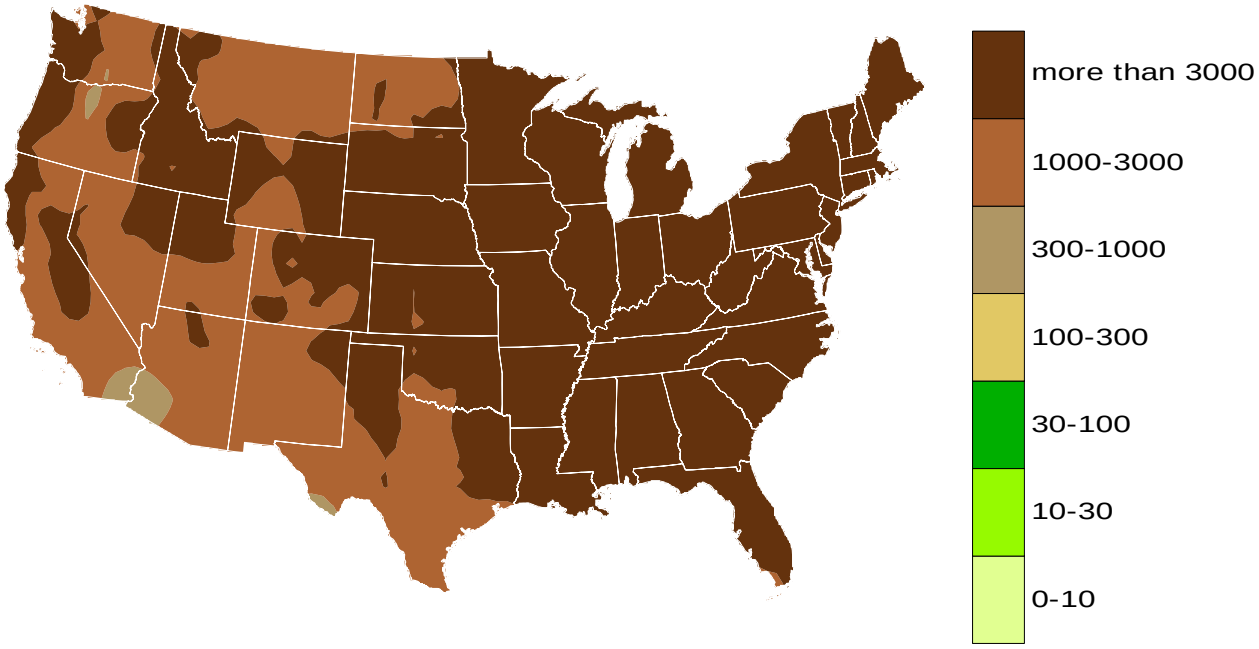

Figure 3.18. Cesium-137 deposition density (Bq/m^2) due to global fallout.

This table (3.13) shows that the deposition of long-lived radionuclides from global fallout is about a factor of 10-15 greater than that from NTS fallout. However, the total deposition of short-lived nuclides such as ^{131}I was much less for global fallout than for NTS fallout. In general, the deposition density of NTS fallout generally declined as the distance from NTS increased. The higher relative proportion of global fallout in the more populous (and wetter) eastern United States resulted in a relatively higher per capita exposure from global fallout.

Table 3.13. Total deposition and population-weighted deposition density of selected radionuclides for NTS fallout and global fallout (sorted by decreasing half-life).

		Total Deposition (10^{15} Bq)		Population weighted deposition density (kBq m^{-2})		
Nuclide	Half-life	NTS	Global	NTS	Global (this study)	Global*
$^{239+240}$Pu	24,100 y/ 6560 y	0.13	~0.4	~0.015	~0.06	0.06
^{137}Cs	30.1 y	2.3	29	0.26	4.4	5.2
^{90}Sr	28.8 y	1.8	19	0.11	2.9	3.2
^{106}Ru	374 d	24	150	2.6	24	24
^{144}Ce	285 d	40	300	4.6	46	48
^{95}Zr	64.0 d	220	310	25	50	38
^{89}Sr	50.5 d	330	210	36	35	20
^{103}Ru	39.3 d	430	210	46	35	28
^{95}Nb	35.0 d	0	400	0	65	64
^{141}Ce	32.5 d	500	210	54	34	21
^{140}Ba	12.8 d	1400	290	140	46	23
^{131}I	8.02 d	1500	110	190	18	19

*Only for the 40-50 degree latitude band (UNSCEAR 1993)

3.1.1 Global Fallout External Dose

The exposure rate in air was calculated as an intermediate step to estimating the dose to an exposed adult (see Appendix G). Doses were calculated from each radionuclide present in the soil as a result of the cumulative deposition density; those calculations used conversion factors from Beck (1980). The dose contributions from each radionuclide were summed to estimate the total monthly effective dose, the annual effective dose from external radiation, and the total effective dose for an individual resident in the same county throughout the period 1953-2000. Population-weighted (per capita) effective doses were also calculated by weighting the individual county estimates by the county population during the time of testing. As for external dose from NTS fallout, it was assumed that the absorbed dose to the red bone marrow and the thyroid (expressed in mGy) is numerically equal to the effective dose (expressed in mSv), and that there is no age dependency in the conversion factors from exposure rate to effective dose rate. The radionuclides that contributed most to both gamma and beta-particle exposures are identified.

The calculations that convert exposure rate to dose assumed the activity of all radionuclides was distributed shallowly in the soil for the first 20 days and then penetrated deeper (due to rainfall) during the next 200 days, with still deeper penetration at later times. These concepts are important to the calculations because as the activity washes to deeper

depths, the ground above it shields people to some extent from the gamma rays emitted by the radionuclides. The actual rate of penetration into the soil will, of course, vary from site to site depending on soil type, amount of precipitation, etc.

The geographic distribution of external dose from global fallout is shown in Figure 3.19. There was little variation across the United States; in general, external doses received were 1 mGy or less. This map pertains equally well for the dose to red bone marrow and to the thyroid gland, both in adults and in children.

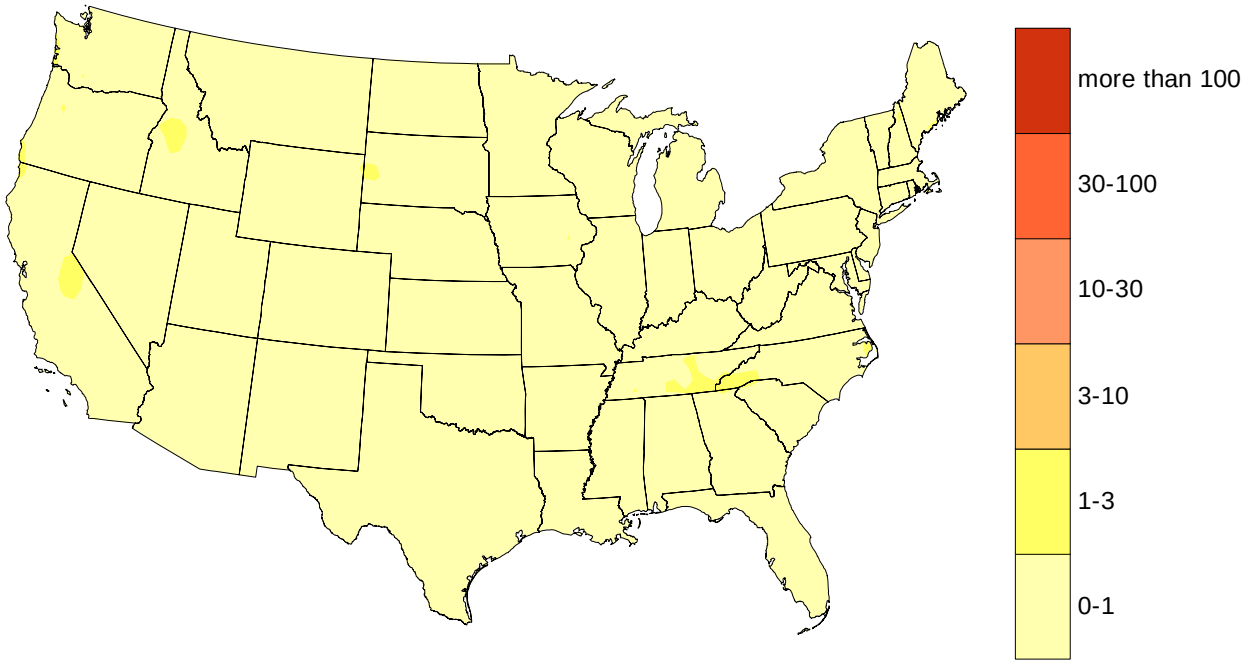

Figure 3.19. External dose (mGy) to the red bone marrow and the thyroid gland resulting from global fallout.

The collective dose delivered as a function of time was investigated by calculating the collective dose for each county (the product of the average dose for a given county multiplied by its population) and then summing over all counties. The annual collective dose versus year of exposure is given in Table 3.14. The population-weighted (per capita dose) dose is also shown. Corresponding estimates for NTS fallout are provided for comparison. Table 3.14. Collective dose and population-weighted external dose versus year of exposure

	Global Fallout		NTS Fallout[a]	
Year	Collective Dose (10^3 person-Gy)	Population-weighted Dose (mGy)	Collective Dose (10^3 person-Gy)	Population-weighted Dose (mGy)
1951			6.5	0.039
1952			15	0.093
1953	1.1	0.007	19	0.12
1954	2.8	0.017	0.2[b]	0.001[b]
1955	1	0.006	12	0.072
1956	4.1	0.025	0.1[b]	0.001[b]
1957	4.9	0.03	20	0.12
1958	6.8	0.042	0.8[b]	0.005[b]
1959	7.7	0.047		
1960	1.6	0.01		
1961	3.3	0.02		
1962	14.5	0.089	4.7[c]	0.029
1963	12.6	0.077		
1964	5.9	0.036		
1965	3.7	0.023		
1966	3.0	0.019		
1967	2.4	0.015		
1968	2.3	0.014		
1969	2.1	0.013		
1970	2	0.012		
1971	1.8	0.011		
1972	1.8	0.011		
1973-2000	34.4	0.211	0.33 (1963-2000)	0.0028
Total	119.8	0.74	79	~0.5

[a]Based on 1954 United States population of 1.63×10^8
[b]From previous years fallout.
[c]Value is imprecise (Test SEDAN)

From Table 3.14, it can be seen that the collective effective dose and the population-weighted dose from global external radiation through the year 2000 were about 50% higher than those from NTS fallout. The population-weighted effective dose from global fallout was estimated to be 0.74 mGy. UNSCEAR (1993) estimated a population-weighted dose from global fallout in the latitude band 40-50 degrees to be about 1 mGy. Considering the variations in fallout with latitude discussed earlier in this report, the present dose estimates

and the UNSCEAR estimate agree well. The highest annual per capita doses occurred in 1962 and 1963 and are comparable to the annual per capita doses from NTS fallout in 1952, 1953, 1955 and 1957. In fact, the collective dose from global fallout through 1972 was comparable to that from the NTS for the same period.

As noted earlier, a large number of fission products are produced in a nuclear explosion; however, only a relatively few account for most of the external dose. Table 3.15 shows the radionuclides in global fallout that are the largest contributors to lifetime exposure. The percentages from each radionuclide vary only slightly with location but vary significantly from year to year, as shown in Figure 3.20. Figure 3.21 shows the population-weighted dose that resulted from each radionuclide and the total as a function of time. The short-lived radionuclides have been grouped. As can be seen, during periods of testing the shorter-lived isotopes contribute relatively more to the dose, while for years with no testing the longer-lived radionuclides are dominant. In contrast to the doses from NTS fallout, very short-lived radionuclides such as ^{132}Te-^{132}I and ^{131}I were insignificant contributors to exposure rates while ^{95}Zr-^{95}Nb accounted for a large portion of the exposure. Most of the cumulative dose from global fallout was due to ^{95}Zr-^{95}Nb and the longer-lived nuclides. Cesium-137 and ^{95}Zr-^{95}Nb accounted for about 70% of the cumulative population exposure (see Table 3.15). In contrast, ^{137}Cs contributed only a small amount (about 2%) of the total dose from NTS fallout.

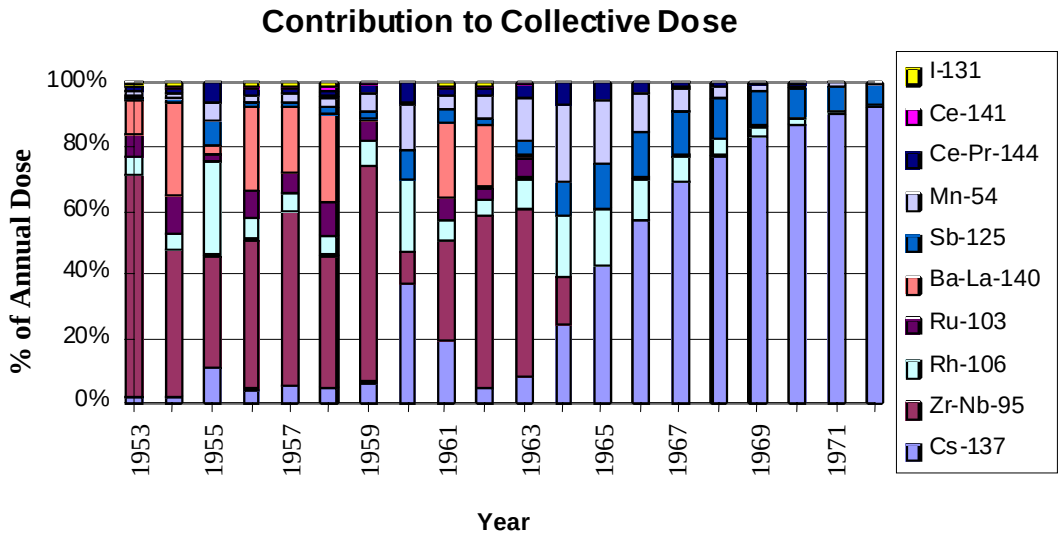

Figure 3.20. Contribution to external exposure from global fallout from individual radionuclides as a function of year.

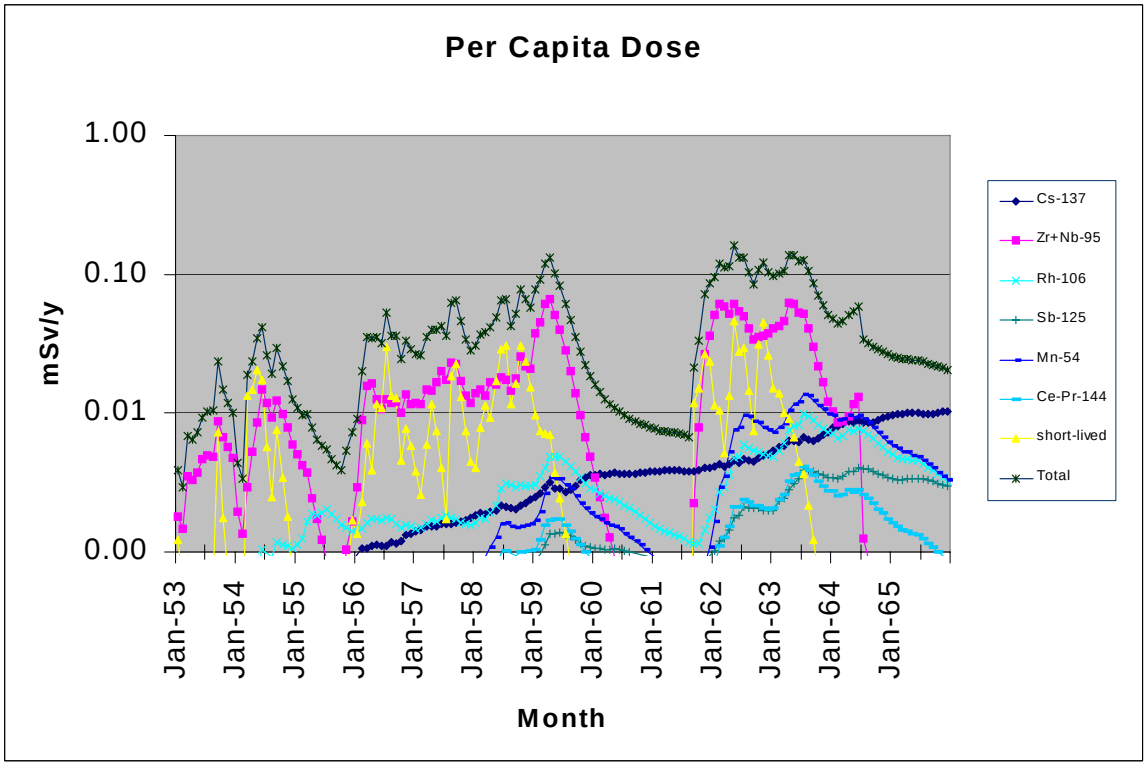

Figure 3.21. Time-dependence of external dose (population-weighted or per capita) from global fallout from individual radionuclides and as sum total.

Table 3.15. Percentage of external dose contributed by various fission products from global and NTS fallout.

Nuclide	Global fallout (1953-2000) (%)	NTS (%)
^{54}Mn	6	0
^{95}Zr-Nb	26	16
$^{97, 97m}$ Zr-Nb	<<1	4
^{103}Ru	3	6
^{106}Ru	6	<<1
^{125}Sb	4	<<1
^{131}I	<1	4
^{132}Te-I	<1	22
^{133}I	<<1	4
^{135}I	<<1	3
^{137}Cs	45	2
^{140}Ba-La	7	34
^{141}Ce	<1	<1

^{144}Ce-Pr	2	<<1
^{239}Np	<<1	4

3.1.1 Global Fallout Internal Dose

In section 3.2.3, absorbed and effective doses to selected organs from internal irradiation were presented for typical residents of the 48 contiguous states as a result of exposure to fallout from tests of nuclear weapon-related devices exploded at the NTS. For that effort, doses from the ingestion of contaminated foods were estimated for 19 radionuclides and seven progeny products that would have originated from decay in the body following ingestion. These radionuclides were selected for analysis on the basis of screening calculations that had been performed previously by Ng et al. (1990) for the ORERP (Off-Site Radiation Exposure Review Project). Those radionuclides were estimated to be responsible for about 95% of the total internal dose from the radionuclides released at the NTS. Most of these radionuclides had relatively short half-lives, but were more important in a dosimetric sense than the long-lived radionuclides due to the rapid transport of the radioactivity into local consumable foods.

In this section, the dose from ingestion of food contaminated by global fallout for the five radionuclides likely contributing the largest exposures (^{3}H, ^{14}C, ^{90}Sr, ^{131}I, and ^{137}Cs) is addressed. Some of the useful information for the reconstruction of these doses comes from historical measurements. In particular, ^{90}Sr was studied extensively during the 1950s and 1960s and its deposition densities were measured throughout the world. At that time ^{90}Sr was considered to be one of the most important radionuclides, as it is long lived and, when ingested with contaminated foodstuffs, concentrates in bone tissues from which it is eliminated at a slow rate. It is worth noting that for this feasibility report, the doses from ^{90}Sr, ^{131}I, and ^{137}Cs were estimated from calculated deposition densities. This is in contrast to the doses from ^{3}H (tritium) and ^{14}C that were estimated from the total amount of activity released in all of the northern hemispheric testing. In general, more accurate doses to individuals can be estimated from deposition density estimates. Furthermore, it should be realized that the effective doses from ^{3}H and ^{14}C are numerically equal to the dose they deliver to any organ. Consequently, both ^{3}H and ^{14}C become uniformly distributed among body organs due to their chemical properties.

The role of ^{131}I in contributing dose to Americans was considerably different for global fallout as compared to NTS fallout. Due to the long time required for fallout debris injected into the stratosphere to fall back to the ground, ^{131}I dispersed from the high-yield tests resulted in much less of a health risk compared to that released as part of NTS fallout. However, from time to time it was noted that high concentrations of ^{131}I in milk did occur in the U.S from global fallout. For this feasibility report it has not been possible to estimate the deposition density of ^{131}I on a county-by-county basis with great accuracy, primarily due to data limitations.

Dose from ^{90}Sr and ^{137}Cs. Ingestion doses from ^{90}Sr and ^{137}Cs originating in global fallout were estimated by a process similar to that used for radionuclides from NTS fallout

(see equation 3.2, this chapter). Values of deposition density of ^{90}Sr were calculated on a county-by-county basis averaged over each month for the years of 1953 through 1972 as indicated in Appendix G. Values for the deposition density of ^{137}Cs were derived from those of ^{90}Sr by multiplying the ^{90}Sr results by a factor of 1.5 [a similar relationship has been used by UNSCEAR (1993)]. Monthly average values of the integrated intake were derived from Whicker and Kirchner (1987) by interpolation of the date-specific values given. The values used in this study are shown in Figures 3.9 and 3.11 for ^{90}Sr and ^{137}Cs, respectively. The ICRP (1998) age-dependent dose coefficients for the general public were used to convert intake to dose. Doses were calculated on a county-by-county basis for those who were adults in 1951 and for a typical individual assumed to be born on 1 January 1951. More details can be found in Appendix H.

Dose from ^{131}I. For the case of exposure to ^{131}I in global fallout, very approximate values of deposition density were estimated on a population-weighted basis, as it was not possible in this feasibility study to provide precise estimates on a county-by-county basis (see Appendix G). Age-dependent integrated intake values were derived from the ORERP calculations. The values used in this study are shown in Figure 3.10. Dose coefficients were taken from the ICRP (1998), and calculations were made for those who were adults in 1951 and for an individual assumed to be born on 1 January 1951. Because the dose from ingestion of ^{131}I varies strongly with age, population-weighted values of dose were calculated by considering the age distribution of the population in 1960 and by calculating a weighted average value of dose.

Population-weighted ingestion doses from ^{131}I in global fallout from 1953 through 1963 (and the sum) are presented in Table 3.16 and average doses from ^{131}I in global fallout for a person born on 1 January 1951 are presented in Table 3.17. As expected, the thyroid dose dominates the dose to other organs. Figure 3.22 shows the annual thyroid dose from ^{131}I in global fallout as a function of year. The years of highest thyroid doses from global fallout were 1956 through 1958, though the years 1952 through 1954 were nearly as great.

Table 3.16. Population-weighted (adult) organ doses (mGy) and effective dose (mSv) from ingestion of ^{131}I deposited in global fallout during 1953-1963.

Year	Thyroid (mGy)	Red Bone Marrow (mGy)	Effective Dose (mSv)
1953	4.42×10^{-03}	1.03×10^{-06}	2.26×10^{-04}
1954	2.51×10^{-02}	5.84×10^{-06}	1.28×10^{-03}
1955	6.22×10^{-04}	1.45×10^{-07}	3.18×10^{-05}
1956	6.41×10^{-02}	1.49×10^{-05}	3.28×10^{-03}
1957	4.38×10^{-02}	1.02×10^{-05}	2.24×10^{-03}
1958	9.38×10^{-02}	2.18×10^{-05}	4.80×10^{-03}
1959	5.79×10^{-05}	1.35×10^{-08}	2.96×10^{-06}
1960	0.00	0.00	0.00
1961	2.34×10^{-02}	5.43×10^{-06}	1.20×10^{-03}
1962	1.32×10^{-01}	3.08×10^{-05}	6.77×10^{-03}
1963	6.71×10^{-04}	1.56×10^{-07}	3.43×10^{-05}
Sum	3.8×10^{-01}	8.9×10^{-05}	2.0×10^{-02}

Table 3.17. Population-weighted (child) organ doses (mGy) and effective doses (mSv) to an individual born on 1 January 1951 from ingestion of ^{131}I deposited in global fallout during 1953-1963.

Year	Thyroid (mGy)	Red Bone Marrow (mGy)	Effective Dose (mSv)
1953	3.03×10^{-02}	3.17×10^{-06}	1.44×10^{-03}
1954	1.28×10^{-01}	1.34×10^{-05}	6.08×10^{-03}
1955	2.98×10^{-03}	3.12×10^{-07}	1.42×10^{-04}
1956	3.96×10^{-01}	4.14×10^{-05}	1.88×10^{-02}
1957	2.63×10^{-01}	2.76×10^{-05}	1.25×10^{-02}
1958	2.61×10^{-01}	4.18×10^{-05}	1.36×10^{-02}
1959	1.01×10^{-04}	1.62×10^{-08}	5.26×10^{-06}
1960	0.00	0.00	0.00
1961	6.46×10^{-02}	1.03×10^{-05}	3.36×10^{-03}
1962	3.60×10^{-01}	5.77×10^{-05}	1.87×10^{-02}
1963	1.54×10^{-03}	2.47×10^{-07}	8.02×10^{-05}
Sum	1.5	2.0×10^{-04}	7.5×10^{-02}

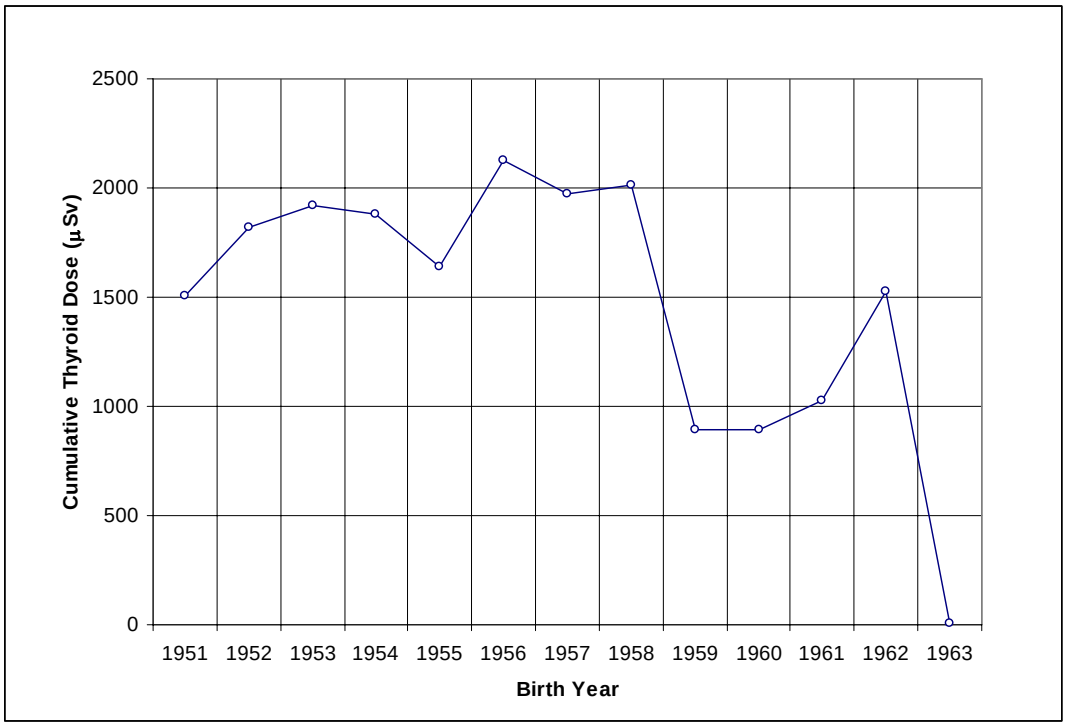

Figure 3.22. Cumulative (1953 through 1963) thyroid dose as a function of birth year. The cumulative dose for an adult, or a person who was born before 1 January 1933, is about 400 µSv.

Dose from ^{3}H and ^{14}C. Doses for ^{3}H and ^{14}C – two globally dispersed radionuclides – were calculated on the basis of the specific activity approach which differs considerably from the methods used for other radionuclides that depend on first estimating deposition density. As the fusion yield in the northern hemisphere is an important input to the calculation for both radionuclides, the data shown in Table 3.11 were used as input values. Another important input is the amounts of ^{3}H and ^{14}C that are created per Mt of fusion. These values are given by UNSCEAR (1993) as 740 PBq Mt^{-1} for ^{3}H and 0.67 PBq Mt^{-1} for ^{14}C.

Doses from ^{3}H were calculated with use of the NCRP (1979) model which simulates the world's hydrological cycle through the use of seven compartments consisting of atmospheric water, surface soil water, deep groundwater, surface streams and fresh water lakes, saline lakes and inland seas, ocean surface, and the deep ocean. The use of the hydrological cycle is appropriate, as most of the ^{3}H released is in the form of tritiated water or is soon converted to that form in soil. Calculations also consider the specific activity of ^{3}H in the various water compartments and the rate of change among the compartments. Example results of the dose over time from the release of 1 PBq of ^{3}H to the northern hemisphere are shown in Figure 3.23. The annual dose decreases rapidly with time after the release due to the mixing of the released ^{3}H into the larger compartments. The summary result of the data shown in that figure is that the release of 1 PBq of ^{3}H to the atmosphere in

the northern hemisphere would result in a dose of 0.38 nSv to each person living in the hemisphere.

For comparison, a rough estimate of the dose from naturally occurring ^{3}H can be made on the basis of the estimated natural production rate of 37 PBq y^{-1} per hemisphere and the measured concentrations of ^{3}H in surface waters. The annual absorbed dose in tissue from naturally occurring ^{3}H was derived in UNSCEAR (1982) to be 10 nGy. This corresponds to a dose of 0.27 nGy per PBq produced, which is in good agreement with the previous estimate of 0.38 nSv per PBq. Based upon the values of the naturally produced ^{3}H and the environmental concentrations gives a rough estimate of the dose from ^{3}H of:

$$240\ \text{Mt} \times 740\ \frac{\text{PBq}}{\text{Mt}} \times 10\ \frac{\text{nGy}}{\text{y}} \times \frac{1\ \text{mGy}}{1{,}000{,}000\ \text{nGy}} \times \frac{1}{37}\ \frac{\text{y}}{\text{PBq}} = 0.048\ \text{m}$$

while the NCRP (1979) model yields a dose (through the year 2000) of 0.066 mSv, as shown in Table 3.18.

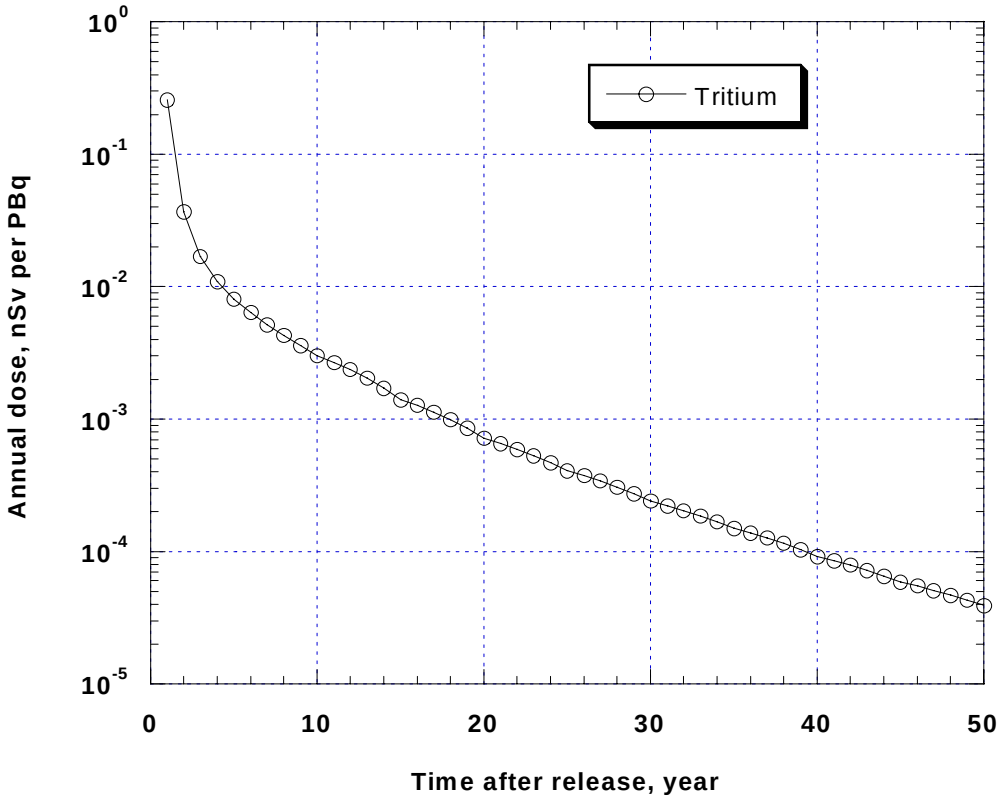

Figure 3.23. Annual dose as a function of time following the release of 1 PBq of ^{3}H to the atmosphere of the northern hemisphere. Results are based upon the NCRP (1979) model of tritium in the hydrological cycle.

The assessment of dose from ^{14}C is particularly difficult, due to its long half-life of 5730 y. The UNSCEAR (1993) has assessed the inter-generational dose due to this radionuclide, and under such considerations, it is the most significant radionuclide in global fallout. The relative importance of ^{14}C is much less if only the dose during the first 50 y is considered. Furthermore, the global carbon cycle is complex – as evidenced by the current controversy over global warming due to the release of carbon dioxide – and dose assessments must rely on complicated models. Thus the projections of dose into the future for this radionuclide are only approximate, but estimates of dose through the year 2000 are firmly based upon measurements of ^{14}C in food, water, and humans.

The dose from the release of ^{14}C can be assessed in a rather similar way, although the carbon cycle is much more complicated. As discussed in UNSCEAR (1982, 1993), the natural production rate of ^{14}C is about 1 PBq, and the resulting equilibrium specific activity produces an annual effective dose of about 0.012 mSv. A calculation similar to that of Equation 3.3 could be made, but it would be potentially misleading due to the very long half-life of ^{14}C and the very long time (more than one individual's lifetime) to achieve equilibrium. Thus, in order to calculate doses over the first 50 y from the release of ^{14}C, a compartment model for the global circulation of carbon was used. The model chosen is that of Titley et al. (1995), which is the latest model that has been widely accepted and builds on previously accepted models. The Titley et al. model is complicated, and contains 23 compartments with separate compartments of two to four layers in each ocean. Carbon is considered to be in the form of CO_2, which is the only form that can enter the food chain. The model takes into account temperature changes, photosynthesis in the surface layers of the oceans, and transfers of carbon down the water column.

Example results of model calculations are shown in Figure 3.24, which is a plot showing the annual doses from the release of 1 PBq of ^{14}C to the northern hemisphere. The summary result of the data shown in that figure is that the release of 1 PBq of ^{14}C to the atmosphere of the northern hemisphere would result in a dose of 0.0007 mSv to each person living in the hemisphere.

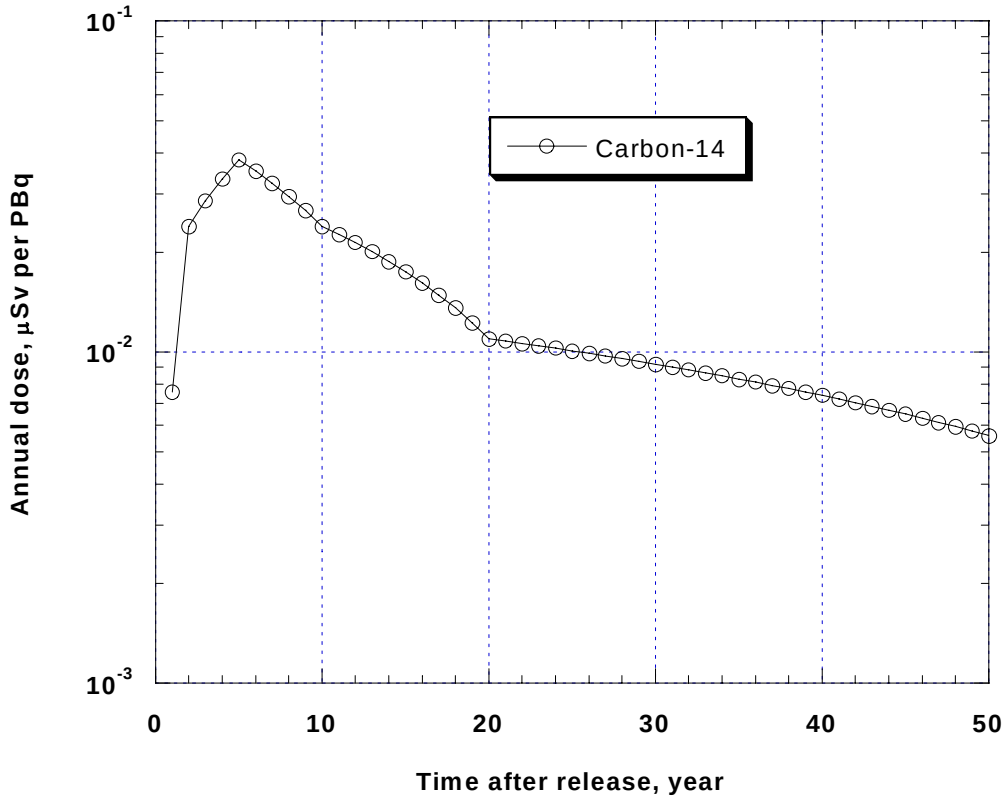

Figure 3.24. Annual effective dose normalized to intake (µSv PBq^{-1}) following the release of 1 PBq of ^{14}C to the atmosphere of the northern hemisphere. Results are based upon the model of Titley et al. (1995).

The calculated effective dose to typical persons from ^{3}H and ^{14}C in global fallout is summarized in Table 3.18. Doses from 1952 through the year 2000 are presented there.

Table 3.18. Effective dose (mSv) from ingestion from the creation or release of ^{3}H and ^{14}C during the testing of large fusion weapons in the Northern Hemisphere.

Year	Fusion Yield (Mt)	^{3}H Effective Dose (mSv)	^{14}C Effective Dose (mSv)	Year	Fusion Yield (Mt)	^{3}H Effective Dose (mSv)	^{14}C Effective Dose (mSv)
1952	5	0.001	0.000032	1977	-	0.00018	0.0026
1953	0.36	0.0002	0.0001	1978	-	0.00016	0.0024
1954	17	0.0034	0.00024	1979	-	0.00014	0.0023
1955	0.88	0.00069	0.00051	1980	-	0.00012	0.0021
1956	13	0.0028	0.00068	1981	-	0.00011	0.002
1957	3.9	0.0013	0.00095	1982	-	0.000097	0.002
1958	31	0.0063	0.0013	1983	-	0.000087	0.0019
1959	0	0.0011	0.0017	1984	-	0.000078	0.0019
1960	0	0.00058	0.0019	1985	-	0.000069	0.0019
1961	69	0.014	0.0024	1986	-	0.000061	0.0018
1962	99	0.021	0.004	1987	-	0.000056	0.0018
1963	-	0.0038	0.0054	1988	-	0.000051	0.0017
1964	-	0.002	0.0056	1989	-	0.000046	0.0017
1965	-	0.0014	0.0062	1990	-	0.00004	0.0017
1966	-	0.0011	0.0063	1991	-	0.000036	0.0016
1967	-	0.00086	0.0058	1992	-	0.000033	0.0016
1968	-	0.00071	0.0053	1993	-	0.000031	0.0015
1969	-	0.00059	0.0048	1994	-	0.000028	0.0015
1970	-	0.0005	0.0044	1995	-	0.000025	0.0015
1971	-	0.00043	0.0041	1996	-	0.000023	0.0014
1972	-	0.00038	0.0038	1997	-	0.000021	0.0014
1973	-	0.00033	0.0035	1998	-	0.000019	0.0014
1974	-	0.00028	0.0032	1999	-	0.000017	0.0014
1975	-	0.00024	0.003	2000	-	0.000015	0.0013
1976	-	0.0002	0.0028				
	Total =				**240**	**0.066**	**0.12**

Internal Doses of Other Radionuclides. The estimates of the population-weighted internal radiation doses from deposition of globally dispersed ^{90}Sr and ^{137}Cs during the years of 1953–1972 are summarized in Table 3.19. The dose from ^{137}Cs to tissues and organs other than the colon are essentially the same as the effective dose. The total population-weighted effective dose from both ^{90}Sr and ^{137}Cs is estimated to be 0.17 mSv. Wide variations in the total population-weighted dose occurred throughout the country, ranging

from 0.007 mSv (Imperial County, CA) to 0.38 mSv (Alpine County, CA) in the Sierra Mountains.

Table 3.19. Total population-weighted organ (mGy) and effective doses (mSv) from the deposition of ^{90}Sr and ^{137}Cs in global fallout during 1953–1972. Upper values are for those who were adults in 1951; lower values are for a person born on 1 January 1951.

	Individual organ or Effective dose				
	Adults in 1951				
Radionuclide	Bone surface (mGy)	Colon (mGy)	Red marrow (mGy)	Thyroid (mGy)	Effective (mSv)
^{90}Sr	0.54	0.017	0.24	0.0086	0.037
^{137}Cs	0.16	0.16	0.15	0.14	0.14
	Persons born on 1 January 1951				
^{90}Sr	1.6	0.034	0.53	0.0023	0.087
^{137}Cs	0.13	0.16	0.16	0.12	0.12

As in the case of NTS fallout, individual county estimates for global fallout ingestion doses are imprecise. Hence, it is not worthwhile to attempt to identify the counties predicted as having the highest or lowest ingestion doses from global fallout. Until the precision of dose estimates is examined in detail, only generalizations can be drawn. Hence, the accompanying maps should only be used to envisage the approximate geographic pattern of doses from global fallout.

Figures 3.25 and 3.26 show the geographic distribution of the estimated internal dose to red bone marrow from global fallout, and the sum of external and internal dose to red bone marrow (both for adults), respectively. As can be seen, the geographic pattern of doses reflects pattern of ^{137}Cs deposition density from global fallout shown in Figure 3.18.

Figure 3.27 shows the internal dose to red bone marrow in persons born on 1 January 1951. The ranges of doses received by children at the time of the tests were similar to that for adults; however, the portion of the country covered by the 1 to 3 mGy range is larger for children.

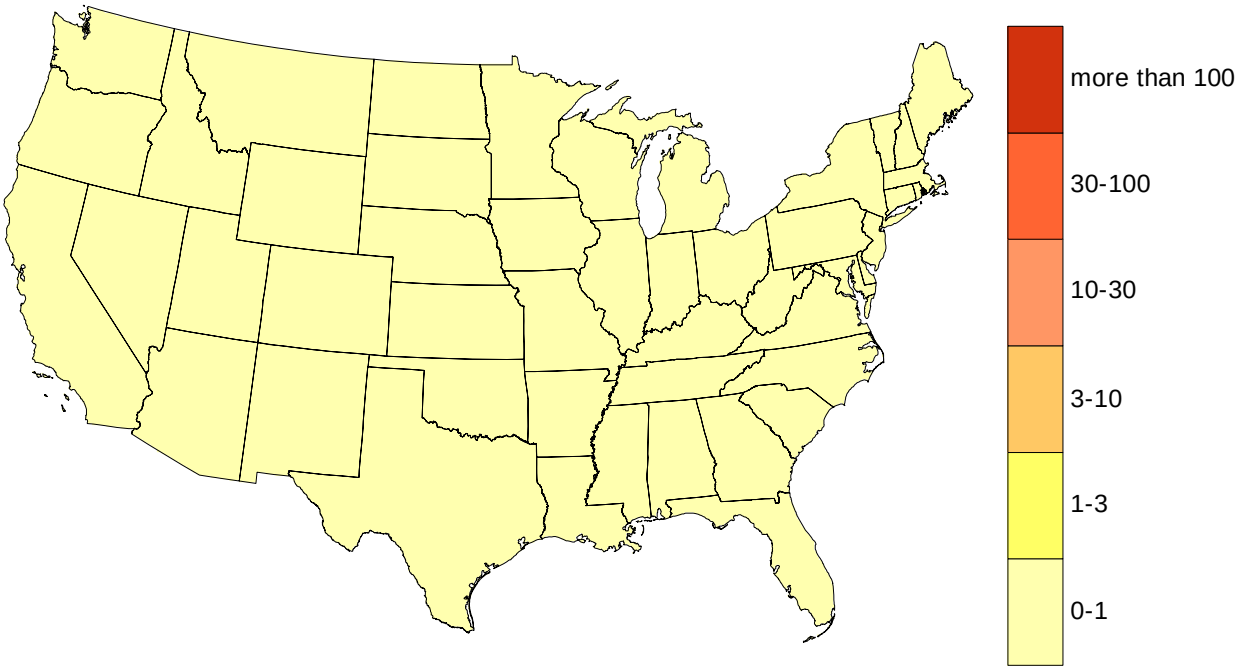

Figure 3.25. Internal dose (mGy) to red bone marrow of adults in 1951 from global fallout.

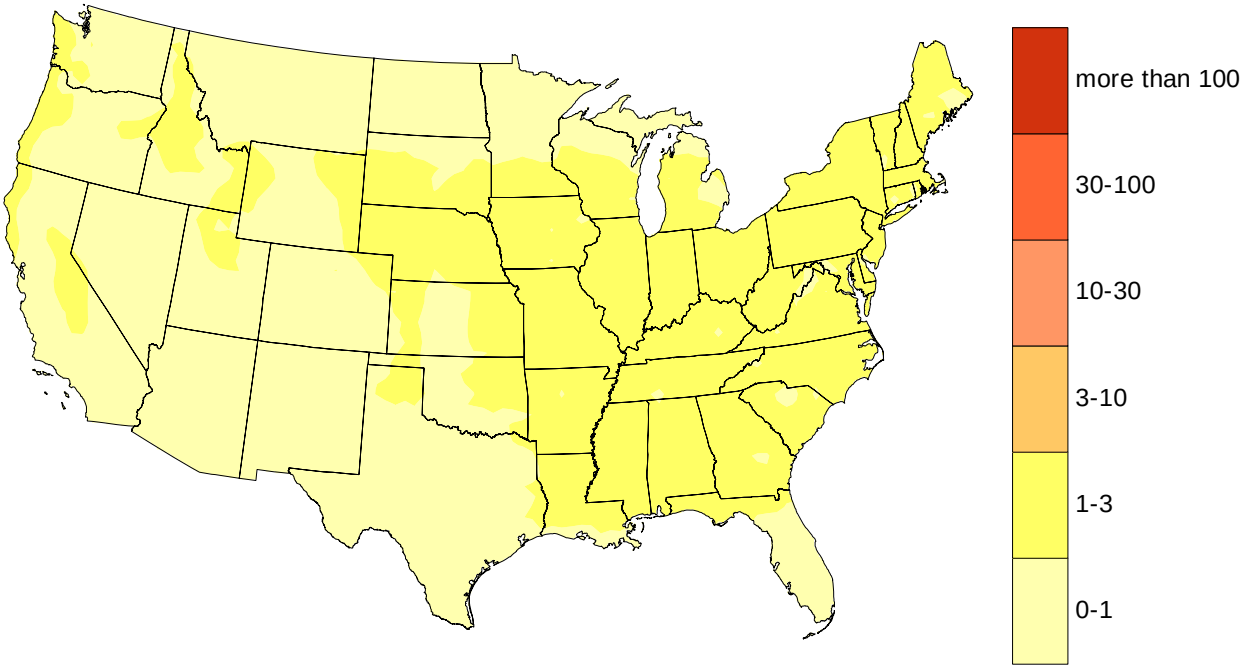

Figure 3.26. Total (external + internal) dose (mGy) to the red bone marrow of adults in 1951 from global fallout.

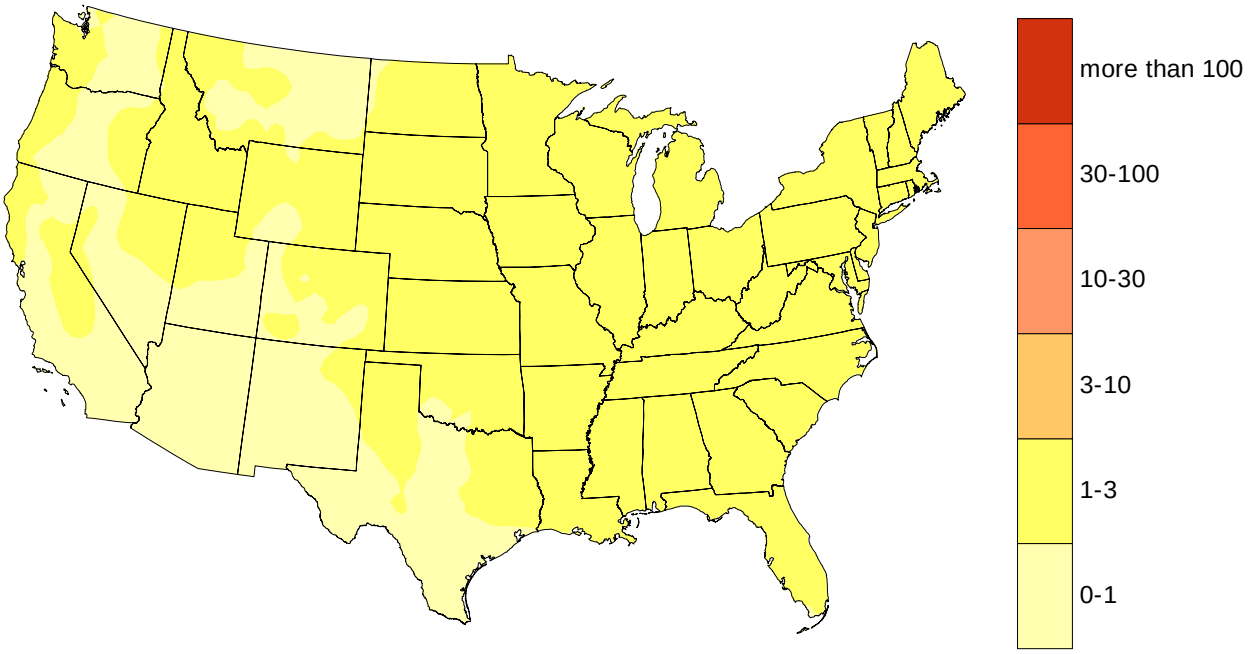

Figure 3.27. Total (external + internal) dose (mGy) to the red bone marrow of persons born 1 January 1951 from global fallout.

Comparison to Dose Estimates from UNSCEAR and Other Sources. One important means of corroboration of the doses estimated here is through a comparison to the doses published by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993) for the 40°–50° latitude band that includes part of the United States. The UNSCEAR dose estimates are from global fallout, originating from the large explosions conducted by the United States in the Pacific Region and by Russia near the Arctic Circle, whereas the doses calculated in this report are for local and regional fallout from the relatively small tests at the NTS. Calculated doses are population-weighted doses for adults and focus on cumulative effective dose with the only age correction having been made for doses from ^{131}I. A comparison of doses arising from the ingestion of contaminated foods is shown in Table 3.20.

In addition, data presented to the United States Congress by Terrill (1963) on concentrations of radionuclides in milk were used to perform calculations useful for validating the assumptions and models used in this report. The results of those comparisons, which are explained in Appendix H, are shown in Table 3.21.

Table 3.20. Comparison of fallout doses from internal irradiation from NTS and from global fallout sources.

	Cumulative Population-Weighted Effective Dose (mSv)		
	This study		UNSCEAR (1993)
Radionuclide	Nevada Test Site	Global fallout[a]	Global fallout[b]
^{3}H	-	0.066[c]	0.048
^{14}C	-	0.12[c]	0.078[d]
^{55}Fe			0.014
^{89}Sr	0.017		0.0023
^{90}Sr	0.0037	0.037	0.17
^{91}Sr	0.0000065		
^{97}Zr	0.00015		
^{99}Mo	0.001		
^{103}Ru	0.0038		
^{106}Ru	0.0072		
^{105}Rh	0.000086		
^{132}Te	0.0078		
^{131}I	0.25	0.020	0.032
^{133}I	0.0019		
^{136}Cs	0.0036		
^{137}Cs	0.01	0.13	0.28
^{140}Ba	0.012		0.00042
^{143}Ce	0.0004		
^{144}Ce	0.0053		
^{147}Nd	0.0011		
^{238}Pu			0.0000009
$^{239+240}Pu$	0.0012		0.0005
^{241}Pu	0.000087		0.000004
^{241}Am			0.0015
Total	0.33	0.4	0.63

[a] Averaged over the United States.
[b] North temperate zone (40°–50°).
[c] To the year 2000.
[d] The UNSCEAR (1993) value of 2.6 mSv was multiplied by a factor of 0.03, the portion estimated to be delivered in 50 y.

Table 3.21. Comparison of effective dose from reported concentrations of ^{90}Sr, ^{131}I, and ^{137}Cs in milk with predicted doses from models used in this report.

	Effective dose to adults (μSv)					
Time Period	From milk concentrations			From model predictions		
	^{90}Sr	^{131}I	^{137}Cs	^{90}Sr	^{131}I	^{137}Cs
1960	1.3	0	0.74	0.81	0	3.0
1961	1.3	2.5	0.74	0.84	1.2	3.6
1962	2.1	4.0	3.3	4.4	6.8	17
1963, first quarter	0.64	<0.31	1.3	0.69	0.034	0.48

In general, the results of this comparison are considered to be satisfactory and indicate that there are no gross errors in the assumptions used in the modeling process. Comparisons such as this can never be perfect and agreement within a factor of two or so is considered very good. Further refinements of the models, however, could likely improve the model predictions.

3.1 Comparison of NTS and Global Fallout Doses

As noted earlier, the small nuclear tests conducted in the atmosphere at the NTS did not create significant amounts of ^{3}H and ^{14}C in comparison to the large amounts that were produced by the testing of fusion devices in the atmosphere conducted by the United States in the Pacific Region and by Russia near the Arctic Circle. For that reason, those two radionuclides were not included in the assessment of doses from the NTS.

Also as discussed earlier, radioactive debris from the NTS originated from relatively small explosions, and much of the debris remained within the lower regions of the atmosphere. Thus, a large fraction of NTS debris was deposited within the United States during the first few days following the explosions. Rainfall was an important determinant of the amount of NTS fallout deposited in each county, but also important was the distance from the NTS. Thus, the variation in the amount of NTS fallout deposition among the counties is likely to be larger than it would be for global fallout.

In general, the cumulative effective dose from the NTS was dominated by short-lived radionuclides, such as ^{131}I, ^{89}Sr, and ^{140}Ba. In contrast, the estimates of cumulative dose from global fallout were dominated by long-lived radionuclides, such as ^{137}Cs and ^{90}Sr.

A summary of population-weighted doses (effective external and organ doses for thyroid and red bone marrow) is presented in Table 3.22. The population-weighted external effective doses were similar (0.5 mSv for NTS, 0.7 mSv for global). The internal thyroid dose from ^{131}I, however, differed significantly for the two sources of fallout (5 mGy from NTS, 1 mGy from global). Lower thyroid doses from global fallout were a result of the

decay of the relatively short-lived ^{131}I (8 d half-life) as it was transported globally from sites worldwide. Conversely, red bone marrow doses were significantly larger for global fallout (about 0.8 mGy) compared to NTS fallout (about 0.08 mGy). The larger red bone marrow doses result from long-lived radionuclides, e.g., ^{90}Sr and ^{137}Cs, which can persist in the environment and in man and can deliver their dose over many years' time.

Table 3.22 Summary of population-weighted effective (mSv) and organ doses (mGy) from NTS and global fallout as a result of exposure to the most important radionuclides. Unless otherwise specified, the values are for adults at the time of the tests.

		NTS Fallout			Global Fallout		
Radionuclide	Half-life	External (Effective) Dose (mSv)	Thyroid Internal Dose (mGy)	Red Bone Marrow Internal Dose (mGy)	External (Effective) Dose (mSv)	Thyroid Internal Dose (mGy)	Red Bone Marrow Internal Dose (mGy)
^{3}H	12.3 years	-	-	-	-	0.066	0.066
^{14}C	5700 years	-	-	-	-	0.12	0.12
^{54}Mn	312 days	-	-	-	0.04	-	-
^{89}Sr	50.5 days	-	0.001	0.031	-	-	-
^{90}Sr	28.5 years	-	-	0.024	-	0.0009	0.23
		-	-	-	-	0.002[a]	0.53[a]
^{95}Zr-^{95}Nb	64.0 days	0.08	-	-	0.19	-	-
^{97}Zr-^{97}Nb	16.7 hours	0.02	-	-	-	-	-
^{103}Ru	39.3 days	0.03	-	-	0.02	-	-
^{106}Ru	374 days	-	0.001	0.002	0.04	-	-
^{125}Sb	2.76 years	-	-	-	0.03	-	-
^{131}I	8.02 days	0.02	4.9	0.001	-	0.39	0.00009
		-	28[a]	-	-	1.5[a]	0.0002[a]
^{132}Te-^{132}I	3.2 days	0.11	0.06	0.001	-	-	-
^{133}I	0.9 days	0.02	0.04		-	-	-
^{136}Cs	13.2 days	-	0.002	0.002	-	-	-
^{137}Cs	30.1 years	0.01	0.009	0.009	0.33	0.13	0.13
^{140}Ba-140La	12.8 days	0.17	-	0.006	0.051	-	-
^{144}Ce	285 days	-	-	-	0.02	-	-
^{239}Np	2.36 days	0.02	-	-	-	-	-
Total (rounded)		0.5	5 30[a]	0.1	0.7	0.7 2[a]	0.6 0.9[a]

[a]Child at the time of tests (born 1 January 1951)

3.2 Summary

The radioactive fallout released from nuclear testing at the Nevada Test Site (NTS) and at other sites worldwide resulted in a combination of many exposures of short duration (primarily from the NTS) as well as a continuum of exposures (from global fallout) to the American people. Figure 3.28 shows the combined deposition density from NTS and global fallout (a summation of Figures 3.2 and 3.18) for ^{137}Cs. The deposition density in the eastern half of the United States is dominated by the contribution from global fallout.

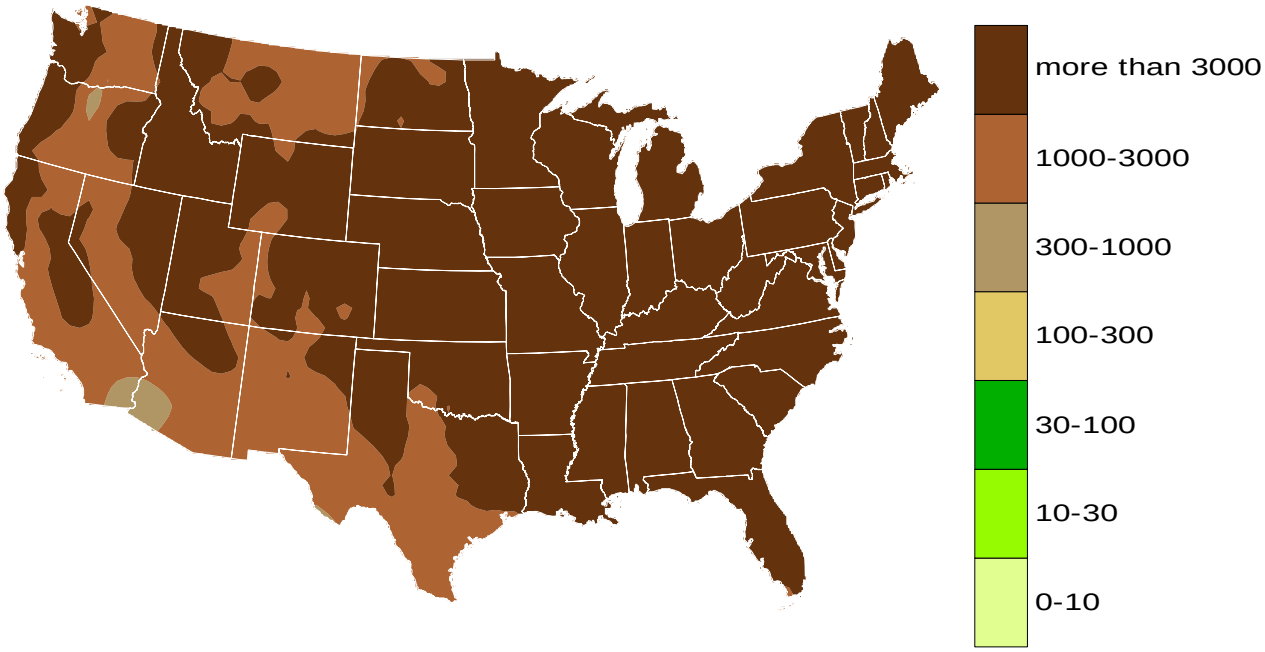

Figure 3.28. Cesium-137 deposition density (Bq/m^2) due to NTS and global fallout.

It is possible to mathematically sum the doses received from both NTS and global sources, though it should be understood that there are numerous assumptions inherent in such calculations. In particular, summing the doses implies that a person lived continuously in a county and was there during the entire fallout and exposure period. Furthermore, inherent in the estimates is the assumption of a typical person, either one who was an adult at the time of fallout or who was a child at the time of the tests (born on 1 January 1951). The typical person is one with moderate consumption habits who lives in structures that provide a specific level of shielding from external radiation. With these assumptions in mind, the following maps are provided to summarize the geographic variation in total dose received from weapons testing fallout at both the NTS and other northern hemisphere locations.

Figure 3.29 shows the estimated external dose to red bone marrow from NTS and global fallout combined. Figure 3.30 shows the estimated internal dose to red bone marrow from NTS and global fallout combined for a child (born on 1 January 1951) at the time of the tests.

Figures 3.31 and 3.32 show the estimated total dose (external plus internal) to red bone marrow from NTS and global fallout combined. Figure 3.31 is for adults, while Figure 3.32 is for children at the time of the tests.

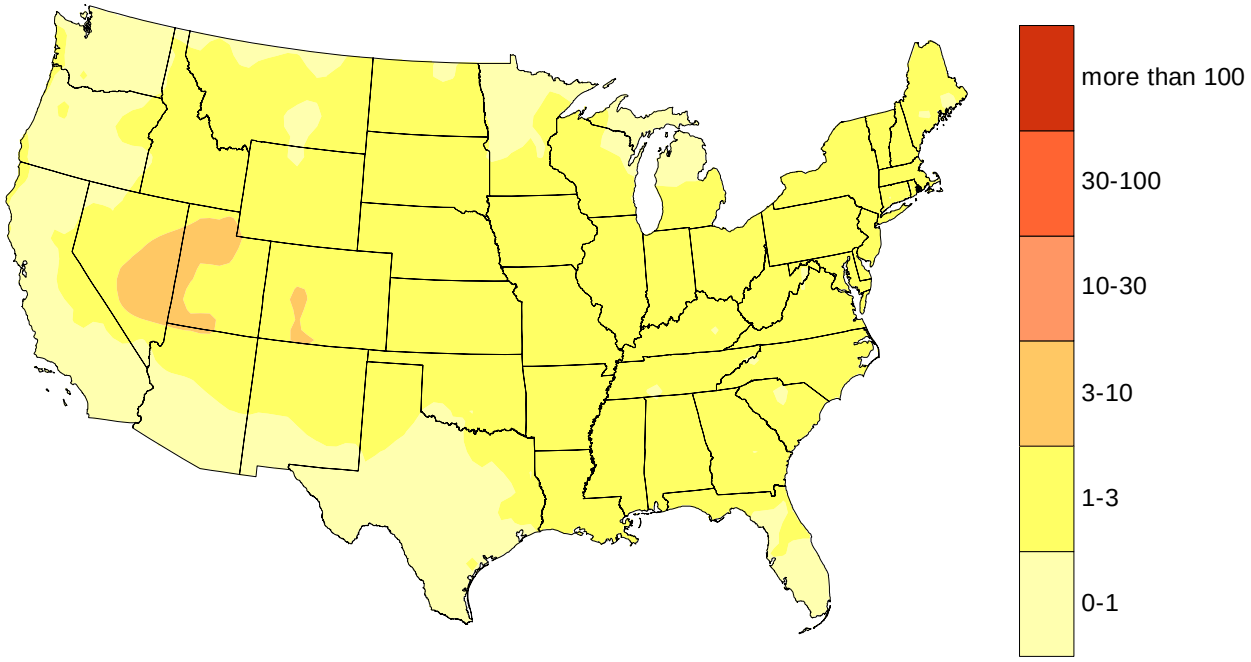

Figure 3.29. External dose (mGy) to the red bone marrow of adults resulting from NTS and global fallout.

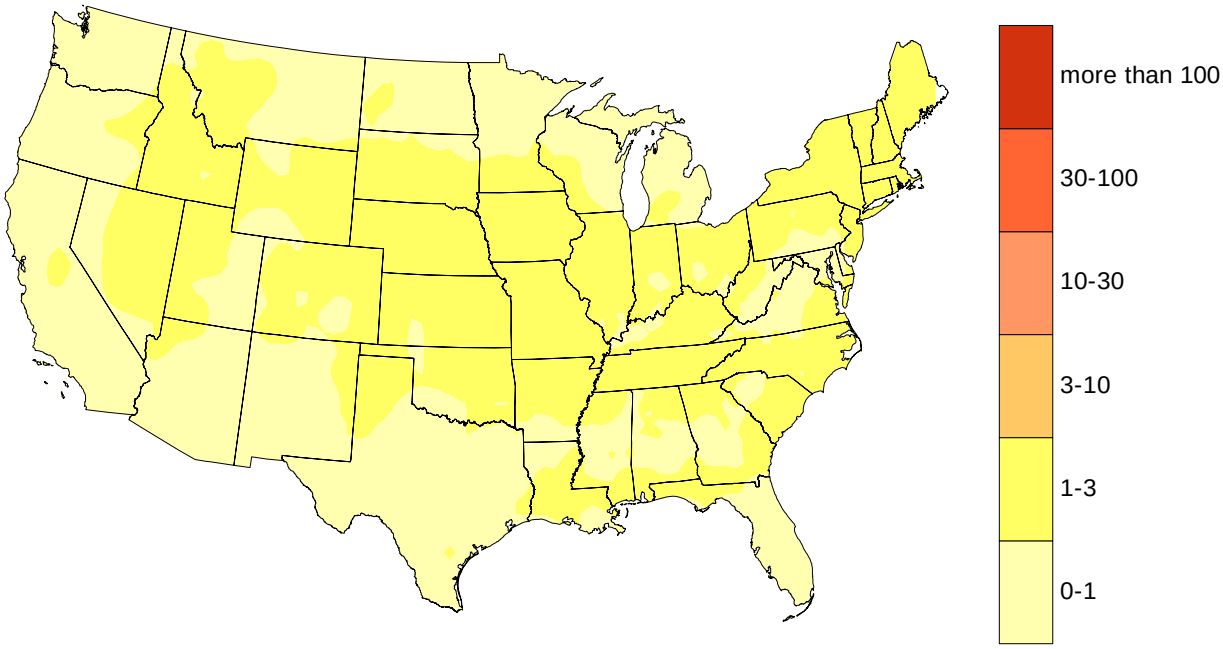

Figure 3.30. Internal dose (mGy) to red bone marrow of persons born 1 January 1951 from NTS and global fallout.

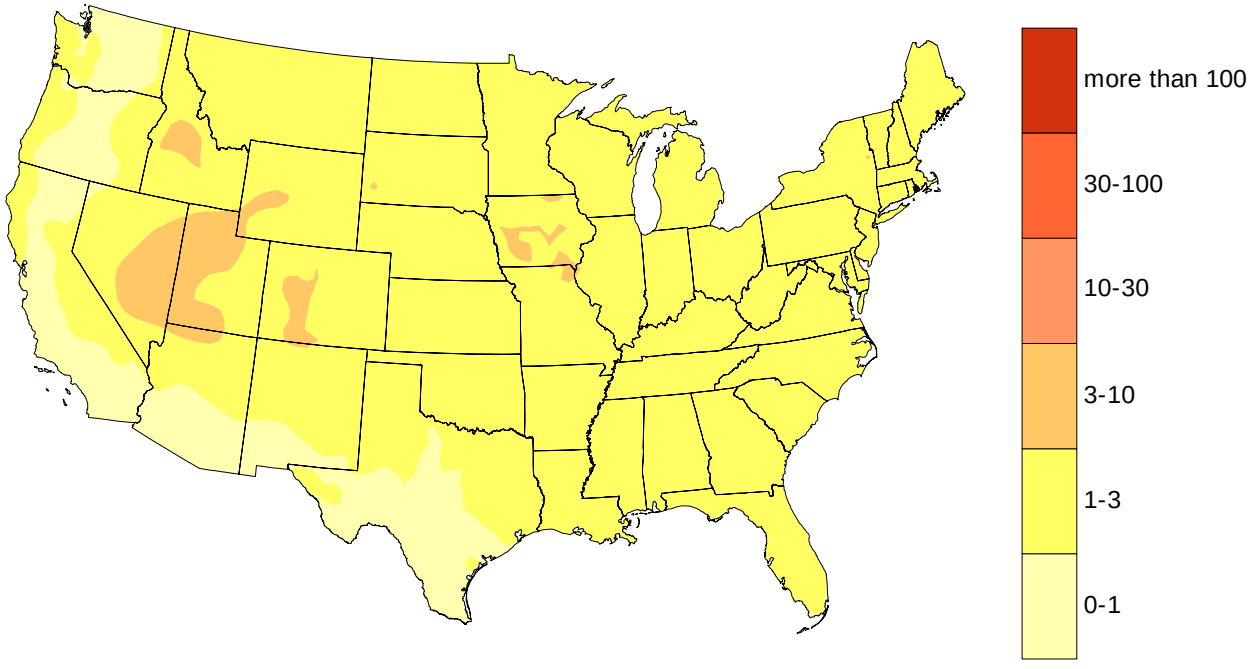

Figure 3.31. Total dose (mGy) to the red bone marrow of adults in 1951 from NTS and global fallout.

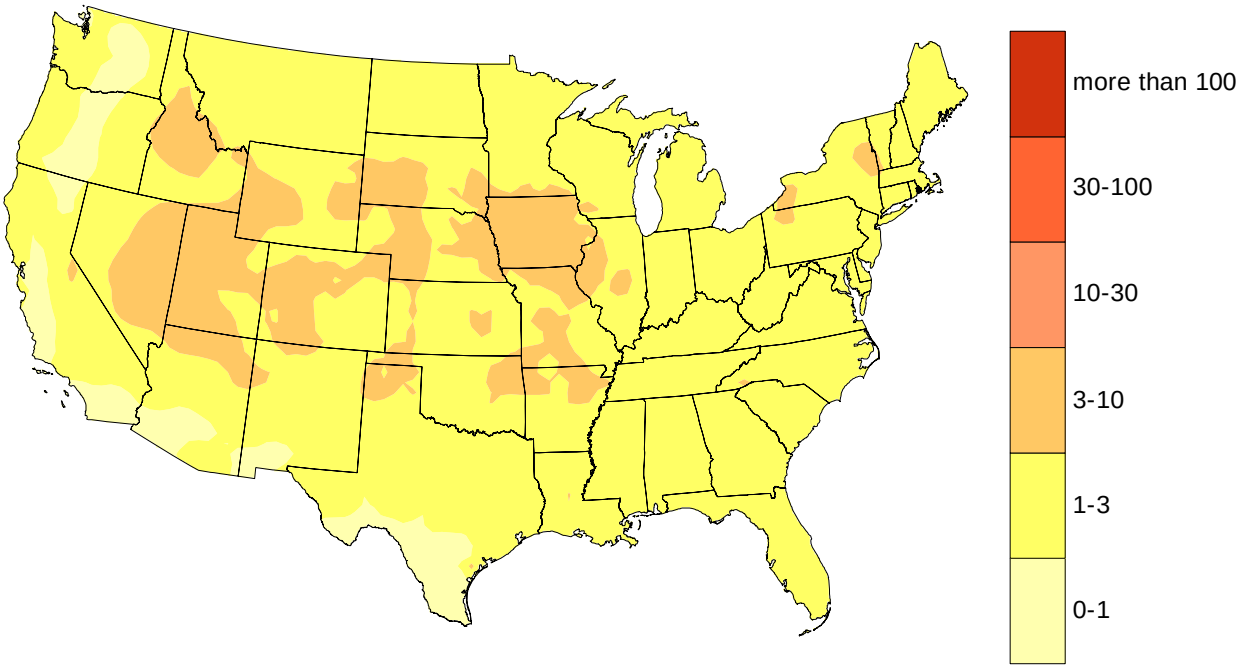

Figure 3.32. Total dose (mGy) to red bone marrow of persons born 1 January 1951 from NTS and global fallout.

In addition to doses from fallout from nuclear weapons tests, the U.S. population was, and continues to be, exposed to other sources of radiation, the most common sources being medical irradiation and natural background. In earlier decades of the 20th century (1920s-1960s), external radiation was administered to the head and neck regions of patients for a variety of medical conditions including acne, Tinea capitis, and to reduce the size of enlarged tonsils or thymus glands. These medical irradiations unintentionally exposed the thyroid glands and likely contributed in part to the incidence of thyroid cancer during those decades (Pottern et al. 1980). The number of people who were exposed to these medical procedures could not be found in the literature, but it is estimated to be in the range from 200,000 to 1 million. Radiation doses to the thyroid glands of patients receiving external beam therapy varied according to the treatment purpose and regimen; it is worthwhile noting that the magnitude of those radiation doses overlapped considerably with the magnitude of doses received from ^{131}I in fallout. Retrospective studies have shown that the thyroid dose from thymus irradiation ranged from 30 mGy to 11 Gy (mean of 1.4 Gy), tonsil irradiation resulted in thyroid doses from 10 mGy to 5.8 Gy (average of about 0.6 Gy or less, depending on the study), and scalp irradiation for Tinea capitis resulted in thyroid doses from 40 mGy to 500 mGy (average of 90 mGy) (Ron et al. 1995). As is shown in Fig. 3.13, the highest regional average of thyroid dose from all NTS tests was on the order of 100 mGy and pertained to children born in the early 1950s in western U.S.

External exposure to natural background is well documented (UNSCEAR 2000). It consists of two components: (1) natural gamma radiation emitted from the terrestrial environment (soil and rocks) by primordial radionuclides (^{238}U, ^{232}Th, ^{40}K, etc.) present in

the earth since its formation; and (2) cosmic rays originating from extra-terrestrial sources. The magnitude of the bone marrow dose from NTS and global fallout can be compared with doses typically received externally from the two components of natural background radiation which varies according to the concentration of primordial radionuclides in local soil and rocks. Figure 3.33 shows the accumulated dose (mGy) to bone marrow from 10 years of exposure to natural gamma radiation. The dose to children and adults is approximately the same. In this comparison, a 10-year interval was chosen because it compares closely to the length of time over which testing at the NTS took place. The accumulated bone marrow dose from natural gamma radiation for the coastal areas of the U.S. over 10 years, is nearly the same as the total from NTS and global fallout (1-3 mGy), while the accumulated bone marrow dose from natural gamma radiation for the central part of the U.S. is several times higher (3-10 mGy) than the total from NTS and global fallout.

Also shown is a U.S. map of the bone marrow dose (mGy) per 10 years from cosmic rays (Fig. 3-34.). The dose from cosmic rays varies primarily as a function of altitude and increases roughly by a factor of 2 for each increase of 1500 m in altitude. It is lowest in the coastal areas (3 mGy in 10 years) and highest in the Rocky Mountains (up to 60 mGy in 10 years). Here again, the 10-year dose from cosmic rays is, in most areas, greater than that from NTS and global fallout combined.

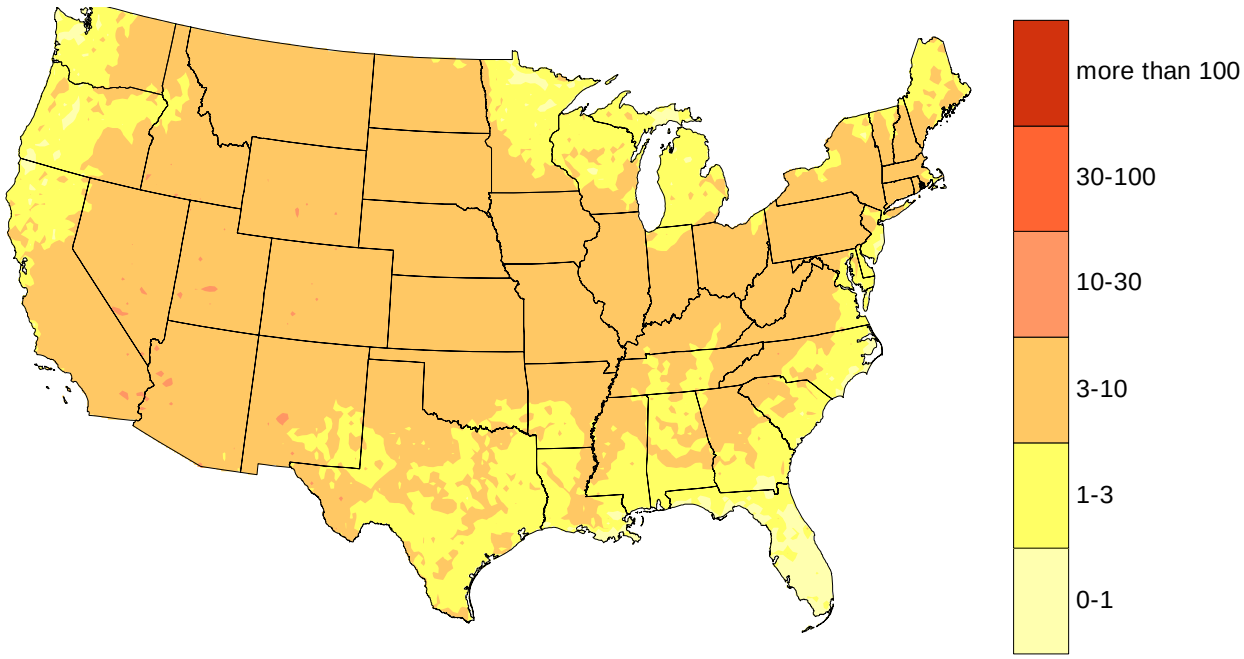

Figure 3.33. Total dose (mGy) to red bone marrow of persons from 10 years of exposure to natural gamma radiation from the terrestrial environment (based on data provided by the U.S. Geological Survey).

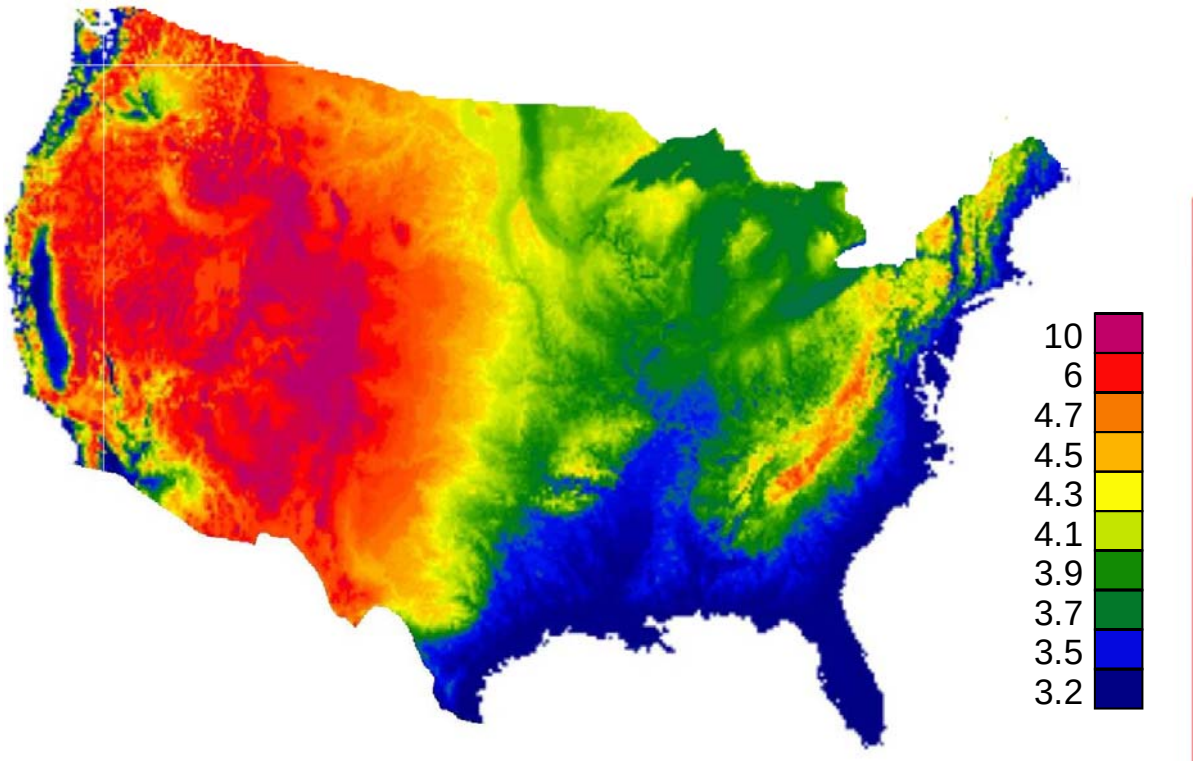

Figure 3.34. Total dose (mGy) to red bone marrow persons from 10 years of exposure to cosmic ray radiation. (Map courtesy of Geological Survey of Canada.)

In addition to the maps, a number of general and specific points can be concluded from the calculations and discussion presented in this chapter. Those points follow.

3.2.1 NTS Fallout

- Doses from external and from internal irradiation were calculated for 61 of the most significant events that occurred at the NTS during 1951, 1952, 1953, 1955, 1957, and 1962.
- About 1/3 of the amount of fission products produced by NTS explosions was deposited within the area of the contiguous United States. A larger percentage of the fallout from surface and tower tests was deposited in the United States.
- Most of the effective dose received by each person from external irradiation was from gamma rays emitted by fission products deposited on the ground. The actual dose received by any individual depended on the fraction of time he/she spent outdoors during the first few weeks after fallout and on the degree of shielding provided by his/her dwelling. The most exposed individuals at any particular location would have been outdoor workers or others who spent most of their day outdoors.
- Residents in the counties immediately downwind from the NTS received much higher exposures than the average, in excess of 3 mSv, while people in the western

and northwestern United States and some areas of the Midwest and Southeast received much less than the average. Most of this exposure occurred within the first 3 weeks after each test and was due to relatively short-lived radionuclides. Over the entire population of the 48 contiguous states, the average effective dose from all NTS tests cumulated through the year 2000 was about 0.5 mSv, equivalent to approximately one year of external exposure from natural gamma radiation.

- Beta radiation from fission products in the surface soil resulted in an additional dose to the skin when outdoors. However, this contribution was not large enough to be considered an important component of total fallout radiation exposure except perhaps for children who played in the soil for very long periods of time.
- The total cumulative population-weighted effective dose from internal irradiation (ingestion) from NTS fallout was about 0.68 mSv. The larger proportions of the total ingestion dose from NTS fallout resulted from the tests of Operation Plumbbob conducted in 1957, Operation Tumbler-Snapper in 1952, and Operation Upshot-Knothole in 1953. The largest contribution from any single event is estimated to have been from Project SEDAN, a cratering experiment in 1962, although the precision of the estimated doses for that event is low due to the absence of information regarding its fission yield and other factors.
- Iodine-131 dominates the ingestion dose received by the American public from tests at the NTS. Other than the doses from ^{131}I to the thyroid, doses to other organs are much smaller and are less than the dose that was estimated to have resulted from external exposure to NTS fallout.
- The radionuclide ^{131}I was by far the most important contributor to collective effective dose from ingestion and accounted for nearly 90% of the total age-corrected collective effective dose. The thyroid is estimated to have received by far the largest collective organ dose of 2,000,000 person-Gy. Most organs received a collective dose of about 15,000 person-Gy; other than the thyroid, the organs receiving the higher doses were the colon (56,000 person-Gy) and the bone surfaces (31,000 person-Gy).
- The more important contributors to internal dose from NTS fallout, other than ^{131}I, were the short-lived radionuclides ^{89}Sr and ^{140}Ba.
- The total contribution of internal dose from $^{239+240}Pu$, even from inhalation, is relatively small compared to other radionuclides.
- The results provided here establish that a reconstruction of external and internal (i.e., ingestion) doses from NTS fallout is feasible, though this conclusion is contingent on availability of estimates of deposition density for each radionuclide of interest.

3.2.2 Global Fallout

- Tests that were conducted between 1952 and 1962 at locations throughout the world other than the NTS are referred to in this report as global nuclear tests that produced global fallout. The global nuclear tests considered in this report are those that were carried out by the United States, the United Kingdom, and the U.S.S.R. The tests that

were conducted by China and France were small in comparison; they have not been considered in this report.

- The total fission yield of the global nuclear tests considered in this report was about 170 Mt of TNT, to be compared with a total fission yield of 1 Mt for the NTS tests.
- The mostly high-yield global nuclear tests injected most of their debris into the stratosphere. Because of the long residence time (on the order of one year) for the transfer of air between stratosphere and troposphere, the fallout from those high-yield tests was relatively depleted of short-lived radionuclides and the fallout pattern was vastly different from that due to NTS tests.
- Fallout from atmospheric global nuclear tests resulted in a per capita effective dose from external irradiation of about 0.7 mSv to the population of the United States, about one and one-half times as great as that resulting from NTS fallout. However, residents in the states immediately downwind from the NTS received much higher than average doses from NTS fallout while the doses in the western and northwestern United States and some areas of the Midwest and Southeast were much less than the average. The doses from global fallout were more uniformly distributed across the United States with differences from place to place reflecting differences in average precipitation. Thus, residents of counties in the eastern and Midwestern United States that received above average rainfall were impacted more than the residents of the more arid Southwestern states. Since the states downwind from the NTS that were affected most by the NTS fallout are, in general, more arid than the eastern United States, the areas most affected by NTS fallout were in general least affected by global fallout.
- Annual per capita doses from global fallout were comparable to annual doses from NTS fallout during the years of testing. However, most of the exposure from the NTS tests occurred within the first 3 weeks of each test and was due to relatively short-lived radionuclides. In contrast, the exposure from global fallout occurred over a much greater span of time, thus the dose rate was more uniform with time.
- The actual dose from external irradiation received by any individual depended on the fraction of time he/she spent outdoors and the degree of shielding provided by his/her dwelling. The most exposed individuals at any particular location would have been outdoor workers or others who spent most of their day outdoors. Beta radiation from fission products in the surface might have been important only for children who played in the soil for significant intervals of time.
- In contrast to fallout from the NTS, where most of the external exposure was due to the short-lived radionuclides (primarily ^{132}I-^{132}Te and ^{140}Ba-^{140}La), ^{95}Zr-^{95}Nb was the major contributor to external dose from global fallout during the years of testing. The cumulative dose through 2000 was dominated by the long-lived ^{137}Cs. Cesium-137 present in soil continues to result in a small radiation exposure to the public even at the present time. As was the case for NTS fallout, the most exposed individuals were outdoor workers, and the least exposed were persons who spent most of their time indoors in heavily constructed buildings.

- The more important contributors to internal dose from NTS fallout were short-lived radionuclides (^{131}I, ^{89}Sr, and ^{140}Ba), whereas for global fallout the more important contributors to internal dose were long-lived radionuclides (^{137}Cs, ^{90}Sr, and ^{14}C).
- Deposition density of short-lived radioactivity (e.g., ^{131}I) cannot be easily estimated for global fallout. Reconstruction of deposition densities of short-lived activity would require review of all relevant literature to supplement the presently sparse data.
- Doses from the NTS and global sources would have been received at different times, primarily during the 1950s for NTS fallout and during 1963-1965 for global fallout.
- The accumulated bone marrow dose received from natural gamma radiation emitted from the terrestrial environment over a 10-year period is about 1-3 mGy for coastal areas of the country. This is similar to the total bone marrow dose from NTS and global fallout combined. However, in the central part of the U.S., the accumulated bone marrow dose received from natural gamma radiation emitted from the terrestrial environment over a 10-year period is about 3-10 mGy, which is several times higher than the total bone marrow dose from NTS and global fallout combined.
- This report has demonstrated that it is feasible to estimate the exposure of the population of the United States from global fallout as a function of location and time. However, the monthly estimates for individual counties are probably quite imprecise and the deposition density and exposure rate probably varied significantly from place to place within a county, particularly for counties with large variations in topography. Therefore, the results presented in this report are not intended to be definitive estimates of the geographic and temporal variations in global fallout across the United States. They are rudimentary estimates though they do demonstrate the feasibility of making such estimates given sufficient data.

3.3 Considerations for Further Research

There are numerous possible subject areas that should be researched for the purpose of improving the crude dose estimates provided in this report and to provide a more complete historical record of the nature of the releases from the weapons testing and the resulting exposures received by Americans from NTS and global fallout. These areas primarily have emerged from noting the limitations of the input data and available models to conduct the work reported here. The research items provided here can generally be categorized as those related to (1) availability of nuclear test data, (2) improvement in models, (3) inclusion of specific locations, and (4) public health.

3.3.1 Possible Research Related to Availability of Nuclear Test Data

- The ability to estimate fallout deposition density from NTS tests was made possible by the calculations based on cloud measurements of the production of the various fission products from each test. However, the composition of the radioactive debris is very dependent on the energies of the neutrons produced in the explosion. Useful

information for improving dose assessments would include a comparison of such data for tests carried out by the United States and U.K. in the Pacific as well as for tests carried out in the Soviet Union. These comparisons may require the declassification of certain data.

- Also classified is the fraction of the total yield of each nuclear test that resulted from fission as opposed to fusion. Again, this information will be needed to make more accurate estimates of deposition density and resultant doses from tests held outside the United States. Declassification of such information would also help to obtain better dose estimates for the test SEDAN conducted at the NTS. In some cases, even the exact value of the total yield is classified. Since tritium is a by-product of fusion, any information on the amount of tritium released from a particular test is probably also classified.
- Declassification of the fission yields and ratios of ^{137}Cs/Pu activity, particularly for NTS tests, would allow for more accurate estimates of plutonium deposition density across the United States.
- In addition to improving the input data, the deposition density estimates and doses might be improved if additional data can be located on the ratios of the deposition of the various nuclides as a function of location in the United States. This would require searching all available archives.

3.3.2 Possible Research Related to Improvement in Models

- The models used to estimate exposure rates and deposition densities until now have been crude. In addition, monthly and individual county estimates are imprecise, particularly for estimates of short-lived radionuclides such as ^{131}I from global fallout. However, comparisons made to date with environmental measurements suggest that the overall geographical distribution of fallout and external dose to the United States population, and the per capita or the collective dose, are all reasonable estimates. Hence, the issues raised in this report are primarily oriented towards improving location-specific (e.g., county) doses.
- There are a variety of ways that considerable improvements in models could be made, thus allowing for more accurate estimates of deposition densities and doses for particular time periods, particularly for years prior to 1958, as well as more accurate predictions of the geographical variation at any particular time. In particular, by weighting the various precipitation measurements in a given county by the population, one might be able to calculate a population-weighted ^{90}Sr deposition density that in turn would allow a better estimate of the dose to a typical resident of that county than the present estimate. An analysis of the gummed-film data for the years prior to 1958, in a manner similar to that carried out for NTS fallout (see Beck et al. 1990; NCI 1997), might also allow better estimates of deposition density as a function of location for years prior to 1958. A further assessment of the variations in precipitation within counties might identify some local hotspots and populations that were exposed to much higher doses than presently known. Areas with large amounts of thunderstorm activity during months of testing could be identified, since this was believed to be one mechanism that resulted in episodes of high fallout of short-lived

radionuclides such as ^{131}I. Detailed information on precipitation is also needed to assess the fraction of deposited radionuclides that is retained by vegetation.

- By determining the precision of data used for critical parameters in each of the steps used in this feasibility study, one could estimate a credibility interval for the estimated monthly doses for each county in a manner similar to that provided by NCI (1997). Without such a systematic analysis it is difficult to assess the validity of any particular county's monthly dose estimate.

- Additional data could also be used to develop a more sophisticated, higher resolution model of the distribution of global fallout ^{90}Sr specific activity with latitude and longitude. This might be accomplished using a technique such as kriging to provide estimates of specific activity that vary smoothly across the country. A more sophisticated model would also attempt to account for the impact of "dry" deposition in arid locations. A thorough review and assessment of the vast amount of other scattered sources of data might also allow the estimates of isotopic ratios for particular months to be improved. It may also allow improvements to the atmospheric model used for estimating nuclide ratios, which would then allow one to more confidently utilize the model for periods with no data. Because the current effort was limited in scope and resources, only a small subset of the vast literature could be evaluated and utilized.

- Iodine-131 may have been a significant contributor to global fallout ingestion dose. The present results suggest ^{131}I deposition density was comparable to that from the NTS in many areas of the country. However, due to the lack of actual data, a much more comprehensive effort will be necessary to provide estimates of ^{131}I deposition density and associated uncertainty comparable to those estimated for NTS fallout. This effort would include development of a model for the likely geographical variation in the deposition of short-lived radionuclides across the contiguous United States.

- In this feasibility study, doses from internal irradiation are calculated with the assumption that the values for the food consumption rates and fractions of foodstuffs consumed that are locally produced are the same for all the regions of the United States. A review of the literature to assess the regional and seasonal differences will be warranted to improve the accuracy of the estimated doses from internal irradiation.

- In this feasibility study, the only pathways of exposure to man that have been considered are external irradiation from radionuclides deposited on the ground and internal irradiation via ingestion. In a more comprehensive study, external irradiation due to immersion in the radioactive cloud and internal irradiation via inhalation should be considered. Also, a number of minor contributors to external exposure were not considered in this feasibility study. Small quantities of ^{60}Co, an activation product, were measured in fallout at some sites during 1962-63, as were small quantities of ^{124}Sb and ^{134}Cs. Small quantities of radioactive tracers were also released during tests in 1958 (^{185}W) and 1962 (^{102}Rh). None of these nuclides are believed to have contributed significantly to doses to individuals. Also not considered in this study was the deposition of a few radionuclides that may

contribute in a minor way to ingestion exposure such as ^{55}Fe, $^{239+240}Pu$, ^{241}Pu, ^{241}Am and ^{99}Tc.

- In this feasibility study, the emphasis has been on the estimation of doses. A more comprehensive study should include an extensive assessment and analysis of the uncertainties attached to those dose estimates.

3.3.3 Possible Research Related to Inclusion of Specific Locations

- The estimates in this report do not include the impact from tests conducted after 1963 by China and France. The atmospheric tests by China in particular, although the total fission yield was only about 20 Mt, were conducted at mid-latitudes in the Northern Hemisphere and did result in additional exposures to the population of the contiguous United States during the 1970s and early 1980s.
- An additional study to be considered is to estimate the doses to the populations of Alaska and Hawaii. These states were not included in the present analysis since they represent special unique situations: Hawaii due to its proximity to the Pacific weapons testing area and Alaska due to its proximity to Soviet testing sites.

3.3.4 Possible Research Related to Public Health

- There are a number of public health related topics that should be considered for future research. These include the determination of individual and life-style related characteristics that would assist in identifying high-risk subpopulations, the inclusion of *in utero* exposures and exposures to nursing infants in the dose calculations, and refinements to current methodologies for making more precise estimates of dose for typical individuals.

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