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The geographic distribution of radionuclide deposition across the continental US from atmospheric nuclear testing

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Abstract

For the first time, calculations for the more than 3000 counties of the US have been completed that estimate the average deposition density (Bq m^{-2}) of more than 40 radionuclides in fallout from atmospheric nuclear weapons tests conducted in the US (1951–1962) and 19 radionuclides from tests conducted elsewhere in the world (1952–1963). The geographic pattern of deposition across the US, as well as the amount of fallout deposited, varied significantly depending on whether the tests were conducted within or outside of the US. Fallout deposited from the Nevada Test Site (NTS) varied geographically as a result of dispersion and dilution in the atmosphere, the wind patterns following each test, and the occurrence of localized rainfall events. In general, states immediately east of the NTS received the highest deposition from tests conducted there. In contrast, the variation in deposition across the country from global fallout was less than for NTS fallout primarily reflecting variations in annual precipitation across larger regions. Hence, in the eastern and mid-western US, where rainfall is above the national average, higher levels of global fallout were deposited than in the more arid southwestern states. This paper presents a summary of the methods used and findings of our studies on fallout from NTS and global fallout, with emphasis on two of the most important radionuclides, ^{131}I and ^{137}Cs .

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1. Introduction and background

Interest among the US public and the scientific community in environmental contamination and the possible health effects resulting from nuclear testing has continued since the 1950s when atmospheric nuclear testing was frequent. In the US, years of litigation by citizens alleging detrimental health effects led to a US Congressional mandate in 1983 through US Public Law 97-414. This law directed the Department of Health and Human Services (DHHS) to conduct scientific research to develop credible methods to estimate the thyroid doses from ^{131}I that were received by individuals from radioactive fallout from nuclear testing, and to assess exposure of the American people to ^{131}I from the Nevada Test Site (NTS) atmospheric nuclear weapons tests. The US National Cancer Institute responded to this mandate and, after more than a decade of research, published a comprehensive report on the dispersion of radioiodine in fallout from the NTS, the contamination of milk across the country, and average thyroid organ doses received by the public from ^{131}I in all of the more than 3000 counties in the contiguous US (NCI, 1997). This voluminous work was followed by further public interest that led, in 1998, to another Congressional request for the DHHS to conduct an initial assessment on radiation dose, as well as to report on the public health implications associated with radioactive fallout from the testing of nuclear weapons worldwide. In response to this request, the DHHS made preliminary estimates of the deposition of the most important radionuclides in fallout, average doses received, and the health risks associated with exposure to fallout from atmospheric nuclear weapons tests conducted between 1951 and 1963 at the NTS and at other sites throughout the world (DHHS, 2001). This paper summarizes findings on deposition of 11 important radionuclides investigated in those studies, with emphasis on the spatial distributions of ^{131}I and ^{137}Cs fallout across the US. Doses received by Americans are not discussed here due to space limitations. Such information can be found in NCI (1997) (see <http://i131.nci.nih.gov/>) and DHHS (2001), see <http://www.cdc.gov/nceh/radiation/fallout/default.htm>).

The testing of nuclear weapons in the atmosphere by the US at the NTS and in the Pacific, and by other countries at various locations worldwide, took place from 1945 to 1980. Over 500 nuclear tests were carried out, having total explosive and fission yields of 440 and 190 Mt, respectively (Beck and Bennett, 2002). Estimations of the local as well as nationwide inventories and spatial patterns of the deposition of fallout radionuclides across the US from these tests should ideally be based on direct measurement data but, because the number of monitoring stations was generally not sufficient to provide a completely detailed description of contamination everywhere, estimates were made using indirect measurements (e.g. exposure rate) having somewhat greater uncertainty. For areas for which there were no measurement data, the deposition of fallout radionuclides was estimated via interpolation of relevant data at nearby, or even moderately distant, locations, although this gave rise to substantially greater uncertainty.

In this context, “fallout” refers to the radioactive debris dispersed through the atmosphere from nuclear tests. The fallout can be of “local” origin, i.e., occur

within a few hundred kilometers of the detonation site, or of “regional” origin, referring to fallout anywhere in the US from the NTS. Fallout could also be “global” if the debris was dispersed via tropospheric or stratospheric circulation from nuclear test sites throughout the world. These global sites that accounted for most of the deposition in the US were those in the northern hemisphere, in particular, in the Pacific and the former Soviet Union. Numerous reviews detail the whereabouts of the various nuclear testing sites, the number of explosions and yields (Carter and Moghissi, 1977; UNSCEAR, 2000; Beck and Bennett, 2002), and in some cases, a summary of exposures received locally and regionally (Simon and Bouville, 2002), or globally (Bouville et al., 2002).

2. Methods

Various environmental monitoring programs were conducted in the US during the years of atmospheric nuclear testing (see Beck and Bennett, 2002, Table 6), though no single program was comprehensive in terms of the types of measurements made, temporal or geographic coverage. The various monitoring data, while seemingly limited for an area as large as the U.S, have proven to be a useful resource for making quantitative estimates of local deposition densities (Bq m^{-2}). The interpretation of the measurement data into nationwide geographic patterns of deposition densities of specific radionuclides is a more recent undertaking (NCI, 1997; DHHS, 2001).

The amount of nuclear debris generated and the geographic distribution of the deposited fallout depend on a large number of variables including the location of test(s), the explosive yield(s), height(s) of the burst(s), the type(s) of placement structure(s) (tower, balloon, etc.), meteorological factors such as the directions and speeds of the winds that can vary at different altitudes both on a local and regional scale, and the presence or absence of precipitation at locations along the trajectories. Because of the complex nature of these mechanisms and phenomena, the geographic distribution of fallout deposition across the US has not been reconstructed through dispersion modeling, but has been assessed primarily on the basis of measurement data augmented with meteorological prediction models only when necessary.

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 a few days time. The degree 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 estimate average radiation doses resulting from each of these tests.

In contrast, the radioactive fallout due to tests conducted far away from the US (called “global fallout”) 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 these 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, variations of the deposition of global fallout in the US with longitude and latitude were relatively small, the main differences due to local and regional differences in precipitation. Fallout from these tests consisted predominantly of long-lived radionuclides, like ^{90}Sr and ^{137}Cs , as most of the short-lived radionuclides decayed before they were deposited on the ground. Environmental measurements made at this time did not make it possible to relate the contamination to a specific test.

Because of those differences, fallout from tests conducted at the NTS and from tests carried out far away from the US are considered separately.

2.1. Deposition of ^{131}I from the NTS

Iodine-131, now recognized as one of the most important radionuclides in terms of public exposures, was not measured directly in the 1950s because most measurements of environmental radioactivity at that time were limited to gross beta (β) activity, or to radiochemical measurements of ^{90}Sr , the radionuclide of most concern at the time. Measurements of ^{131}I in the environment were not performed to any significant extent before 1960.

The data on which we relied for estimating the amounts of ^{131}I deposited on the ground were: (1) ground-level exposure rates (Beck and Anspaugh, 1991; Thompson et al., 1994); and (2) measurements of total β -activity deposited on sticky paper (more commonly called *gummed film*) as part of a systematic monitoring program by the US Health and Safety Laboratory (Harley et al., 1960; Bouville and Beck, 2000).

For counties nearest the NTS, the primary data used for estimation were exposure-rate measurements made for several days following each test with portable survey instruments. These exposure-rate measurements, together with other, less extensive, monitoring data, were evaluated and archived by the Offsite Radiation Exposure Review Project (ORERP) of the Department of Energy (Church et al., 1990). From these data, two databases were developed: the Town Data Base (Thompson et al., 1994) and the County Data Base (Beck and Anspaugh, 1991). Both databases provided exposure rates normalized to 12 h post-detonation (H + 12) and estimated times of transit (measured in hours) for the fallout to arrive at the measurement location (typically called the *time of arrival*). The areas included in the two databases were parts or the entirety of the states of Arizona, California, Colorado, Idaho, New Mexico, Nevada, Oregon, Utah, and Wyoming.

Monitoring of fallout deposition at greater distances was carried out primarily by the Health and Safety Laboratory (HASL) of the Atomic Energy Commission (AEC) in cooperation with the US Weather Bureau (Harley et al., 1960; Beck, 1984; Bouville and Beck, 2000). Beginning in the fall of 1951, the monitoring technique employed consisted of collectors in the form of trays of water, though these devices were replaced by gummed paper for the 1952 test series. The gummed

paper was replaced by an acetate-backed rubber-base cement gummed film in 1953, and this medium was used until the program ended in 1960. A $0.3 \text{ m} \times 0.3 \text{ m}$ (1 ft^2) area of gummed film was positioned horizontally on a stand about 0.9 m above the ground. Usually two replicate films were exposed simultaneously during a 24-h period. The collected samples were ashed and counted for total β -activity. The number and types of monitoring sites in operation in the US varied from one year to another; the maximum number of sites was 95 in 1953.

In this research, measurement data of either exposure rate or β -activity per unit area were converted to deposition density (Bq m^{-2}) of ^{131}I via relationships and factors developed by Hicks (1981, 1982, 1984). Factors specific to each test at the NTS were developed to take account of differences in bomb composition and design, though some of these data remain classified. One critical element in converting either type of measurement to a specific radionuclide activity is the time of the measurement relative to the time of the detonation. It is also known that factors such as distance and whether wet or dry deposition is involved affects the composition of the radionuclide mixture deposited on the ground, though the Hicks methodology, as used here, does not make adjustments for these factors.

The quantitative estimation of the deposition densities of ^{131}I (Bq m^{-2}) from the gross β -activity measurements was a use not foreseen in the original design of the gummed-film monitoring program (Beck et al., 1990). However, the value of these data for that purpose has been proven in several dose reconstruction studies (Beck and Bennett, 2002). When there were sufficient numbers of ^{131}I deposition estimates across the US, they were used, together with precipitation data, to interpolate values of deposition in counties in which there were no β -activity measurements. The interpolation procedure used kriging, a statistical technique that minimizes estimation variance from a predefined covariance model (see, for example, Clark, 1979; Isaaks and Srivastava, 1989; Cressie, 1993). Where kriging was unlikely to be satisfactory because of limitations in the availability of deposition estimates, a simpler method was employed using the deposition estimate from the nearest county having monitoring data and the precipitation data for both counties (NCI, 1997).

The daily deposition densities in each county following individual NTS tests were summed to obtain totals for each test. It should be understood that the total deposition densities reported by NCI (1997) and DHHS (2001), and in Figs. 1–3, are time-integrated values, i.e. they represent a summation of the activity deposited at the times of deposition, without taking radioactive decay into account.

2.2. Deposition of radionuclides other than ^{131}I from the NTS

The estimation of radionuclides other than ^{131}I from the NTS relied on previously published methods, e.g. Hicks (1982, 1990); Beck et al. (1990); Church et al. (1990); Beck (1996), and NCI (1997) estimates of ^{131}I (see Fig. 1). In this research, we estimated deposition densities for 42 additional radionuclides generated from about 60 of the approximately 100 atmospheric tests conducted at the NTS. These

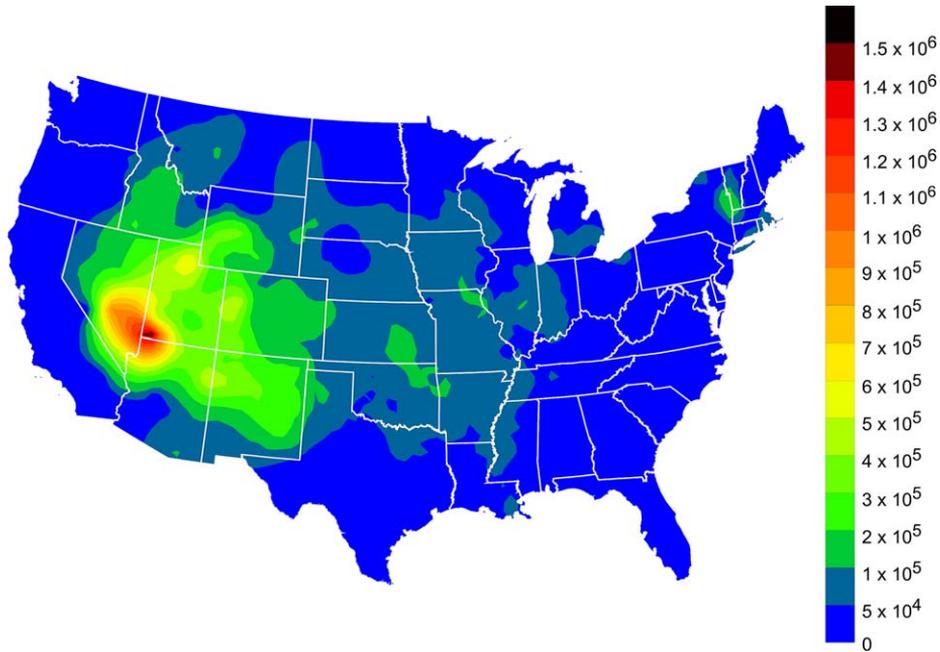


Fig. 1. Estimated ^{131}I deposition density (Bq m^{-2}) from NTS fallout across the continental US.

60 tests account for over 95% of the total ^{131}I produced there. The radionuclides considered included all those that contributed significantly to either external exposure or to internal exposure via ingestion. They included isotopes of the elements strontium, yttrium, zirconium, niobium, molybdenum, technetium, ruthenium, rhodium, iodine, tellurium, cesium, barium, lanthanum, cerium, praseodymium, neodymium, promethium, neptunium, plutonium, and americium.

The starting point for the estimation of the deposition of these various radionuclides was the daily ^{131}I deposition density estimates (the sum of which is shown in Fig. 1) from NCI (1997). Calculations were carried out separately for each county of the US and, in some cases, for areas smaller than counties when the deposition varied greatly within the county. The daily estimates were summed to provide totals for each test, each year, and for the entire NTS testing program. The county-specific deposition densities of each nuclide were calculated using the following three steps:

1. The daily ^{131}I deposition density estimates were decay corrected back to 12 h post-detonation (H + 12).
2. Using the relationships developed by Hicks (1981), the calculated ratio of each radionuclide being estimated to the corresponding ^{131}I value at H + 12 (including the ^{131}I that will subsequently grow in from precursors) was calculated as a function of fallout arrival time.

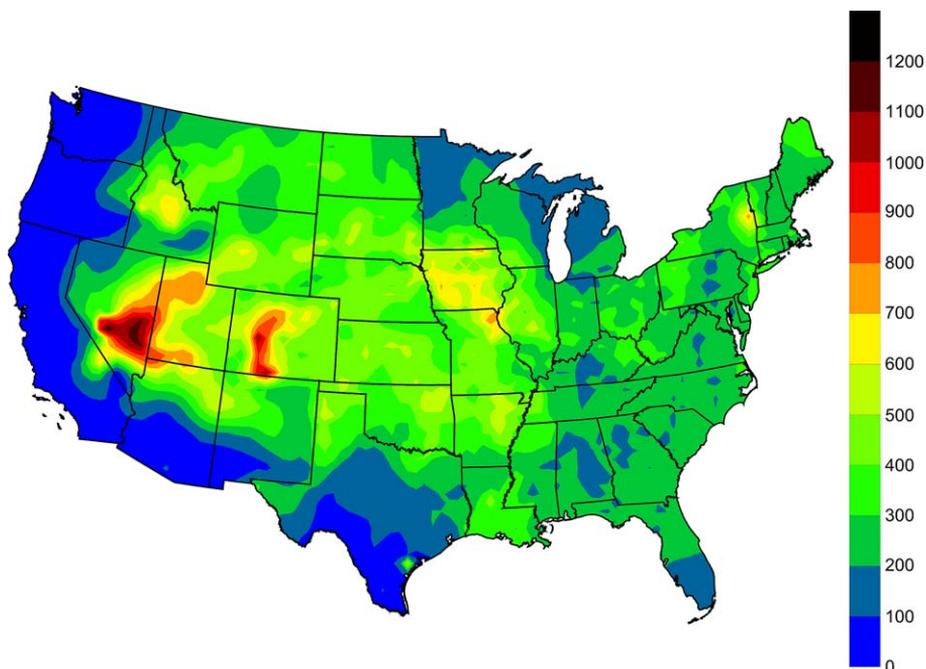


Fig. 2. Estimated ^{137}Cs deposition density (Bq m^{-2}) from NTS fallout across the continental US.

3. The ^{131}I deposition density estimate for each day of fallout (corrected back to H + 12), obtained in step 1, was multiplied by the nuclide-specific ratio calculated for each day's arrival (obtained in step 2) to estimate the deposition density on each day for the particular nuclide.

Generally, about 10 days of measurements had to be considered for each nuclear test, although a few tests produced significant fallout for periods of up to 2 weeks. Daily deposition densities were calculated only for short-lived nuclides (those with half-lives less than 30 days). For longer-lived nuclides, their ratios to ^{131}I at H + 12 did not vary significantly over the first several weeks of fallout and, thus, the total test deposition could be calculated directly from the sum of the daily ^{131}I depositions.

Plutonium isotopes were also present in the fallout from Nevada weapons tests. Plutonium isotopes do not contribute significantly to external exposure, contribute in only a minor way to ingestion dose and, normally, contribute only a small fraction of the fallout-related inhalation dose (Church et al., 1990). Nevertheless, there remains public interest in the isotopes of plutonium and for this reason, deposition estimates for such nuclides were made. These latter estimates were necessarily crude, however, because the ratios of Pu to ^{137}Cs , ^{90}Sr , etc. are still classified. Average deposition of $^{239+240}\text{Pu}$ in counties of the US was estimated to vary from

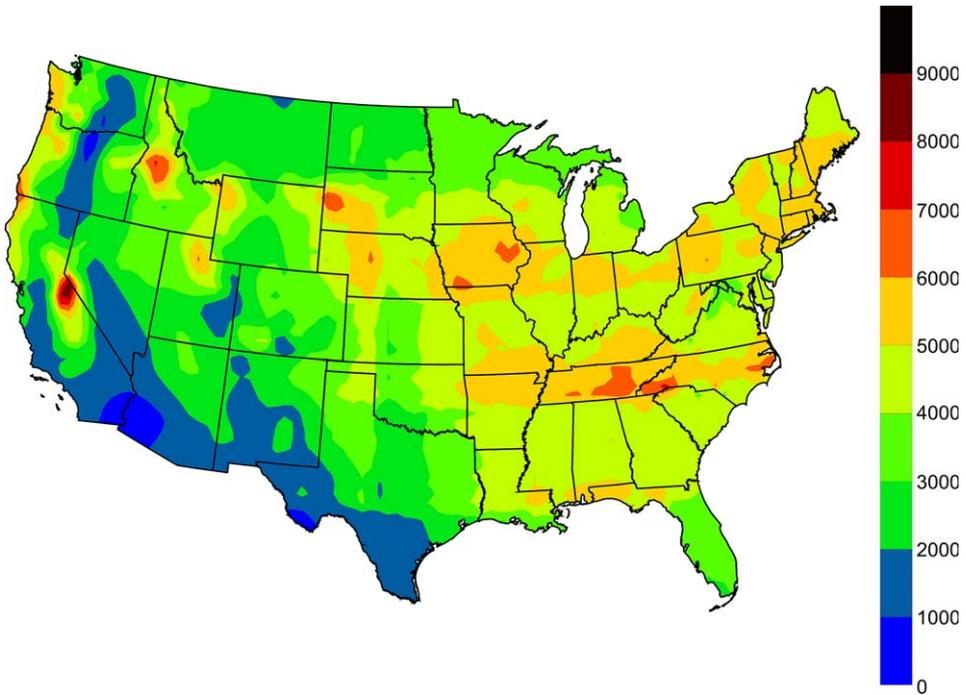


Fig. 3. Estimated ¹³⁷Cs deposition density (Bq m⁻²) from global fallout across the continental US.

0 to 150 Bq m⁻² (see Beck and Bennett, 2002, Fig. 18). No further discussion of plutonium deposition is presented here. Interested readers are referred to Appendix D of DHHS (2001), (see <http://www.cdc.gov/nceh/radiation/fallout/default.htm>).

2.3. Deposition of radionuclides from global fallout

Global fallout occurred mainly in the early 1960s and was primarily composed of long-lived radionuclides (e.g. ⁹⁰Sr and ¹³⁷Cs). Relatively abundant measurements of ⁹⁰Sr, which was at that time considered to be more hazardous than ¹³⁷Cs, were made throughout the US.

The estimation of the geographic distribution of global fallout depends heavily on data on rainfall patterns across the US. Previous US studies have demonstrated that the deposition of ⁹⁰Sr and ¹³⁷Cs in global fallout was generally proportional to the amount of precipitation over localized areas (Collins and Hallden, 1958; Martell, 1959; Alexander et al., 1961; Hardy and Alexander, 1962; Hardy et al., 1968; Krey and Beck, 1981; Beck and Krey, 1983). However, the relationship between deposition density and rainfall (Bq m⁻² per cm of rain) was known to vary significantly with both latitude and longitude across the continental US. Historical data show that there was a maximum in the 35–40° latitude band.

The deposition at low latitudes was observed to be less than at the latitude of peak deposition by about a factor of two (Alexander et al., 1964). Similarly, a variation in the deposition density of ^{90}Sr per unit rainfall with longitude was observed from 1958–1965 at HASL monitoring sites. These data indicate a clear trend of a relatively constant deposition density per unit rainfall in the eastern US and a steep increase towards the mountainous area of western Colorado, Utah, and Wyoming (Beck and Bennett, 2002). The deposition density per unit rainfall reached a peak at approximately the longitude of Salt Lake City and dropped steeply towards the West Coast to levels lower than in the northeastern US. The observed dependencies with latitude and longitude were used to create a simple time-independent model of the variation of ^{90}Sr deposition over the country in order to estimate ^{90}Sr deposition densities for each county of the continental US (DHHS, 2001).

Data on daily precipitation amounts were obtained from records of over 8000 US Weather Service cooperative monitoring sites, some of which have operated since about 1900. For this work, daily rainfall amounts at each measurement station were summed to produce a single estimate of monthly precipitation. A representative value for the rainfall within each county for each month during the years 1953–1972 was obtained by averaging the data for each site in operation in the county during that month. If no data were available for a county in a particular month, the value for the nearest county, as defined by the shortest distance between county centroids, was used.

Prior to 1954, there were no reported measurements of ^{90}Sr from which to make a direct determination of the deposition density per unit rainfall. However, soil sample data were available for a few sites in the eastern US. These provided a crude estimate of the total deposition of ^{90}Sr from global fallout up to 1954. Almost all of that deposition was assumed to have occurred in 1953, primarily as a result of the high yield US tests carried out in the Pacific in late 1952. Because monitoring of fallout deposition was carried out at only a limited number of sites in the US, a simple model of deposition density of ^{90}Sr per centimeter of precipitation was constructed for estimation purposes by assuming a constant value within 25 areas defined by latitude and longitude covering the US (see DHHS, 2001, Appendix F).

The method used to estimate the deposition of radionuclides from global fallout comprises five steps:

1. The average precipitation for each month for each county of the continental US was estimated from US Weather Service records;
2. The deposition density of ^{90}Sr per unit precipitation in the northeast US for each month from 1952 through 1971 was estimated from monitoring data where available. The deposition for other areas of the US was estimated from measured monthly precipitation and a simple model describing the variation of ^{90}Sr deposition density per unit precipitation as a function of latitude and longitude;
3. The ratio of the deposition of each nuclide of interest to the deposition of ^{90}Sr for each month during the period 1953–1972 was estimated using actual data if data were available, or, if no data were available for a particular period, a

model was used to estimate the ratio of the deposition density of that nuclide to that of a nuclide of similar half-life for which data were available;

4. The monthly deposition density of each radionuclide was then calculated by multiplying its estimated ratio to ^{90}Sr for that month by the estimated ^{90}Sr deposition density for that month; and
5. The total amount of each radionuclide deposited on the ground in each county was calculated as the summation of the estimated monthly depositions.

It should be noted that the method described here does not account for dry deposition. For most areas of the US, dry deposition was probably less than 10% of the total deposition. Nevertheless, for any month in which the precipitation was very low, dry deposition may have been more significant than estimated. The estimates for fallout in the arid west are likely to be under-estimated, though the total fallout in these counties would still have been relatively small compared to counties with annual precipitation rates equal to, or greater than, the national average.

3. Findings and discussion

The findings from these investigations are discussed at length in [NCI \(1997\)](#), [DHHS \(2001\)](#), and [Beck and Bennett \(2002\)](#). This discussion is limited to a summary of the geographic pattern of deposition of ^{131}I and ^{137}Cs and to the total nationwide deposition of nine other radionuclides.

The time-integrated deposition density of ^{131}I (Bq m^{-2}) from all NTS tests, calculated as the geometric mean value for each county and interpolated (smoothed) via commercially available mapping software, is shown in [Fig. 1](#). The estimated time-integrated deposition densities for all counties ranged from less than 50 kBq m^{-2} to about 1400 kBq m^{-2} . The pattern of deposition shows the highest values in an oval shaped area that extends from the NTS in a southeast direction over the corner of the state of Utah (Washington County, Utah). The average deposition density in these counties was 1000 kBq m^{-2} or larger. A considerably larger area with lower deposition values (600 kBq m^{-2} or less) extended north, northeast, and southeast in an irregularly shaped pattern with the NTS as the focal point. Most of the rest of the US, in particular the coasts and the distant eastern states, had very low levels of deposition of ^{131}I from the NTS except for isolated locations where rainout events occurred. The well-documented elevated deposition in northern New York State was due to heavy thunderstorm activity during passage of the cloud from shot SIMON in April, 1953 ([Hoecker and Machta, 1990](#); [Beck et al., 1990](#)).

The geographic pattern of deposited ^{131}I from global fallout is still under investigation. Uncertainties in individual county deposition estimates are presently too great to produce a reliable map or geographic pattern. However, in our research we estimated a total deposition of ^{131}I of about $1.1 \times 10^7 \text{ Bq}$ over the US from global fallout ([Table 1](#)). Calculations indicated that fallout from the NTS deposited about 13 times more ^{131}I within the US than did global fallout ([DHHS, 2001](#)) even

Table 1

Total deposition (Bq) and population-weighted deposition density (kBq m⁻²) of selected radionuclides in the US from NTS and global fallout (DHHS, 2001)

Nuclide	Half-life	Total deposition ($\times 10^{15}$ Bq)		Population-weighted deposition density (kBq m ⁻²)	
		NTS	Global	NTS	Global
¹³¹ I	8.02 d	1480	110	190	18
¹⁴⁰ Ba	12.8 d	1400	290	140	46
¹⁴¹ Ce	32.5 d	500	210	54	34
¹⁰³ Ru	39.3 d	430	210	46	35
⁸⁹ Sr	50.5 d	330	210	36	35
⁹⁵ Zr	64.0 d	220	310	25	50
¹⁴⁴ Ce	285 d	40	300	4.6	46
¹⁰⁶ Ru	374 d	24	150	2.6	24
⁹⁰ Sr	28.8 y	1.8	19	0.11	2.9
¹³⁷ Cs	30.1 y	2.3	29	0.26	4.4
²³⁹⁺²⁴⁰ Pu	24,100 y/6560 y	0.13	~0.4	~0.015	~0.06

though the fission yield of NTS tests was only about 0.5% of the total fission yield worldwide (Beck and Bennett, 2002).

The time-integrated deposition density of ¹³⁷Cs from all NTS tests examined through 1962 is shown in Fig. 2. The pattern of deposition is similar to that for ¹³¹I (Fig. 1), although, due to its long half-life, the decrease in ¹³⁷Cs activity in the eastern US with increasing distance from the NTS is less than that for ¹³¹I. Time-integrated deposition densities ranged from more than 1 kBq m⁻² near to the NTS and along a high-rainfall corridor of the Rocky Mountains in Colorado to about 0.7 kBq m⁻² on the Central Plains, and to less than 0.1 kBq m⁻² for the coastal areas of the US. Similar to the case for ¹³¹I, the regional and local variations are due primarily to variations in precipitation.

The fraction of the total ¹³⁷Cs deposited in the continental US from NTS fallout varied by year. For example, the Plumbbob series in 1957 deposited 35% of the total NTS-related ¹³⁷Cs, followed by the Upshot Knothole series in 1953 that deposited 23%. In each county, the fraction of the total activity deposited in each year differed due to variations in directions and altitudes of fallout trajectories. Two tests (SIMON and HARRY) from the 1953 Upshot-Knothole series deposited the most ¹³⁷Cs of any NTS test. Test HARRY deposited the most ¹³¹I (NCI, 1997). The total amount of ¹³⁷Cs deposited in the continental US from all NTS tests was about 2.3×10^{15} Bq.

The time-integrated deposition density of ¹³⁷Cs from global fallout is shown in Fig. 3 and has a clearly different geographic pattern from that of NTS fallout, primarily reflecting the greater long-term average precipitation rates in the eastern US compared to the western states. Deposition of ¹³⁷Cs in global fallout over the eastern US varied between about 2.5 and 8 kBq m⁻² with large areas receiving 5–6 kBq m⁻². Most of the western US received relatively uniform but considerably lower deposition of about 2.5 kBq m⁻² or less. Some exceptions were small regions

in California, Idaho, and South Dakota, where high rainfall resulted in small areas of deposition equal to the highest areas in the eastern US.

The total deposition (Bq) for 10 other selected radionuclides from both NTS and global sources is shown in Table 1. The quantities of radionuclides that were deposited primarily reflect their fission yields and half-lives. In general, the deposition patterns for nuclides originating either in NTS fallout or in global fallout would be similar to their respective patterns of deposition of NTS and global ^{137}Cs . Table 1 also includes the time-integrated deposition density in each county weighted by its population and then summed. The population-weighted total is an appropriate indicator of the deposition that resulted in collective exposures to the US population.

As noted, precipitation was the main mechanism for the deposition of fallout from the high yield tests that injected their debris into the stratosphere. The three maps graphically indicate that counties in the eastern and mid-western US that received rainfall above the national average received more total deposition than counties in the more arid southwestern states. Since the states downwind of the NTS affected most by NTS fallout are, in general, more arid than the eastern US, the areas most affected by NTS fallout were generally the least affected by global fallout.

Other generalizations can be drawn from the figures and table provided. For example, fallout in the US from the NTS contributed only about 5% of the total deposition of the long-lived radionuclides, e.g. ^{90}Sr and ^{137}Cs . Most of the deposition of these radionuclides originated from high yield weapons tests carried out in the Pacific and in the former Soviet Union. Conversely, the deposition of short-lived radionuclides from the NTS, such as ^{89}Sr , ^{140}Ba and ^{131}I , was several times that deposited by global fallout. For example, the total deposition of ^{131}I in the US from NTS fallout was about 1.5×10^{18} Bq, compared to 1.1×10^{17} Bq from global fallout (Table 1). These results are consistent with the fact that although the total fission yield of NTS tests was about 1 Mt, compared to about 150 Mt for tests outside the US, most of the debris from the large thermonuclear tests outside the US was injected into the stratosphere. According to UNSCEAR (1993), the average residence time for this stratospheric debris before re-entering the troposphere and depositing is about 1 y. This delay in fallout deposition accounts for the reduced deposition of the short-lived activity relative to the amounts produced.

Not obvious from the maps is that tests conducted at the NTS deposited only about one-third of the ^{137}Cs they produced within the continental US. The proportion of the radioactivity produced by different tests that was deposited within a few hundred kilometers, as opposed to more distant locations, varied according to the method of device placement. For example, nuclear devices exploded on metal towers generated a larger proportion of heavy metallic particles that were deposited very close to the NTS, while air bursts that generated few such particles appeared to deposit greater fractions at distances of 1500–2500 km.

It is clear from the investigations we conducted that our calculations have numerous uncertainties, possibly the most significant source being the limited measurement data on which county deposition density estimates were based. Gum-

med-film measurements made at up to only about 100 locations after NTS tests required extensive interpolation to estimate deposition over large distance scales. Moreover, county estimates can only represent, at best, an average over the county, but cannot accurately or completely characterize local areas where meteorological or geographic characteristics resulted in higher or lower than average deposition.

In the area near to the NTS, estimating deposition from the large set of exposure rate measurements processed by the ORERP constitutes the preferred estimation method because these measurements were specific to a location and time and the response of the instruments is well understood and less variable than the gummed-film measurements.

4. Concluding remarks

The geographic pattern of deposition of ^{137}Cs from NTS and global fallout has been evaluated as well as the geographic pattern of ^{131}I deposition from NTS fallout. In addition, the deposition patterns and total nationwide inventories of numerous other fallout-related radionuclides have been evaluated for the first time. The geographic distribution of ^{131}I from global fallout is still highly uncertain, although the total nationwide deposition has been estimated.

Many of the calculations can be improved through further identification of historical data, more detailed analysis of data sets and, possibly, through the development of more sophisticated models of wet and dry deposition as well as latitude and longitude variations. Some limitations will remain, however, in that the amount of useful historical data will always be limited with respect to the size and geographic variability of the continental US. Nevertheless, these unique estimates of radionuclide deposition have been part of an effective response to public inquiries about the consequences of atmospheric nuclear testing in the US. Average doses and consequential health risks to the American population have also been assessed but are not discussed here. Interested readers are referred to the cited references.

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