Radiation Exposures in Utah from Nevada Nuclear Tests

Harold L. Beck and Philip W. Krey

Summary. The exposure of the population of Utah to external gamma-radiation from the fallout from nuclear weapons tests carried out between 1951 and 1958 at the Nevada Test Site has been reconstructed from recent measurements of residual cesium-137 and plutonium in soil. Although the highest exposures were found in the extreme southwest part of Utah, as expected, the residents of the populous northern valleys around Provo, Salt Lake City, and Ogden received a higher mean dose and a significantly greater population dose (person-rads) than did the residents of most counties closer to the test site. However, population doses from external exposure throughout Utah were far too low to result in any statistically observable health effects.

From 1951 through 1958, nuclear weapons tests were carried out at the Nevada Test Site (NTS) (Fig. 1). In recent years, concern has developed regarding the impact of fallout from those tests, both in the immediate vicinity of the NTS and in other parts of the United States. Claims have been filed against the government asserting that exposure to NTS fallout resulted in cancer or other illness, and bills have been introduced in Congress to compensate persons found to be victims of such exposures. Lyon *et al.* (*1*) recently reported that a statistically significant increase in mortality from childhood leukemia occurred in the population of a group of "high-fallout" counties in southern Utah (see Fig. 2) compared with control groups from periods before and after the years of testing. They reported that no comparable increase was observed in the population of the "low-fallout" counties of northern Utah.

For this apparent increase in leukemia mortality to have resulted from exposure to NTS fallout, based on currently accepted estimates of risk, significantly higher exposures than previously reported would have been required. However, the monitoring data obtained after the tests and used to estimate these exposures were limited geographically, extending only as far as southwest Utah, and were subject to large uncertainties (*2–4*). We therefore attempted to reconstruct the exposure to the population of Utah, for both the high- and low-fallout counties of Lyon *et al.*, by a completely independent method. We used (i) contemporary measurements of residual ^{137}Cs and plutonium in soil samples from undisturbed sites and (ii) in situ gamma-spectrometric analyses of ^{137}Cs soil activity. The fraction of the total ^{137}Cs at each site attributable to NTS fallout as opposed to global fallout (that is, fallout from non-NTS tests) was inferred from the ratio of ^{240}Pu to ^{239}Pu in the soil at each site. This fraction was then used to estimate the total deposition of all fission and activation products and, from this, the external radiation exposure and bone dose.

Experimental Procedure

Approximately 150 sites were investigated during the summer of 1979 in 56 population centers in Utah and western Colorado, as shown in Fig. 2. These sites were mostly grass-covered lawns which were verified through local sources to have been undisturbed for at least 30 years except for watering and minor maintenance. Well-maintained lawns were chosen in preference to pristine sites since we would expect them to have collected and retained essentially all the fallout deposited (*5–8*), whereas wind and water erosion might have removed some of the original fallout from the generally sparsely vegetated pristine sites, particularly in the more arid southern and eastern parts of Utah.

At each site the flux of uncollided 662-keV gamma-rays from ^{137}Cs in the soil was measured 1 meter above the ground by in situ gamma-ray spectrometry with a large Ge(Li) diode. This method provides reliable estimates of total soil activity of both naturally occurring and man-made radionuclides, provided the distribution of the sources with depth in the soil is known (*9*). The in situ ^{137}Cs flux measurements were used as a guide (assuming that the depth profile of ^{137}Cs did not vary too much from site to site) for choosing one or more representative sites per town for soil sampling and for eliminating sites thought to have been disturbed. At each of the soil sampling sites, eight to ten cores, 8.9 centimeters in diameter and approximately 18 cm apart, were taken in depth increments of 0 to 2.5, 2.5 to 5, 5 to 10 (sometimes omitted), and 10 to 30 cm (or 5 to 30 cm). The samples were dried, crushed, blended, and pulverized, and aliquots from each depth increment were analyzed for ^{137}Cs. Samples representing individual depth increments and composite cores to 30 cm were also analyzed for ^{239}Pu plus ^{240}Pu ($^{239 + 240}Pu$) and later for their plutonium mass isotopic composition. Details of the soil sampling, preparation, analyses, and concurrent quality assurance program have been reported, along with the results of each analysis and descriptions of the sampling sites (*10*).

The measured distribution of depth profiles of ^{137}Cs in the soil samples was used to obtain estimates of ^{137}Cs inventory at sites surveyed only by in situ spectrometry. We assumed that the depth profile at these sites could be represented by the mean of this distribution with an uncertainty related to the spread of the distribution. These estimates, although less precise than those obtained by soil sampling [standard deviation (S.D.), ±25 and ±8 percent, respectively]; served to corroborate that the soil sampling data were representative, fill in the pattern of deposition, and identify inconsistencies in the soil sample results.

The ±25 percent S.D. includes both the variance due to counting error (≤ ±5 percent S.D.) and that due to variations in the source depth profile from site to site. Systematic errors in the in situ analysis were found to be insignificant in

Harold L. Beck and Philip W. Krey are, respectively, senior staff member of the Radiation Physics Division and director of the Analytical Chemistry Division at the Environmental Measurements Laboratory, U.S. Department of Energy, New York 10014. The material presented in this article constituted part of the testimony for the federal government in the case of *Allen et al.* vs. *The United States of America*, in which it was charged that nuclear weapons tests at the Nevada Test Site in the 1950's caused a high incidence of cancer in nearby residents. Testimony in the trial was completed in December 1982 and a final ruling is pending.

comparison with the measurement precision. A comparison of ^{137}Cs inventories at the 43 sites where measurements were made by both in situ spectrometry and soil sample analysis indicated a systematic difference of < 5 percent. The systematic error in ^{137}Cs soil sample analysis is estimated to be < 5 percent, based on the analysis of standards traceable to the National Bureau of Standards. The quality of individual in situ measurements was monitored by comparing inferred natural background exposure rates with rates measured using a high-pressure ionization chamber.

The ±8 percent S.D. for the ^{137}Cs inventories obtained by soil sampling was inferred from the mean variance of duplicate samples from 11 towns. It includes an uncertainty due to counting, which is generally less than ±3 percent. Primarily it reflects the precision with which fallout can be estimated by this method of soil sampling. The in situ spectral analyses for total ^{137}Cs inventory and the determination of the variances in both the in situ and soil sampling techniques have been discussed in detail (*11*).

Our best estimate of the total ^{137}Cs soil inventory as of 1979 for each town surveyed is shown in Fig. 3. This value represents the mean for each town, calculated by weighting the individual determinations in the town by the inverse of their respective variances. The standard deviation of this best estimate is about ±5 to 10 percent for towns where soil samples were taken and about ±20 to 30 percent for towns where the estimate was based solely on in situ spectrometric measurements. Since the estimates based on soil samples generally had a much smaller variance than those from in situ measurements, the final estimates are highly biased toward the former. The standard deviation is smaller for the more populated towns, where more sites were surveyed. The number of sites surveyed in each town ranged from as few as one or two in smaller towns to nine in Salt Lake City. The individual ^{137}Cs inventories and standard deviation for each site surveyed have also been reported (*11*).

Calculation of Nevada Test Site Fallout Fraction

The total ^{137}Cs inventory at each site generally includes a small contribution from NTS, overshadowed by a much larger contribution from the worldwide fallout that occurred primarily during the late 1950's and early 1960's as a result of large-scale atmospheric testing of mega-

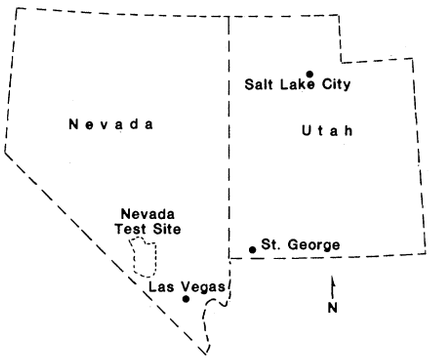

Fig. 1. Map showing the location of the NTS. Las Vegas, Nevada, and St. George and Salt Lake City, Utah, are shown for reference.

ton-sized devices in the Pacific and the Soviet Union. The large variations in ^{137}Cs inventory across the state, shown in Fig. 3, primarily reflect variations in this global fallout, deposited mainly through rainout, and correspond to the large geographic variations in mean annual precipitation in Utah (*11*). It was thus not possible to precisely determine the NTS fraction from the observed pattern of total ^{137}Cs inventories, although we can make a rough estimate of the expected global fallout from the mean annual rainfall in a town.

We can precisely determine the NTS fraction from the plutonium mass isotopic data, however. Because of the differences in weapon construction and the much greater neutron fluxes associated with the later high-yield tests, the atom ratio of ^{240}Pu to ^{239}Pu in accumulated global fallout is much larger than in the fallout from the generally lower yield tests at NTS. This ratio for global fallout accumulated through 1979 is 0.180 ± 0.006, based on a worldwide program of sampling conducted at 21 sites in 1970 and 1971 between 30° and 60°N (*12*). The standard deviation was calculated from the observed variance of these data. This ratio was confirmed in samples collected in the eastern United States in 1979 (*10*). We have shown that the appropriate ratio for NTS fallout in

Fig. 2. Location of population centers where ^{137}Cs inventories were measured. Circled values are numbers of sites surveyed. The heavy line divides the state into the regions of high and low fallout defined by Lyon *et al.* (*1*).

Utah is 0.032 ± 0.003, based on soil samples taken from the Salt Lake City area in the late 1950's and on classified isotopic ratios known for the individual NTS tests (*10*). We found that a single ratio could be adopted for all sites in Utah because variations from test to test were relatively small prior to 1957, when most of the fallout was deposited, and most of the sites probably received fallout from a number of tests. As discussed later, for most sites the determination of NTS fallout is not sensitive to small variations in the ratio.

The standard deviation of this isotopic ratio was estimated from the observed variance in the classified ratios for individual tests as well as from other experimental data regarding the credible range of possible values. The determination of the best value for this ratio and its standard deviation for Utah sites has been discussed in detail (*10*).

For a soil sample containing plutonium from one or both of these sources, the fraction of the total $^{239+240}$Pu activity from each source can be calculated as follows (*13, 14*):

$$\frac{(\mathrm{Pu})_N}{(\mathrm{Pu})_G} \equiv Y = \frac{(R_G - R_S)}{(R_S - R_N)} \frac{(1 + 3.73\,R_N)}{(1 + 3.73\,R_G)} \quad (1)$$

where Pu is the $^{239+240}$Pu activity, R is the atom ratio of ^{240}Pu to ^{239}Pu, 3.73 is the half-life ratio of ^{239}Pu to ^{240}Pu, and the subscripts G, N, and S represent global, NTS, and sample, respectively. Since

$$(\mathrm{Pu})_G + (\mathrm{Pu})_N = (\mathrm{Pu})_S$$

$$(\mathrm{Pu})_G = \frac{(\mathrm{Pu})_S}{1 + Y} \quad (2)$$

Studies conducted in 1971 showed that the activity ratio of ^{137}Cs to $^{239+240}$Pu from global fallout is a constant in soil throughout the north temperate zone (*6*). Our best estimate of this ratio as of 1979, based on the data and samples collected in 1979, is 53 ± 0.5 (S.D.). The standard deviation estimate is based on the variance of all the observations. The NTS ^{137}Cs in each soil sample can thus be calculated from Eq. 2 as

$$(^{137}\mathrm{Cs})_N = (^{137}\mathrm{Cs})_S - 53 \times (\mathrm{Pu})_G \quad (3)$$

$$(^{137}\mathrm{Cs})_N = (^{137}\mathrm{Cs})_S - 53 \times \frac{(\mathrm{Pu})_S}{1 + Y} \quad (4)$$

This method does not require a knowledge of the ratio of NTS ^{137}Cs to NTS $^{239+240}$Pu, which varied widely, and it provides correct results even if all or most of the NTS fallout at a site resulted from only uranium-fueled weapons.

Because of the uncertainties in the various soil analyses and in the constants in Eq. 1, the lowest reliable estimate that could be made of NTS ^{137}Cs from our data was usually about 5 millicuries per square kilometer (*10*). This corresponds to about 9 mCi/km^2 when corrected for decay to the approximate mean time of the actual deposition. A sensitivity analysis demonstrated that for most sites the uncertainty in R_N was usually a minor contributor to the total uncertainty in the NTS ^{137}Cs determination. The imprecision in total ^{137}Cs and total plutonium inventories accounts for most of this uncertainty since the NTS ^{137}Cs, obtained from Eq. 4 as a difference, was usually only a small fraction of the total ^{137}Cs in the soil. In general, the estimated standard deviation in our NTS ^{137}Cs inventories by this method ranged from 5 to 10 mCi/km^2. These uncertainties were calculated by combining the standard deviations of the soil analyses, discussed earlier, with the uncertainties in the constants used in Eqs. 1 to 4. Systematic errors in sample analysis are not included but are considered to be negligible in comparison.

In order to estimate NTS ^{137}Cs at sites where no soil sample was taken or where the soil analysis results were suspect, we used the known correlation of global fallout within limited geographic regions with amount of rainfall (*15, 16*). Using our ^{137}Cs results for the soil sampling sites, we found that for Utah a least-squares fit resulted in $(^{137}\mathrm{Cs})_G = 2.22\,P + 26$ mCi/km^2, where P was the annual precipitation in centimeters (*10*). The uncertainty in this fit suggested that the global ^{137}Cs could be estimated from the annual precipitation to within ±13 percent (S.D.) for any site in Utah with annual rainfall within the range covered by the observed correlation, which was 15 to 50 cm. This value of global ^{137}Cs was then subtracted from the total ^{137}Cs inventory at the site. Since the total inventory could be estimated to only

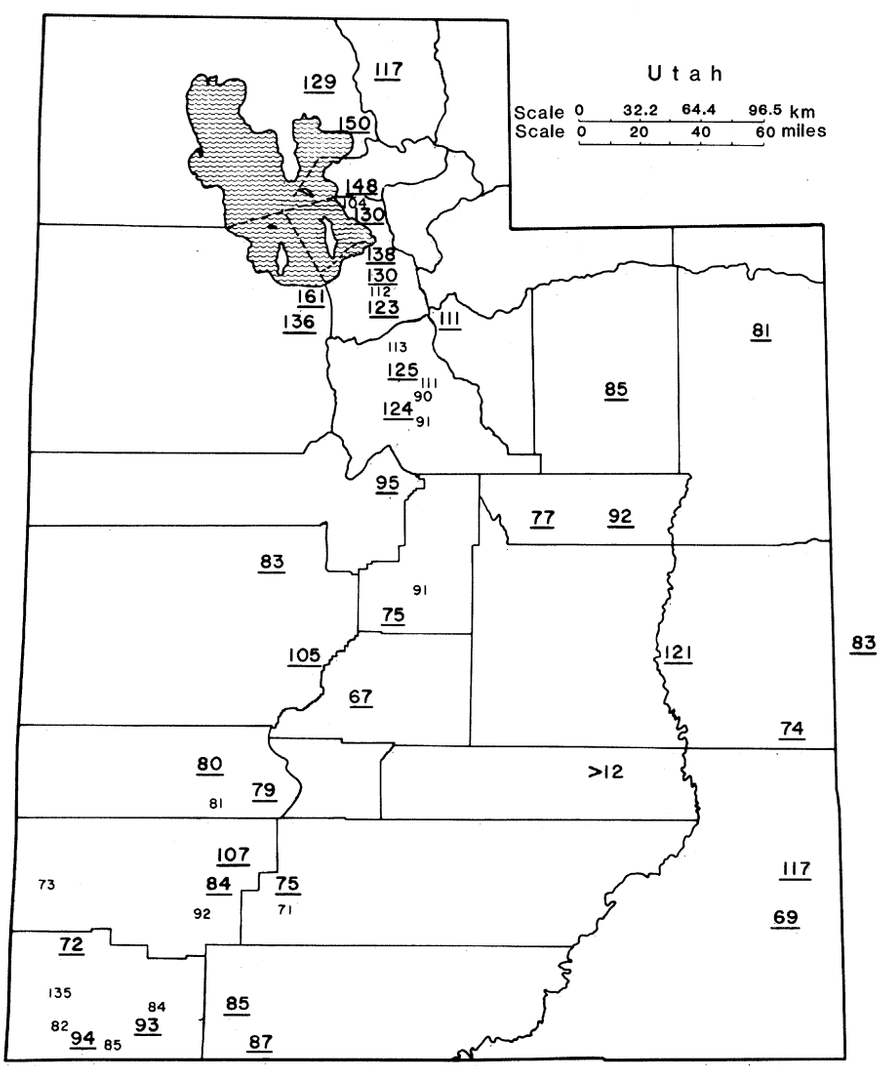

Fig. 3. Total ^{137}Cs inventories (millicuries per square kilometer) in Utah population centers as of 1979. Underlined values are from soil sample analyses; values in smaller type are less precise estimates from in situ spectrometry.

about ±25 percent from the field spectral data, using the statewide mean depth profile at sites where the actual depth profile was not measured, and about ±10 percent if the exact depth profile was known for that site, these rainfall-based estimates of NTS ^{137}Cs were generally of lower precision than the estimates based on soil samples. They did, however, serve to fill in the fallout pattern and to confirm the overall consistency of the soil sampling results.

The general validity of this method has also been confirmed by an independent estimate of NTS ^{137}Cs deposition made for the Enterprise area in southwest Utah by Krey *et al.* (*17*). Krey *et al.* dated the various layers of sediment in an undisturbed core taken from Enterprise reservoir and determined that the areal deposition of ^{137}Cs before 1958 was less than 19 mCi/km^2. Since some of this ^{137}Cs is known to be due to global fallout, this result is in excellent agreement with the value of 14 mCi/km^2 for NTS ^{137}Cs inferred from soil samples taken in the vicinity of the reservoir and analyzed according to the method described in this article. Similar experiments are in progress at bodies of water in north-central Utah.

Our final best estimates of NTS ^{137}Cs and NTS $^{239+240}$Pu inventories as of 1979 for each town surveyed are shown in Fig. 4, a and b, respectively.

Calculation of Exposure

The estimated NTS ^{137}Cs deposition for each town was used to determine the total deposition of all fission and activation products and, from that, the total free-air radiation exposure to the population. Hicks (*18, 19*) calculated the relative deposition of each fission product and activation product for each NTS test as a function of time after detonation. He also calculated the resulting free-air exposure rate at 1 m above the ground in an open field as a function of time for a unit measure of this fallout. These calculations were reported for various degrees of fractionation (reduction in the relative concentrations of refractory elements due to their tendency to fall out closer to ground zero than do volatile elements). Hicks (*19*) presented data indicating that, for the distances of interest in this study, 50 percent of the refractories were generally lost. Using Hicks' calculations, we found that one can derive a single factor for all NTS tests to convert ^{137}Cs deposition to integrated exposure (*20*). This factor depends only on the time of arrival of the fallout and varies from 73 to 44 mR/mCi-km^2 over the range of expected arrival times, which is 3 to 24 hours.

Using our best estimates of the mean time of arrival of fallout in various areas of Utah, we applied this factor to the 1979 NTS ^{137}Cs inventories shown in Fig. 4a after they were corrected to the approximate mean time of actual deposition. The results are shown in Fig. 5. The uncertainties in these exposure estimates are only slightly greater than those for the NTS ^{137}Cs inventories because the total uncertainty in the conversion factor from deposition to exposure is only about ±20 percent (S.D.). This combines the statistically independent uncertainties due to variations in nuclide fractionation (±10 percent S.D.), weathering of nuclides into the soil (±5 percent S.D.), time of arrival of fallout (±10 to 15 percent S.D.), and variations from site to site in the conversion factor from soil activity to exposure (±5 to 10 percent S.D.). These uncertainty estimates are discussed in detail in Beck and Krey (*20*), where we also list the fallout arrival times used for each town surveyed.

We note that our estimated exposures are probably conservative, that is, biased high. Our sampling sites were chosen because they were thought to have collected and retained all the fallout deposited on them. We would expect the true exposure rates in most areas where people live or congregate to have been reduced by wind and water erosion of fallout from streets, paved surfaces, or unstabilized soil, or by human activities that remove fallout from the surface soil or redistribute it deeper in the ground.

Although some of our estimates for individual towns have large uncertainties, particularly the lower values, we consider that the results shown in Figs. 4 and 5 reasonably reflect the actual pattern of fallout and exposure in Utah. By averaging over population groups, we can make more precise estimates of exposure for various areas of Utah. We were particularly interested in comparing the mean exposures to the populations of the high-fallout and low-fallout groups of counties of Lyon *et al.* (*1*). To do this, we computed (i) the population-

Table 1. Estimates of population exposure by county.

County	1950 population (×10^3)	Population-weighted mean individual exposure (R)	Population exposure (×10^3 person-R)
	*"Low-fallout" counties**		
Box Elder	19.7	0.6 ± 0.6	10
Tooele	14.6	0.7 ± 0.7	10
Cache	33.5	1.1 ± 0.7	37
Rich	1.7	~ 1.1 ± 1.1†	1.9
Weber	83.3	1.8 ± 0.5	150
Davis	30.9	1.3 ± 0.5	40
Morgan	2.5	~ 1.5 ± 0.8	3.8
Salt Lake	275.0	1.2 ± 0.5	330
Summit	6.7	1.1 ± 0.7	7.4
Daggett	0.4	~ 0.7 ± 0.7	0.3
Wasatch	5.6	0.5 ± 0.5	3
Utah	81.9	1.5 ± 0.5	120
All counties	556	1.3 ± 0.3	713
	*"High-fallout" counties**		
Juab	6.0	0.6 ± 0.4	4
Millard	9.4	1.5 ± 0.4	14
Beaver	4.9	0.7 ± 0.5	3
Iron	9.6	0.7 ± 0.5	7
Washington	9.8	3.5 ± 0.7	34
Kane	2.3	0.7 ± 0.7	2
Garfield	4.2	0.4 ± 0.4	2
Piute	1.9	~ 0.8 ± 0.8	1
Wayne	2.2	~ 0.8 ± 0.8	2
Sevier	12.1	0.2 ± 0.4	2
Sanpete	13.9	0.5 ± 0.4	7
Emery	6.3	1.9 ± 1.1	12
Carbon	24.9	0.3 ± 0.2	8
Duchesne	8.1	0.2 ± 0.3	2
Uintah	10.3	0.7 ± 0.5	7
Grand	1.9	0.9 ± 0.9	2
San Juan	5.3	1.1 ± 1.2	6
All counties	133	0.86 ± 0.14	115
State total	689	1.2 ± 0.2	828

*As defined by Lyon *et al.* (*1*). †The symbol ~ indicates that the value was extrapolated from neighboring counties.

weighted mean exposure for each county in Utah, extrapolating for towns not surveyed from the results for other towns in the same or neighboring counties, and (ii) the overall population-weighted mean for each of the two groups of counties. As shown in Table 1, we found that the ~ 133,000 people living in the high-fallout counties received an average exposure of 0.86 ± 0.14 (S.D.) R, compared to an average exposure of 1.3 ± 0.3 R for the ~ 556,000 persons living in the low-fallout counties. The standard deviations used here and in Table 1 are the result of propagating the estimated uncertainties in the exposures which were calculated for each individual town.

Discussion of Results

As shown in Fig. 4, the patterns of deposition of ^{137}Cs and $^{239+240}Pu$ from NTS were generally the same, with relatively high values in extreme southwest Utah, a decline with distance from the NTS to fairly low levels in the south-central region around Richfield and Gunnison, and then an increase to relatively high levels in the more populated north-central and northern valley areas around Provo, Salt Lake City, and Ogden. In fact, the NTS plutonium deposition at Provo was the highest measured anywhere in Utah. Higher than expected levels of NTS fallout were also found in eastern Utah and as far away as Grand Junction, Colorado. These higher than expected levels in northern Utah resulted in an estimated mean population exposure for the group of "low-fallout" counties which was approximately 50 percent greater than that for the group of "high-fallout" counties and, because of the greater population of the former, an approximately six times greater total population exposure (person-roentgens). Persons living in Salt Lake City received greater exposures than most Utah residents who lived far closer to NTS, although only about one-third as much as residents of Washington County.

The elevated fallout in and around Salt Lake City was not entirely unexpected. It was suggested a number of years ago by Hardy *et al.* (*21*) on the basis of comparisons of Salt Lake City and New York City with respect to soil sample analyses for ^{90}Sr. Hardy *et al.* estimated that Salt Lake City had received about 16 mCi of NTS ^{90}Sr per square kilometer through 1958. We used that information in inferring the appropriate ratio of ^{240}Pu to ^{239}Pu for NTS fallout in Utah (*10*). Also, data from the Atomic Energy Commission fallout monitoring network of gummed film collectors suggested that there was more NTS fallout at Salt Lake City and Grand Junction than at other U.S. sites more removed from NTS (*22–24*). Very few data are available for sites closer to NTS. The gummed film data indicate, however, that a large fraction of the fallout in Salt Lake City probably came from about a half-dozen tests where the cloud originally took a northerly track from NTS and later veered toward the northeast. The fallout at Grand Junction usually resulted from tests where the cloud track was originally toward the east (*25–28*).

The exposure estimates shown in Fig. 5 can be compared with exposure estimates based on the original postshot monitoring data for towns for which estimates are available from both sources. The original monitoring data have been converted to open field free-air exposures to correspond to our estimates, using factors provided by Anspaugh and Church (*29*). As shown in Table 2, the agreement is well within the reported uncertainties.

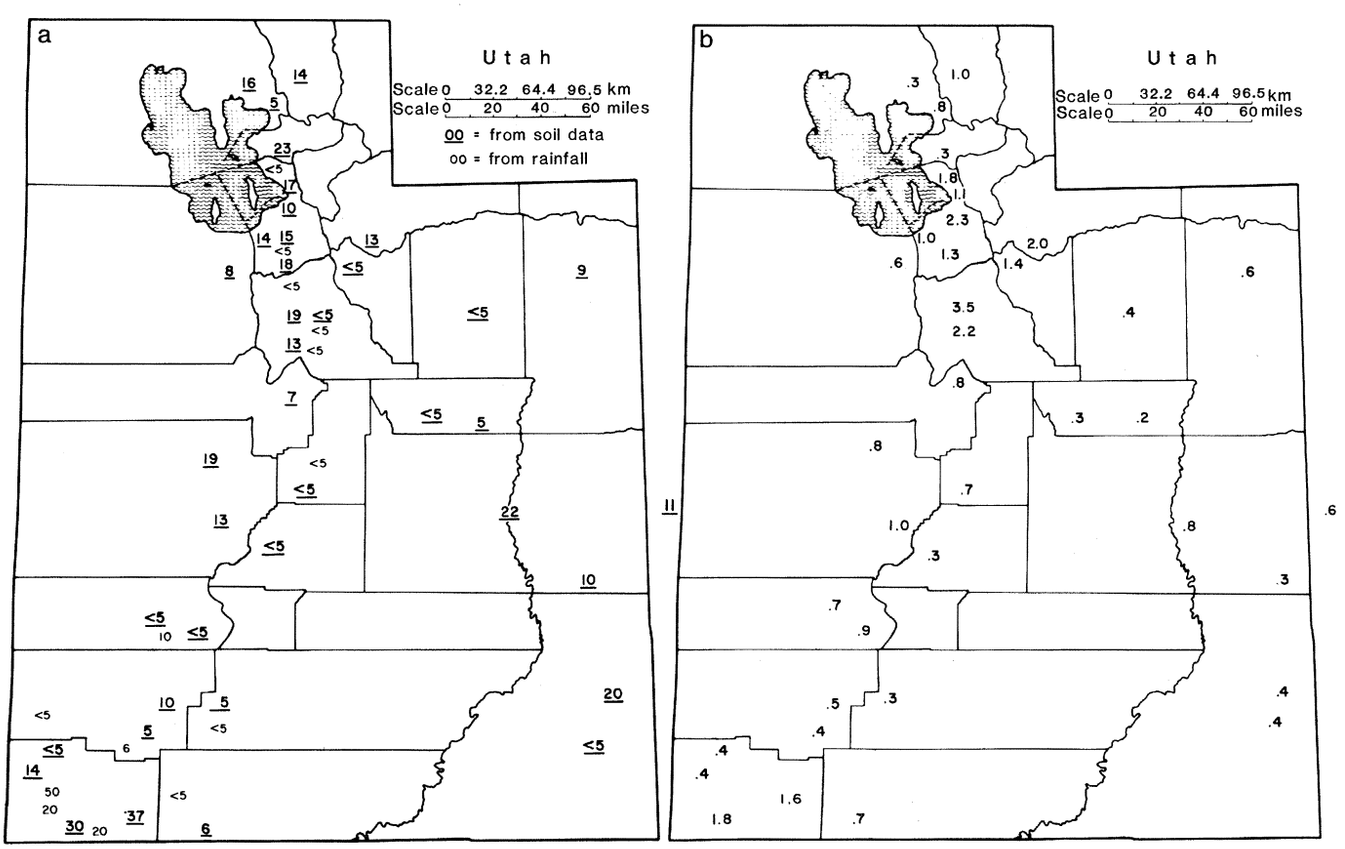

Fig. 4. (a) Best estimates of NTS ^{137}Cs in undisturbed Utah soils as of 1979. Underlined values are derived from plutonium isotopic analysis, while values in smaller type are less precise estimates made from mean precipitation and in situ spectrometry (see text). (b) Best estimates of NTS $^{239+240}Pu$ in Utah soils as of 1979. Values are millicuries per square kilometer.

Significance of Estimated Nevada Test Site Fallout

In order to place our estimated NTS fallout exposures for Utah in proper perspective, we have compared them with the exposures the same population received from global fallout and from natural background radiation. To do this, we first estimated the doses to bone resulting from our calculated open field free-air exposures. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) suggested that an average factor of 0.32 be used to convert open field exposures in roentgens to gonadal and bone doses in rads (*30*). This factor accounts for shielding by dwellings, the fraction of time spent indoors versus outdoors, and the self-shielding of the body. The factor will, of course, vary depending on life-style, type of housing, and so on, and thus the value appropriate for various areas of Utah may be slightly different from this suggested worldwide mean. The error resulting from use of the UNSCEAR factor is probably small and certainly less than the error in the exposure estimates themselves.

Our analysis includes only the doses from external exposure. The dose to bone from ingested and inhaled radionuclides was probably minor compared with that from external exposure. The former results primarily from long-lived nuclides such as ^{90}Sr and ^{137}Cs (*30*), while most of the external exposure from NTS fallout was from short-lived nuclides and occurred during the first few weeks after deposition (*20*). UNSCEAR estimated that the bone dose from internal exposure to global fallout was about equal to that from external exposure (*30*). But for global fallout, short-lived activity produced only a small fraction of the total external exposure because the arrival time was much longer than that for NTS fallout. Thus, the internal exposure dose to bone from NTS fallout would have been considerably less than the external exposure dose. Even if the internal pathway is found to be significant for some organs (such as thyroid), one would expect the geographic division of the internal dose to parallel the general fallout pattern. Studies are being made to estimate the dose from internal exposure more precisely and to determine the appropriate exposure-to-dose conversion factors for various areas of Utah (*31*).

Applying the UNSCEAR factor to the mean exposures found for selected population groups in Utah, including those considered by Lyon *et al.*, we obtain the estimated bone doses shown in Table 3. For comparison, we also show the corresponding bone dose to the same populations from natural background radiation (*32*) and global fallout (*30*).

Table 2. Comparison of integral exposure estimates with estimates based on monitoring data obtained after the tests at NTS. Values in parentheses are percent uncertainties. The estimated uncertainties in the monitoring data range from ± 40 to 60 percent (*2–4, 29*).

Town	Exposure estimate (R)	
	This article	Monitoring data
Beaver	≤ 0.6	0.5
Cedar City	0.6 (100)	0.9
Enterprise	1.7 (30)	1.3
Hatch	≤ 0.6	1.1
Hurricane–La Verkin	4.2 (50)	6.5
Kanab	0.7 (100)	2.9
Kanarraville	0.7 (300)	2.9
Milford	≤ 0.6	0.2
Minersville	0.6 (200)	0.4
Modena	≤ 0.6	1.0
Mt. Carmel	≤ 0.6	1.6
Panquitch	0.4 (100)	0.8
Parowan	1.1 (80)	0.8
St. George	3.7 (25)	6.1
Veyo	5.9 (100)	4.5
Washington	2.4 (100)	5.8

Table 3 shows that in Washington County, where the largest exposures to NTS fallout occurred, average bone doses due to external exposure were ten times greater than those the typical U.S. resident received from global fallout, while for residents of northern Utah the bone dose from NTS fallout was four times greater than that from external exposure to global fallout. Furthermore, for the average Utah citizen the bone dose per year from natural background radiation is about 14 mrad greater than the U.S. average, primarily because Utah has higher elevations and corresponding higher cosmic-ray exposures than most other areas of the United States. Over a life-span of 70 years, the natural background incremental dose is about twice the dose from NTS fallout. As shown in Table 3, residents of Beaver County received even higher natural background doses.

The doses calculated for all areas of Utah were far lower than required to cause a significant increase in leukemia mortality, based on the currently accepted best estimate of lifetime risk, which is about 2×10^{-5} per rad (*33*). In addition, Lyon *et al.* (*1*) estimated that, based on the experience of other exposed populations, "a marrow dosage of between 6 and 10 rads would be necessary to produce the excess of leukemia deaths that we found." Table 3 shows that the population of the "high-fallout" region to which Lyon *et al.* refer received an aver-

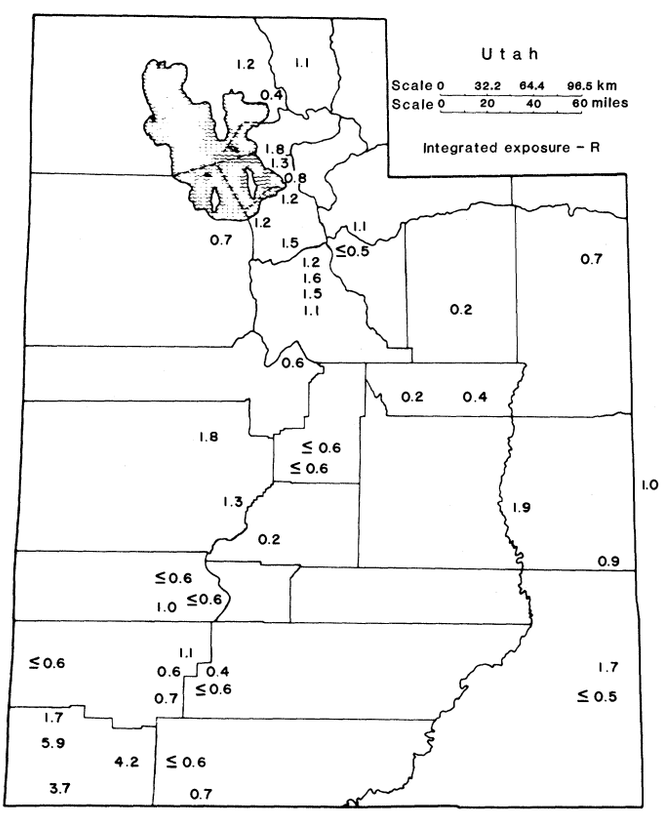

Fig. 5. Estimated mean open field free-air integral exposures [roentgens (R)] from NTS fallout in surveyed population centers.

Table 3. Estimated mean bone doses to Utah populations from external radiation.

Region	Estimated mean bone dose (mrad)		
	NTS fallout, time-integrated (this article)	Global fallout, time-integrated (*30*)	Natural background, per year (*32*)
Northern Utah ("low fallout")	420	~ 100	69
Southern Utah ("high fallout")	280	~ 50 to 75*	76
Washington County	1120	~ 50*	65
Beaver County	220	~ 60*	100
Utah, mean	400	~ 95*	70
United States, mean		~ 100	56

*Based on relative global fallout inventories (*10*).

age bone dose of about 0.3 rad. Based on our estimates of uncertainty at each stage of our analysis, the maximum error in this value is probably not more than a factor of 2, even considering the additional uncertainty in converting from exposure to bone dose. It thus seems unlikely that the excess leukemias observed by Lyon *et al.* resulted from exposure to NTS fallout. A relation between excess leukemias and exposure to NTS fallout is also inconsistent with our estimate that the much larger population of the "low-fallout" counties of northern Utah received an even larger mean dose with no corresponding relative increase in leukemia incidence.

Conclusions

The data collected during this study allowed us to confirm the exposure estimates made from the fallout monitoring data obtained after the nuclear weapons tests at NTS. They were also used to make exposure estimates for areas in Utah for which few or no monitoring data were available. From these estimates of NTS fallout and exposure, we conclude that:

1) Although the highest exposures to NTS fallout occurred in Washington County, in the extreme southwest part of Utah, as expected, the northern valleys of Utah received larger amounts of NTS fallout than did most counties much closer to NTS.

2) The population of northern Utah received higher average bone doses than did the residents of southern Utah. Thus the state should not be divided into geographic subgroups based solely on distance from NTS for the purpose of conducting epidemiologic studies of NTS fallout effects.

3) On the basis of currently accepted risk factors, bone doses to the population of southern Utah were far too low to account for the excess childhood leukemia mortality reported by Lyon *et al.* (*1*). Since the results of our study generally confirm the exposure estimates made from postshot monitoring data, it seems clear that this excess mortality did not occur because the exposures from NTS fallout were significantly greater than previously reported. Furthermore, the geographic pattern of fallout and exposure that we found is inconsistent with the conclusion that those leukemias resulted from exposure to NTS fallout, since no comparable increase in leukemia mortality was reported for northern Utah, where the total population dose was about six times greater than that for southern Utah.

4) The bone and whole-body doses that most Utah citizens received from external exposure to NTS fallout were small in comparison with the lifetime doses they receive from natural background radiation and only slightly greater than the average dose that they and most other U.S. residents receive from global fallout. Thus it seems unlikely that these exposures would have resulted in any observable health effects.

The NTS fallout inventories determined from soil sample analyses, which formed the basis for our exposure and dose estimates, are supported and confirmed by data obtained by a number of independent methods and sources. These include the global fallout–precipitation correlation, reservoir sediment analyses, measurements of ^{90}Sr in soils from the late 1950's, and gummed film data for Salt Lake City and Grand Junction.

References and Notes

1. J. L. Lyon, M. R. Klauber, J. W. Gardner, K. S. Udall, *N. Engl. J. Med.* **300**, 397 (1979).
2. G. M. Dunning, in *Fallout from Nuclear Weapons Tests, Hearings before the Joint Committee on Atomic Energy* (Government Printing Office, Washington, D.C., 1959), vol. 3, p. 2021.
3. A. V. Shelton, R. H. Gaeke, W. R. Kennedy, K. H. Larsen, K. M. Wagler, O. R. Placak, unpublished report of the Test Manager's Committee to Establish Fallout Doses to Communities near the Nevada Test Site (Coordination and Information Center, Reynolds Electric and Engineering Company, Las Vegas, Nev., 1959).
4. B. Shleien, *Health Phys.* **41**, 243 (1981).
5. E. P. Hardy, P. W. Krey, H. L. Volchok, *Nature (London)* **241**, 444 (1973).
6. E. P. Hardy, *USAEC Rep. HASL-288* (1975), p. I-2.
7. P. W. Krey, *Health Phys.* **30**, 209 (1976).
8. E. P. Hardy, M. W. Meyer, J. S. Allen, L. T. Alexander, *Nature (London)* **219**, 584 (1968).
9. H. L. Beck, J. DeCampo, C. Gogolak, *USAEC Rep. HASL-258* (1972).
10. P. W. Krey and H. L. Beck, *U.S. Dep. Energy Rep. EML-400* (1981).
11. H. L. Beck and P. W. Krey, *U.S. Dep. Energy Rep. EML-375* (1980).
12. P. W. Krey, E. P. Hardy, C. Pachucki, F. Rourke, J. Coluzza, W. K. Benson, *IAEA Rep. IAEA-SM-199/39* (1976), p. 671.
13. E. P. Hardy, P. W. Krey, H. L. Volchok, *USAEC Rep. HASL-257* (1972), p. I-95.
14. P. W. Krey and B. T. Krajewski, *USAEC Rep. HASL-249* (1972), p. I-67.
15. E. Hardy and L. T. Alexander, *Science* **136**, 881 (1962).
16. L. T. Alexander, R. N. Jordon, R. F. Dever, E. P. Hardy, G. H. Hamada, L. Machta, R. J. List, *USAEC Rep. TID-6567* (1961).
17. P. W. Krey, E. P. Hardy, M. Heit, *U.S. Dep. Energy Rep. EML-372* (1980).
18. H. G. Hicks, *Lawrence Livermore Lab. Rep. UCRL-53152* (1981), parts 1 to 8.
19. ———, *Health Phys.* **42**, 585 (1982).
20. H. L. Beck and P. W. Krey, *U.S. Dep. Energy Rep. EML-401* (1982).
21. E. P. Hardy, H. L. Volchok, P. W. Krey, *USAEC Rep. HASL-257* (1972), p. I-71.
22. M. Eisenbud and J. H. Harley, *Science* **124**, 251 (1956).
23. ———, *ibid.* **128**, 399 (1958).
24. J. H. Harley, N. A. Hallden, L. D. Y. Ong, *USAEC Rep. HASL-93* (1960).
25. R. J. List, *USAEC Rep. NYO-4512* (1953), part 2.
26. ———, *USAEC Rep. NYO-4602* (1954).
27. ———, *USAEC Rep. NYO-4696* (1956).
28. Unpublished data, Environmental Measurements Laboratory, U.S. Department of Energy, New York.
29. L. R. Anspaugh and B. W. Church, *U.S. Dep. Energy Rep. NVO-226* (1982).
30. UNSCEAR, *Report of the United Nations Scientific Committee on the Effects of Ionizing Radiation* (United Nations, New York, 1977).
31. The internal and external radiation exposure to residents of states downwind of the NTS is being reevaluated by a special multilaboratory Department of Energy (DOE) Offsite Radiation Exposure Review Project. This evaluation will include doses received from internal exposure due to ingestion and inhalation as well as external exposure and will consider variations in lifestyles and housing and their effects on exposure-to-dose conversion factors. Preliminary data from this project reported to the Dose Assessment Advisory Group in public hearings conducted at the DOE Nevada Operations Office indicate that the internal bone-dose pathway is small compared to the direct exposure pathway.
32. H. L. Beck, *U.S. Dep. Energy Rep. EML-362* (1979).
33. T. Straume and R. Lowry Dobson, *Health Phys.* **41**, 666 (1981).