

UCRL-CR-136121
B500874

Inventory and Distribution of Residual ^{137}Cs On and Near the Nevada Test Site

L.R. Anspaugh and R.D. McArthur

September 20, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Work performed under the auspices of the U. S. Department of Energy by the University of California Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (423) 576-8401
<http://apollo.osti.gov/bridge/>

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161
<http://www.ntis.gov/>

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
<http://www.llnl.gov/tid/Library.html>

Inventory and Distribution of Residual ^{137}Cs

on and near the Nevada Test Site

Lynn R. Anspaugh

Lynn R. Anspaugh, Consulting, P.O. Box 171319, Salt Lake City, Utah 84117

Richard D. McArthur

Las Vegas, Nevada

Abstract—The Nevada Test Site (NTS) was used for the testing of nuclear-weapons related devices from 1951 through 1992. The purpose of this paper is to derive estimates of the total amount of ^{137}Cs released by these explosions and to combine three different sets of data in order to estimate the amount of ^{137}Cs that was deposited within the nearby region consisting of the States of Nevada, Utah, Arizona, and New Mexico, and parts of Colorado, Wyoming, Idaho, Oregon, and California. The estimated release of ^{137}Cs is 6390 TBq most of which was released before the voluntary moratorium at the end of October 1958. Based upon measurement data the amount of ^{137}Cs deposited within the NTS itself and the domain of the study is 585 TBq, or about 10% of the total release. Isopleths of deposition on the NTS and within the domain of the study are presented.

INTRODUCTION

Following the first test of a nuclear explosive device on 16 July 1945 at Alamogordo, New Mexico, the next five tests were carried out in the Pacific on the Bikini (1946) and Enewetak (1948) Atolls. By then it was clear that the use of such remote test sites was expensive and inconvenient. The outbreak of the Korean War raised serious concerns about the ability to maintain security at these remote locations, and the successful, unanticipated test of a nuclear device by the former Soviet Union in August 1949 accelerated U.S. plans for the development of advanced nuclear weapons. Thus, the Atomic Energy Commission (predecessor agency of the Department of Energy and the Nuclear Regulatory Commission) reversed a prior decision and recommended that a continental test site be established (Friesen 1985) that would be used primarily for the testing of smaller devices. The selection of an area carved from the Las Vegas Bombing and Gunnery Range was approved by President Truman on 18 December 1950, and this site became known as the Nevada Test Site (NTS).

The first test at the NTS was conducted on 27 January 1951; the last test at NTS occurred on 23 September 1992 (DOE 1994). In all, 928 tests were conducted at the NTS with 828 of these underground and 100 in the atmosphere (DOE 1994). Several of the underground tests vented radioactive materials to a varying degree (Hicks 1981; DOE 1994; Schoengold et al. 1996). Listed in Table 1 are all of the tests at the NTS that are indicated in Hicks (1981) and DOE (1994) to have released radioactive materials to the off-site environment.

Testing in the atmosphere was common at the NTS until the end of October 1958, when a voluntary moratorium was entered into by the then nuclear powers. This moratorium was broken by the former Soviet Union in September 1961. The U.S. also resumed testing, but tests

at the NTS with few exceptions were designed to be contained. On 5 August 1963 the U.S. and the Soviet Union signed the Limited Test Ban Treaty (LTBT) that banned testing in the atmosphere. Exception for a few experiments on the use of nuclear devices for peaceful purposes (the Plowshare Program), which was allowed under specific conditions of the LTBT, all tests conducted at the NTS since the LTBT have been designed to be contained.

The purpose of the present paper is to examine the amounts of ^{137}Cs that have been released by these tests and to compare the released amounts with the amounts that were deposited within the region nearby the NTS. Fig. 1 indicates the domain of the study; it includes the NTS itself and the Phase I and Phase II areas of the Off-Site Radiation Exposure Review Project (ORERP) (Church et al. 1990). This area includes all of the States of Nevada, Utah, Arizona, and New Mexico and parts of the States of Colorado, Wyoming, Idaho, Oregon, and California. A secondary objective is to provide a map of the distribution of ^{137}Cs deposition around the NTS. Such information should be useful for continuing investigations of the possible impacts of the releases from the NTS (see, e.g., NRC 1999).

METHODS

Calculation of the release of ^{137}Cs

Estimates of the amount of ^{137}Cs released by atmospheric explosions were performed primarily on the basis of data contained in Hicks (1981), whose methodology is detailed in Hicks (1982, 1990). For the significant atmospheric explosions the amount of ^{137}Cs released, Q_{Cs} , is given by

$$Q_{\text{Cs}} = \frac{P_{\text{Cs}}}{F} \quad (1)$$

where P_{Cs} is the activity per unit area of ^{137}Cs normalized to unit exposure rate at 12 hours post detonation [Bq m^{-2} per $\text{C kg}^{-1}\text{s}^{-1}$ ($\mu\text{Ci m}^{-2}$ per mR h^{-1})] and F is the fraction of the total activity per unit area normalized to unit exposure rate at 12 hours post detonation [m^{-2} per $\text{C kg}^{-1} \text{s}^{-1}$ (m^{-2} per mR h^{-1})]. Values for both P_{Cs} and F are tabulated in Hicks (1981) and are based on detailed calculations that considered the unique characteristics of each nuclear device.

For vents of explosions (designated in Table 1 with the word vent) designed to be contained a different set of results from Hicks (1981) were used. In this case values of F were not provided, but values of P_{Cs} were provided, as were values of P_{Tot} at time of venting for different categories of vents. Also provided were values of Q_{Tot} for each event at the time of venting. In such cases the release of ^{137}Cs was calculated as

$$Q_{Cs} = \frac{P_{Cs}}{P_{Tot}} \cdot Q_{Tot} \quad (2)$$

For cratering events (Sedan, Palanquin, Cabriolet, Buggy, and Schooner) it was not possible to use the Hicks (1981) approach, as not enough information was provided. Values of Q_{Cs} for these cases were calculated as

$$Q_{Cs} = \frac{1}{2} \cdot \alpha \cdot Y \cdot A \cdot f_{Cs} \cdot \lambda_{Cs} \quad (3)$$

where the factor of 2^{-1} represents the approximate amount of material released by the cratering event (as opposed to retained in the crater), α is the fractional yield of the explosion due to fission (as opposed to fusion), Y is the yield of the explosion (kt), A is the number of fissions per kt, f_{Cs} is the fractional yield of ^{137}Cs atoms per fission and λ_{Cs} is the decay constant of ^{137}Cs . For the larger cratering events (Sedan and Schooner) it is clear that much of the explosive yield was due to fusion, but values of α have not been provided. For the estimates here the value for α of 0.05 is used, which is the value reported by Russia (Mikhailov et al. 1996) for a 140-kt

excavation explosion on 15 January 1965. For the smaller events a value of a of 1.0 is used. These estimated values are highly uncertain, but the fraction of the total release of ^{137}Cs produced by these events is small. Values of Y are given in Table 1, A and f_{Cs} are taken to be 1.45×10^{23} fissions kt^{-1} and 0.055 atoms fission $^{-1}$, respectively (Glasstone and Dolan 1977), and λ_{Cs} is $7.32 \times 10^{-10} \text{ s}^{-1}$ for a half life of 30.0 y (ICRP 1983).

In some cases the estimated release of ^{137}Cs is given in Table 1 as simply “0.” In these cases the releases were either too small to have been considered by Hicks (1981), or data in Schoengold et al. (1996) indicate that no ^{137}Cs had been released.

Determination of the activity per unit area of ^{137}Cs in the Phase I and II areas

Between 1980 and 1985, all of the available data on fallout from the NTS were reanalyzed as part of the ORERP (Beck 1984; Anspaugh et al. 1990; Beck et al. 1990; Cederwall et al. 1990; Church et al. 1990; Quinn 1990; Ward and Whicker 1990; Whicker et al. 1990; Beck and Anspaugh 1991; Grossman and Thompson 1993; Thompson et al. 1994). At the same time, new data were collected on the amount of ^{137}Cs in surface soil both on and off the NTS. As a result of these efforts, it is now possible to estimate more precisely the amount of ^{137}Cs deposited in the western U.S. and to map its distribution with greater resolution.

The current estimates of ^{137}Cs deposition are based on the combined results of three projects sponsored by the U.S. Department of Energy. One project focused on the NTS itself, while the other two focused on off-site regions.

On-site measurements. The distribution of ^{137}Cs on the NTS was studied as part of the Radionuclide Inventory and Distribution Program (RIDP). This program's overall objective was to estimate the total inventory and distribution of all man-made radionuclides of NTS origin in the surface soil of the NTS. The scope of the program was unique in that a complete

radiological survey of an area the size of the NTS had never before been attempted. Data collection alone took five years (1981 to 1985) of nearly continuous effort, and data analysis was not completed for an additional five years.

The strategy adopted for the RIDP combined three methods: Aerial surveys, soil-sample collection and analysis, and field-gamma-ray spectrometry. The aerial surveys, carried out with an array of scintillation detectors mounted on a helicopter, showed overall distribution patterns but were not useful for quantifying individual radionuclides. They were used primarily to delineate contaminated areas and to help in designing ground-based surveys of those areas. Soil samples at various depths were collected from each contaminated area and analyzed to determine the distribution of various radionuclides with depth. Many samples were further analyzed to measure the concentrations of radionuclides that are not easily quantified by the primary measurement technique, gamma-ray spectrometry.

Spectrometric methods for measuring gamma-emitting radionuclides in situ were developed in the 1970s (Beck et al. 1972; Anspaugh 1976). For the RIDP, a collimated high-purity germanium detector was attached to a retractable mast mounted on a vehicle capable of off-road travel. Measurements were made with the detector suspended about 7.4 m above the ground. At each measurement location, a 4096-channel energy spectrum was recorded over a 15-minute count period. A computer program was then used to analyze the spectrum to determine the concentration of various radionuclides.

The survey of the NTS included all the ground zeros of above-ground nuclear tests and all other accessible regions of the NTS where significant contamination occurred. Soil samples were collected at about 400 locations and gamma-ray spectra were recorded at about 3,700 locations. The data were analyzed to estimate the total amount (inventory) and distribution of 16 man-

made radionuclides on the NTS. The project results were published in a series of five reports, all of which are cited in a final summary report (McArthur 1991) that gives total inventory estimates and distribution maps covering the entire NTS.

Off-site measurements, Phase I. In 1979 the Department of Energy initiated the ORERP to re-evaluate the radiation doses that populations downwind from the NTS received from weapons testing at the NTS. The dose estimates for this project came from models that used the deposition density of various radionuclides as input parameters. Thus a major focus of the ORERP was to obtain the best possible estimates of deposition densities in the downwind region.

The original charter of the ORERP called for estimating doses in the region most heavily affected by NTS fallout. That region, later termed the Phase I region and so indicated in Fig. 1, encompassed Clark, Esmeralda, Lincoln, and Nye Counties in Nevada and Washington County in Utah.

The primary source of data for estimates of deposition density in the Phase I region was monitoring data collected during and immediately after each test. These data consist of readings from hand-held survey meters carried by monitors stationed off-site in the general region where fallout was expected. The readings, which were usually values of exposure rate in mR h^{-1} , were recorded along with the time, location, and other information in hand-written logs.

Approximately 119,000 such measurements were recorded from more than 225 nuclear tests carried out between 1951 and 1972 (Grossman and Thompson 1993).

Another source of data for Phase I was the fallout patterns produced by the Weather Bureau (Nagler and Telegados 1956) and other agencies shortly after each test. These fallout patterns were based on both the data from the survey meters and the prevailing weather

conditions. The fallout patterns for 11 of the more important tests were reanalyzed by the Weather Service Nuclear Support Office as part of the ORERP (Quinn 1990).

Both sets of data were extensively analyzed to estimate the time of fallout arrival and the geometric mean-exposure rate 12 h after detonation (H+12) at every community of interest in the Phase I area. The uncertainty in the estimates was also estimated. Details of the calculations are given in Thompson (1990) and Thompson et al. (1994). Sets of estimates for a matrix of 352 communities by 74 nuclear tests are contained in the Town Data Base (Thompson et al. 1994), which serves as a major data source for the work reported here.

Once \dot{X}_{12} , the exposure rate at H+12 is established for a particular event at a particular location the activity per unit area of ^{137}Cs (or of 176 other radionuclides) can be immediately calculated on the basis of data tabulated in Hicks (1981). Then, the activity per unit area of ^{137}Cs , De_{Cs} , is given by

$$De_{Cs} = \dot{X}_{12} \cdot P_{Cs} \quad (4)$$

Off-site measurements, Phase II. As dose estimation for the Phase I region was proceeding, Beck and Krey (1983) reported that residents of the Salt Lake City area of Utah had received a greater population dose of radiation than had residents of most counties closer to the NTS. Consequently, the ORERP's advisors recommended that an attempt be made to estimate doses outside the limited region covered by fallout monitors. This effort was termed Phase II, and the additional area included all of Arizona and New Mexico, all of Nevada and Utah that was not in the Phase I region, and parts of Colorado, Wyoming, Idaho, Oregon, and California (Fig. 1).

No large data set comparable to the Phase I survey-meter readings was available for the Phase II area. Dose estimates were therefore based on a number of historical and contemporary data sets of various sizes and quality.

The most important data set for the Phase II estimates consisted of measurements of fallout collected on gummed film after each test. The gummed film collectors were part of a worldwide network operated by the Atomic Energy Commission between 1951 and 1960. Data from the collectors were originally not considered useful for quantifying fallout, but a re-evaluation that included a better estimate of the collection efficiency of the film showed that reasonably precise estimates of deposition densities were possible (Beck 1984; Beck et al. 1990). About 25 sites in the network provided data for the Phase II region.

Additional data on ^{137}Cs deposition were provided by soil samples collected in Utah and western Colorado in 1979 (Beck and Krey 1983) and throughout the rest of the Phase II region in 1982 and 1983 (McArthur and Miller 1989). The samples were analyzed for ^{137}Cs , $^{239+240}\text{Pu}$, and the ratio of ^{239}Pu -to- ^{240}Pu . The results were then used to calculate the amount of ^{137}Cs in each sample that came from NTS fallout (most of the ^{137}Cs in a typical location came from global fallout; the ratio of ^{239}Pu -to- ^{240}Pu is critical in distinguishing the two sources of fallout). The relationships that make this calculation possible are given in Beck and Krey (1983).

Estimates of ^{137}Cs deposition density from soil samples were obtained at about 200 sites. However, these estimates are of the total ^{137}Cs deposition from NTS tests; the method could not determine how much ^{137}Cs was deposited by a particular test. The gummed film collectors did give estimates for individual tests, but for fewer sites (typically 10 to 20 sites per test). Because of the relative lack of data, it was decided not to estimate ^{137}Cs deposition densities for separate communities as had been done for the Phase I region, but for counties or parts of counties. The estimates were based primarily on gummed film and soil data, though data from the Town Data Base, fallout patterns, air and precipitation samples, and several other sources were also considered when available. To make the results comparable with the results from Phase I, the

estimates of deposition density were converted to estimates of mean-exposure rate, and times of fallout arrival were also estimated. The entire process is described in Beck and Anspaugh (1991). The estimates of fallout-arrival times and mean-exposure rates for 55 tests and 142 counties or parts of counties are contained in the County Data Base (Beck and Anspaugh 1991), an analog of the Town Data Base. Conversion between values of external gamma-exposure rate at H+12 and the deposition density of ^{137}Cs at a particular location for a particular test are accomplished through the values tabulated by Hicks (1981).

Estimate of total ^{137}Cs inventory based on the three data sets

Beck and Anspaugh (1991, table 7) report a cumulative (over all tests) estimate of the ^{137}Cs deposition density for most counties in the combined Phase I and Phase II regions. These estimates were obtained from results in the Town and County data bases by (1) converting the values of exposure rate to values of deposition density using ratios given by Hicks (1981); (2) converting the geometric means to arithmetic means; and (3) summing over all tests. The cumulative values slightly overestimate the total amount of ^{137}Cs present at any one time, as the deposition in many locations took place over several years and some of the early deposits of ^{137}Cs would have decayed before the additional deposition occurred. This is a relatively minor consideration for ^{137}Cs , which has a radiological half life of 30 y.

Three counties in the region of interest are not listed in table 7 of Beck and Anspaugh (1991), as these counties were created since the start of testing. The cumulative ^{137}Cs deposition density in those counties was estimated from the values for adjacent counties. Several other counties have multiple entries in table 7 because different parts of the county had greatly different deposition densities for one or more tests. The multiple estimates for each such county were averaged to give a single value of the cumulative deposition density for that county.

The total inventory of ^{137}Cs deposited in each county was then calculated by multiplying the estimated cumulative deposition density by the area of the county. Summing the inventories over all counties gives a total estimated inventory for the off-site area.

The total inventory of ^{137}Cs deposited by NTS tests is the sum of the estimated on-site and off-site inventories.

RESULTS

Release of ^{137}Cs

The results for the calculated releases of ^{137}Cs from the NTS are given in Table 1 for each event. These results are estimated to be accurate to within $\pm 20\%$. The total release is estimated to be 6.4 PBq almost all of which was released before the voluntary moratorium on testing at the end of October 1958.

Estimates of residual ^{137}Cs in surface soil

On-site. McArthur (1991) reported that ^{137}Cs was widely distributed across the northern part of the NTS with the isopleths as shown in Fig. 2. The total estimated inventory was found to be 11 TBq decay corrected to 1 January 1990. This would correspond to an inventory in 1955 (the approximate midpoint of the major test series) of about 25 TBq. This reflects the amount of ^{137}Cs that was still in surface soil at the time of the measurements. An additional amount was removed during a variety of clean-up operations.

Off-site. The results by counties of the estimated inventories in the off-site areas of the Phase I and II domain are presented in Table 2. The estimated total is 560 ± 35 TBq.

Combined on- and off-site total. The total estimated ^{137}Cs in surface soil (as of the time of the tests) is the sum of the on- and off-site values, which is 585 ± 35 TBq.

Distribution of ^{137}Cs

The distribution pattern of ^{137}Cs in the off-site region is shown fairly well by a plot of the cumulative estimates of deposition density for each county on a map of the western U.S. Two problems were encountered in constructing such a plot. First, the counties in Wyoming and Colorado that are represented in the County Data Base all have relatively high deposition (370 Bq m^{-2} or more); how much farther to the northeast deposition at this level may have occurred is not clear. Second, the data are too sparse to adequately show the distribution pattern in the immediate vicinity of the NTS. Additional data were therefore sought that would help resolve these problems.

Table 7 of Beck and Anspaugh (1991), the source of the cumulative estimates, does include values for three cities northeast of the Phase II region. All three (Scottsbluff, Nebraska; Rapid City, South Dakota; and Billings, Montana) have estimated cumulative deposition densities of 180 Bq m^{-2} or less. Estimates for five other cities closer to the Phase II region are available from gummed film data. Beck (1984: fig. 4) reports values of 180 Bq m^{-2} for Casper and Cheyenne, Wyoming, and Colorado Springs, Colorado, and 150 Bq m^{-2} for Pueblo, Colorado. Beck et al. (1991) report 400 Bq m^{-2} for Denver. These additional data enable a 370 Bq m^{-2} isopleth to be drawn through Wyoming and Colorado with greater confidence.

To better determine the distribution pattern near the NTS, cumulative estimates of deposition density were calculated from the data in the Town Data Base. The calculations were the same as those described above for the County Data Base: Conversion of geometric mean to arithmetic mean, conversion of exposure rate to deposition density using ratios from Hicks (1981), and summation over all nuclear tests. The resulting values for individual towns and ranches near the NTS were then noted on a map of southern Nevada. Once all the data had been

noted on a map, isopleths were drawn on the maps by hand. The resulting distribution map is shown in Fig. 3.

DISCUSSION

A unique feature of this report is the combination of three disparate sets of data into a combined data set that allows the data to be analyzed as an ensemble. This combination of data is only possible due to the tabulations of Hicks (1981), which in turn are based on very detailed information on the nuclide yield (including activation products) for each test and on the conversion from deposition density to external gamma-exposure rate for many radionuclides of interest as calculated by Beck (1980).

The combination of these data sets allows for the calculation of the total amount of ^{137}Cs deposited in the Phase I and II areas (Fig. 1). The total amount 585 ± 35 TBq can be compared with the total amount released, which is 6390 TBq. Thus, only about 10% of the total release is accounted for on surface soil within the NTS itself and near downwind region. Some additional amount would have been cleaned up and disposed of within the NTS, but this additional fraction would have been small compared to the total amount. The estimated 10% of the total fraction is consistent with earlier estimates by Beck et al. (1990) and by the NCI (1997) of the total amounts of ^{137}Cs and ^{131}I , respectively, estimated to have been deposited within the continental U.S. Beck et al. (1990), based upon gummed film data and isopleths for the entire country, had estimated that 21% of the ^{137}Cs from the tests through Hardtack II had been deposited within the continental U.S.; they further speculated that the total deposition, including that on the NTS itself, would have been 25 to 30% of the total release of ^{137}Cs . In the course of its study of thyroid doses delivered to the residents of the U.S. from nuclear tests at the NTS, the NCI (1997) estimated the deposition of ^{131}I in each county of the U.S.; their summary value was that

about 25% of the ^{131}I released was deposited within the U.S. Thus, the three studies are consistent with each other, but the information in all three studies is strongly dependent upon the data of the gummed film network.

The isopleths of ^{137}Cs deposition in Fig. 3 are also consistent with those drawn by Beck et al. (1990) for the entire country. As expected, due to the additional information available for the NTS itself and the Phase I region, the isopleths in Fig. 3 provide more detailed information for the areas closer to the NTS. It is well known that the primary vector that brings fallout to the earth is precipitation. The tests at the NTS were always conducted with the intent of avoiding rainfall in the nearby area; a consequence was that fallout clouds could travel a considerable distance before encountering precipitation. Thus, although the outer contour in Fig. 3 is closed, it is quite likely that there were areas outside of this contour that received deposition levels that exceeded 370 Bq m^{-2} . This would be consistent with the deposition maps for ^{131}I contained in NCI (1997).

About 60% of the total release of ^{137}Cs from the NTS was associated with tests with a yield of ≥ 20 kt. This energy is sufficient to inject the debris to high altitudes from which it would be deposited rather slowly. Thus injection at high altitudes would have provided enough time for many clouds to exit the U.S. before they encountered major precipitation. Thus, much of the fallout that is missing from the U.S. was probably deposited in the Atlantic Ocean, Europe, and Canada.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract W-7405-Eng-48. Much of the work was performed while the authors were employed at the Lawrence Livermore National Laboratory of the University of California (LA) and the Desert Research Institute of the University of Nevada (RM). Work on this report was completed under a consulting contract between Lawrence Livermore National Laboratory and Richard McArthur and under Purchase Order B500874 between Lawrence Livermore National Laboratory and Lynn R. Anspaugh, Consulting.

REFERENCES

- Anspaugh, L. R. In situ methods for quantifying specific radionuclides. IEEE Trans. Nucl. Sci. NS-23:1190–1196; 1976.
- Anspaugh, L. R.; Ricker, Y. E.; Black, S. C.; Grossman, R. F.; Wheeler, D. L.; Church, B. W.; Quinn, V. E. Historical estimates of external g exposure and collective external g exposure from testing at the Nevada Test Site. II. Test series after Hardtack II, 1958, and summary. Health Phys. 59:525–532; 1990.
- Beck, H. L. Exposure rate conversion factors for radionuclides deposited on the ground. New York: U.S. Department of Energy Environmental Measurements Laboratory; Report EML-378; 1980.
- Beck, H. L. Estimates of fallout from Nevada weapons testing in the western United States based on gummed-film monitoring data. New York: U.S. Department of Energy, Environmental Measurements Laboratory; Report EML-433; 1984.
- Beck, H. L.; Krey, P. W. Radiation exposures in Utah from Nevada nuclear tests. Science 220:18–24; 1983.
- Beck, H. L.; Decampo, J.; Gogolak, C. In situ Ge(Li) and Na(Tl) gamma-ray spectrometry. New York: Health and Safety Laboratory, Atomic Energy Commission; Report HASL-258; 1972.
- Beck, H. L.; Anspaugh, L. R. Development of the county database: Estimates of exposure rates and times of arrival of fallout in the ORERP Phase-II area. Las Vegas: U.S. Department of Energy Nevada Operations Office; Report DOE/NV-320; 1991.

- Beck, H. L.; Helfer, I. K.; A. Bouville, A.; Dreicer, M. 1990. Estimates of fallout in the continental U.S. from Nevada weapons testing based on gummed-film monitoring data. *Health Phys.* 59:565–576; 1990.
- Cederwall, R. T.; Ricker, Y. E.; Cederwall, P. L.; Homan, D. N.; Anspaugh, L. R. Ground-based air-sampling measurements near the Nevada Test Site after atmospheric nuclear tests. *Health Phys.* 59:533–540; 1990.
- Church, B. W.; Wheeler, D. W.; Campbell, C. M.; Nutley, R. V.; Anspaugh, L. R. Overview of the Department of Energy's Off-Site Radiation Exposure Review Project (ORERP). *Health Phys.* 59:503–510; 1990.
- Department of Energy. United States nuclear tests. July 1945 through September 1992. Las Vegas: U.S. DOE Nevada Operations Office; Report DOE/NV-209 (Rev. 14); 1994.
- Friesen, H. N. A perspective on atmospheric nuclear tests in Nevada. Las Vegas: U.S. Department of Energy Nevada Operations Office; Report NVO-296; 1985.
- Glasstone, S.; Dolan, P. J. The effects of nuclear weapons. Washington: U.S. Departments of Defense and Energy; 3rd Ed.; 1977.
- Grossman, R. F.; Thompson, C. B. Creation of a data base of survey meter readings in the western United States after nuclear tests. Las Vegas: U.S. Environmental Protection Agency, Environmental Monitoring Systems Laboratory; Report EPA/600/R-93/034; 1993.
- Hicks, H. G. Results of calculations of external gamma radiation exposure rates from fallout and the related radionuclide compositions. Livermore: Lawrence Livermore Laboratory; Report URCL53152, parts 1-8; 1981.
- Hicks, H. G. Calculation of the concentration of any radionuclide deposited on the ground by off-site fallout from a nuclear detonation. *Health Phys.* 42:585–600; 1982.

Hicks, H. G. Additional calculations of radionuclide production following nuclear explosions and Pu isotopic ratios for Nevada Test Site events. *Health Phys.* 59:515–523; 1990.

International Commission on Radiological Protection. Radionuclide transformations. Energy and intensity of emissions. Oxford: Pergamon Press; ICRP Publication 38; *Annals ICRP* 11–13; 1983.

McArthur, R. D. Radionuclides in surface soil at the Nevada Test Site. Las Vegas: Water Resources Center, University of Nevada Desert Research Institute; Publication #45077 (DOE/NV/10845-02); 1991.

McArthur, R. D.; F. L. Miller, F. L. Off-Site Radiation Exposure Review Project: Phase II Soils Program. Las Vegas: Water Resources Center, University of Nevada Desert Research Institute; Publication #45064 (DOE/NV/1038423 Rev.); 1989.

Mikhailov, V. N.; Andryshin, I. A.; Bogdan, V. V.; Vashchinkin, S. A.; Zelentsov, S. A.; Zolotukhin, G. E.; Karimov, V. M.; Kirichenko, V. V.; Matushchenko, A. M.; Silkin, Yu. S.; Strukov, V. G.; Kharitonov, K. V.; Tcdhernyshev, A. K.; Tsrykov, G. A.; Shumaev, M. P. USSR nuclear weapons tests and peaceful nuclear explosions. 1949 through 1990. Moscow: Ministry of the Russian Federation for Atomic Energy and Ministry of Defense of the Russian Federation; 1996.

Nagler, K. M.; Telegado, K. The distribution of significant fallout from Nevada tests. Las Vegas: U.S. Weather Bureau; unpublished report; 1956. (Available from the Coordination and Information Center, Bechtel Nevada, Las Vegas).

National Cancer Institute. Estimated exposures and thyroid doses received by the American people from iodine-131 in fallout following Nevada atmospheric nuclear bomb tests. Bethesda: NCI; 1997.

- National Research Council. Exposure of the American people to iodine-131 from Nevada nuclear-bomb tests. Review of the National Cancer Institute report and public health implications. Washington: National Academy Press; 1999.
- Quinn, V. E. Analysis of meteorological and radiological data for selected fallout episodes. *Health Phys.* 59:577–592; 1990.
- Schoengold, C. R.; DeMarre, M. E.; Kirkwood, E. M. Radiological effluents released from U.S. continental tests 1961 through 1992. Las Vegas: U.S. Department of Energy Nevada Operations Office; Report DOE/NV-317 (Rev. 1); 1996.
- Thompson, C. B. Estimates of exposure rates and fallout arrival times near the Nevada Test Site. *Health Phys.* 59:555–563; 1990.
- Thompson, C. B.; McArthur, R. D.; Hutchinson, S. W. Development of the Town Data Base: Estimates of exposure rates and times of fallout arrival near the Nevada Test Site. Las Vegas: U.S. Department of Energy Nevada Operations Office; Report DOE/NV-374; 1994.
- Ward, G. M.; Whicker, F. W. Milk distribution and feeding practice data for the PATHWAY model. *Health Phys.* 59:637–643; 1990.
- Whicker, F. W.; Kirchner, T. B.; Breshears, D. E.; Otis, M. D. Estimation of radionuclide ingestion: The “PATHWAY” food-chain model. *Health Phys.* 59:645–657; 1990.

Table 1. List of nuclear explosions at the NTS that released radionuclides to the offsite environment and the estimated release of ^{137}Cs from each event. The primary sources of information are DOE (1994) and Hicks (1981).

Operation	Test	Type	Date	Yield (kt)	^{137}Cs release (TBq)
Ranger	Able	Airdrop	27-Jan-51	1	6.32×10^0
	Baker	Airdrop	28-Jan-51	8	5.11×10^1
	Easy	Airdrop	1-Feb-51	1	6.39×10^0
	Baker-2	Airdrop	2-Feb-51	8	5.11×10^1
	Fox	Airdrop	6-Feb-51	22	1.40×10^2
Buster	Baker	Airdrop	28-Oct-51	3.5	2.27×10^1
	Charlie	Airdrop	30-Oct-51	14	8.92×10^1
	Dog	Airdrop	1-Nov-51	21	1.34×10^2
	Easy	Airdrop	5-Nov-51	31	1.98×10^2
Jangle	Sugar	Surface	19-Nov-51	1.2	7.64×10^0
	Uncle	Crater	29-Nov-51	1.2	7.65×10^0
Tumbler-Snapper	Able	Airdrop	1-Apr-52	1	6.36×10^0
	Baker	Airdrop	15-Apr-52	1	6.35×10^0
	Charlie	Airdrop	22-Apr-52	31	1.98×10^2
	Dog	Airdrop	1-May-52	19	1.20×10^2
	Easy	Tower	7-May-52	12	7.66×10^1
	Fox	Tower	25-May-52	11	7.01×10^1
	George	Tower	1-Jun-52	15	9.54×10^1
	How	Tower	5-Jun-52	14	8.96×10^1
Upshot-Knothole	Annie	Tower	17-Mar-53	16	1.02×10^2
	Nancy	Tower	24-Mar-53	24	1.51×10^2
	Ruth	Tower	31-Mar-53	0.2	1.27×10^0
	Dixie	Airdrop	6-Apr-53	11	6.90×10^1
	Ray	Tower	11-Apr-53	0.2	1.27×10^0
	Badger	Tower	18-Apr-53	23	1.44×10^2
	Simon	Tower	25-Apr-53	43	2.71×10^2
	Encore	Airdrop	8-May-53	27	1.72×10^2
	Harry	Tower	19-May-53	32	2.04×10^2
	Grable	Airburst	25-May-53	15	9.57×10^1
	Climax	Airdrop	4-Jun-53	61	3.88×10^2
Teapot	Wasp	Airdrop	18-Feb-55	1	6.46×10^0
	Moth	Tower	22-Feb-55	2	1.29×10^1
	Tesla	Tower	1-Mar-55	7	4.50×10^1
	Turk	Tower	7-Mar-55	43	2.69×10^2
	Hornet	Tower	12-Mar-55	4	2.52×10^1
	Bee	Tower	22-Mar-55	8	5.16×10^1

Table 1 (continued)

	Ess	Crater	23-Mar-55	1	6.36×10^0
	Apple-1	Tower	29-Mar-55	14	9.00×10^1
	Wasp'	Airdrop	29-Mar-55	3	1.92×10^1
	HA	Airdrop	6-Apr-55	3	1.93×10^1
	Post	Tower	9-Apr-55	2	1.27×10^1
	Met	Tower	15-Apr-55	22	1.42×10^2
	Apple-2	Tower	5-May-55	29	1.84×10^2
	Zucchini	Tower	15-May-55	28	1.79×10^2
Project 56	No. 1	Surface-Safety expt.	1-Nov-55	0	0
	No. 2	Surface-Pu dispersal	3-Nov-55	0	0
	No. 3	Surface-Pu dispersal	5-Nov-55	No yield	0
	No. 4	Surface-Pu dispersal	18-Jan-56	V. slight	0
Project 57	No. 1	Surface-Safety expt.	24-Apr-57	0	0
Plumbbob	Boltzmann	Tower	28-May-57	12	7.60×10^1
	Franklin	Tower	2-Jun-57	0.14	8.94×10^1
	Lassen	Balloon	5-Jun-57	0.0005	0
	Wilson	Balloon	18-Jun-57	10	6.31×10^1
	Priscilla	Balloon	24-Jun-57	37	2.33×10^2
	Hood	Balloon	5-Jul-57	74	4.64×10^2
	Diablo	Tower	15-Jul-57	17	1.06×10^2
	John	Rocket	19-Jul-57	2	1.09×10^1
	Kepler	Tower	24-Jul-57	10	6.24×10^1
	Owens	Balloon	25-Jul-57	9.7	6.07×10^1
	Pascal-A	Shaft-unstemmed	26-Jul-57	Slight	3.63×10^1
	Stokes	Balloon	7-Aug-57	19	1.20×10^2
	Shasta	Tower	18-Aug-57	17	1.07×10^2
	Doppler	Balloon	23-Aug-57	11	6.94×10^1
	Franklin'	Balloon	30-Aug-57	4.7	2.96×10^1
	Smoky	Tower	31-Aug-57	44	2.76×10^2
	Galileo	Tower	2-Sep-57	11	6.91×10^1
	Wheeler	Balloon	6-Sep-57	0.197	1.26×10^0
	Coulomb-B	Surface	6-Sep-57	0.3	1.91×10^0
	Laplace	Balloon	8-Sep-57	1	6.39×10^0
	Fizeau	Tower	14-Sep-57	11	6.96×10^1
	Newton	Balloon	16-Sep-57	12	7.60×10^1
	Whitney	Tower	23-Sep-57	19	1.19×10^2
	Charleston	Balloon	28-Sep-57	12	7.71×10^1
	Morgan	Balloon	7-Oct-57	8	5.05×10^1
	Coulomb-C	Surface-Safety expt.	9-Dec-57	0.5	0

Table 1 (continued)

Hardtack II	Otero	Shaft	12-Sep-58	0.038	2.46×10^{-1}
	Eddy	Balloon	19-Sep-58	0.083	5.31×10^{-1}
	Mora	Balloon	29-Sep-58	2	1.30×10^1
	Hidalgo	Balloon	5-Oct-58	0.077	4.89×10^{-1}
	Quay	Tower	10-Oct-58	0.079	5.06×10^{-1}
	Lea	Balloon	13-Oct-58	1.4	9.09×10^0
	Hamilton	Tower	15-Oct-58	0.0012	7.78×10^{-3}
	Dona Ana	Balloon	16-Oct-58	0.037	2.38×10^{-1}
	Vesta	Surface	17-Oct-58	0.024	1.55×10^{-1}
	Rio Arriba	Tower	18-Oct-58	0.09	5.72×10^0
	Socorro	Balloon	22-Oct-58	6	3.90×10^1
	Wrangall	Balloon	22-Oct-58	0.115	7.38×10^{-1}
	Rushmore	Balloon	22-Oct-58	0.188	1.21×10^0
	Catron	Tower	24-Oct-58	0.021	1.36×10^{-1}
	Sanford	Balloon	26-Oct-58	4.9	3.09×10^1
	De Baca	Balloon	26-Oct-58	2.2	1.43×10^1
	Chavez	Tower	27-Oct-58	0.0006	3.89×10^{-3}
	Humboldt	Tower	29-Oct-58	0.0078	5.05×10^{-2}
	Santa Fe	Balloon	30-Oct-58	1.3	8.44×10^0
	Blanca	Tunnel-vent	30-Oct-58	22	3.96×10^{-3}
Titania	Tower	30-Oct-58	0.0002	3.22×10^{-4}	
Subtotal (1951–1958)					6.31×10^3
Nougat	Antler	Tunnel-vent	15-Sep-61	2.6	4.87×10^{-3}
	Feather	Tunnel-vent	22-Dec-61	0.15	8.85×10^{-6}
	Pampas	Shaft-vent	1-Mar-62	9.5	2.82×10^{-5}
	Danny Boy	Crater	5-Mar-62	0.43	2.79×10^0
	Platte	Tunnel-vent	14-Apr-62	1.85	2.68×10^{-2}
	Eel	Shaft-vent	19-May-62	4.5	2.68×10^{-2}
	Des Moines	Tunnel-vent	13-Jun-62	2.9	2.56×10^{-1}
Storax	Sedan ^a	Crater	6-Jul-62	104	1.52×10^1
	Johnnie Boy	Crater	11-Jul-62	0.5	3.19×10^0
	Small Boy	Tower	14-Jul-62	Low	1.04×10^1
	Little Feller I	Surface	17-Jul-62	Low	1.16×10^{-1}
	Bandicoot	Shaft-vent	19-Oct-62	12.5	6.98×10^{-2}
	Yuba	Tunnel-vent	5-Jun-63	3.1	1.73×10^{-8}
	Double Tracks	Surface-storage trans.	15-May-63	0	0
Clean Slate I	Surface-storage trans.	25-May-63	0	0	
Clean Slate III	Surface-storage trans.	5-Jun-63	0	0	

Table 1 (concluded)

Niblick	Eagle	Shaft-vent	12-Dec-63	5.3	1.77×10^{-5}	
	Oconto	Shaft-vent	23-Jan-64	10.5	0	
	Pike	Shaft-vent	13-Mar-64	<20	2.79×10^{-3}	
Whetstone	Alva	Shaft-vent	19-Aug-64	4.4	8.59×10^{-5}	
	Drill	Shaft-vent	5-Dec-64	<20	9.61×10^{-6}	
	Parrot	Shaft-vent	16-Dec-64	1.3	5.33×10^{-3}	
	Sulky	Shaft	18-Dec-64	0.092	5.88×10^{-1}	
	Alpaca	Shaft-vent	12-Feb-65	0.33	5.64×10^{-4}	
	Palanquin ^b	Crater	14-Apr-65	4.3	1.26×10^1	
	Tee	Shaft-vent	7-May-65	7	1.66×10^{-6}	
	Diluted Waters	Shaft-vent	16-Jun-65	<20	1.37×10^{-4}	
	Flintlock	Red Hot	Tunnel-vent	5-Mar-66	<20	1.58×10^{-4}
		Pin Stripe	Shaft-vent	25-Apr-66	<20	2.28×10^{-4}
Double Play		Tunnel-vent	15-Jun-66	<20	9.45×10^{-5}	
Latchkey	Derringer	Shaft-vent	12-Sep-66	7.8	2.78×10^{-4}	
	Nash	Shaft-vent	19-Jan-67	39	1.09×10^{-5}	
	Midi Mist	Tunnel-vent	26-Jun-67	<20	2.05×10^{-7}	
	Umber	Shaft-vent	29-Jun-67	10	6.03×10^{-4}	
Crosstie	Door Mist	Tunnel-vent	31-Aug-67	<20	6.30×10^{-5}	
	Hupmobile	Shaft-vent	18-Jan-68	7.4	1.25×10^{-4}	
	Cabriolet ^b	Crater	26-Jan-68	2.3	6.71×10^0	
	Buggy ^b	Crater	12-Mar-68	5.4	1.58×10^1	
Bowline	Schooner ^a	Crater	8-Dec-68	30	4.38×10^0	
Mandrel	Pod	Shaft-vent	29-Oct-69	16.7	9.05×10^{-5}	
	Scuttle	Shaft-vent	13-Nov-69	1.7	4.87×10^{-6}	
	Snubber	Shaft-vent	21-Apr-70	12.7	5.71×10^{-5}	
	Mint Leaf	Tunnel-vent	5-May-70	<20	6.30×10^{-5}	
	Emery	Baneberry	Shaft-vent	18-Dec-70	10	3.93×10^{-4}
Grommet	Diagonal Line	Shaft-vent	24-Nov-71	<20	1.07×10^{-6}	
Tinderbox	Riola	Shaft-vent	25-Sep-80	1.07	4.57×10^{-7}	
Grenadier	Misty Rain	Tunnel-vent	6-Apr-85	<20	0	
Charioteer	Glencoe	Shaft-vent	22-Mar-86	29	0	
	Mighty Oak	Tunnel-vent	10-Apr-86	<20	0	
Total (1951–1992)					6.39×10^3	

^a Calculated according to eqn (3) with $\alpha = 0.05$.

^b Calculated according to eqn (3) with $\alpha = 1.0$.

Table 2. Calculated cumulative deposition of ^{137}Cs from NTS tests in the counties and in the total area of the Phase I and II regions.

County	State	Deposition (TBq)	Std. dev. (TBq)
Apache	AZ	19	5.4
Cochise	AZ	1.2	0.60
Coconino	AZ	30	8.8
Gila	AZ	0.91	0.46
Graham	AZ	0.89	0.44
Greenlee	AZ	0.35	0.18
La Paz	AZ	0.86	0.43
Maricopa	AZ	1.8	0.87
Mohave	AZ	26	5.6
Navaho	AZ	11	2.9
Pima	AZ	3.5	0.88
Pinal	AZ	1.0	0.51
Santa Cruz	AZ	0.36	0.12
Yavapai	AZ	1.6	0.78
Yuma	AZ	1.1	0.21
Inyo	CA	12	4.9
Los Angeles	CA	0.39	0.20
Mono	CA	0.87	0.29
San Bernadino	CA	5.8	1.9
Delta	CO	1.6	0.44
Dolores	CO	1.2	0.41
Garfield	CO	4.5	1.1
La Plata	CO	5.4	0.65
Mesa	CO	5.4	0.95
Moffat	CO	4.5	0.91
Montezuma	CO	2.0	0.59
Montrose	CO	3.0	0.86
Ouray	CO	0.52	0.16
Rio Blanco	CO	4.0	0.93
San Juan	CO	0.37	0.11
San Miguel	CO	1.2	0.37
Ada	ID	0.60	0.10
Bannock	ID	0.43	0.11
Bear Lake	ID	1.1	0.38
Bingham	ID	0.60	0.20
Bonneville	ID	0.53	0.18
Canyon	ID	0.17	0.056
Caribou	ID	1.0	0.34
Cassia	ID	1.5	0.49

Table 2 (continued)

Elmore	ID	1.8	0.59
Franklin	ID	0.57	0.13
Gooding	ID	0.49	0.21
Jerome	ID	0.14	0.029
Lincoln	ID	0.69	0.23
Minidoka	ID	0.36	0.073
Oneida	ID	0.80	0.23
Owynee	ID	5.1	1.5
Power	ID	0.54	0.13
Twin Falls	ID	1.1	0.37
Bernalillo	NM	1.2	0.22
Catron	NM	3.3	0.66
Chavez	NM	4.7	1.2
Cibola	NM	5.2	1.7
Colfax	NM	2.9	0.72
Curry	NM	0.94	0.27
De Baca	NM	1.6	0.45
Dona Ana	NM	0.73	0.37
Eddy	NM	1.2	0.40
Grant	NM	0.76	0.38
Guadalupe	NM	2.6	0.58
Harding	NM	1.6	0.41
Hidalgo	NM	0.66	0.33
Lea	NM	1.3	0.42
Lincoln	NM	3.7	1.4
Los Alamos	NM	0.094	0.021
Luna	NM	0.57	0.28
McKinley	NM	7.8	2.1
Mora	NM	1.5	0.37
Otero	NM	1.3	0.63
Quay	NM	2.2	0.55
Rio Arriba	NM	4.5	1.1
Roosevelt	NM	1.6	0.47
San Juan	NM	4.8	1.1
San Miguel	NM	3.6	0.90
Sandoval	NM	5.0	1.4
Santa Fe	NM	2.0	0.55
Sierra	NM	1.2	0.40
Socorro	NM	3.8	0.63
Taos	NM	1.5	0.42
Torrance	NM	3.5	0.96
Union	NM	2.9	0.73
Valencia	NM	1.2	0.31

Table 2 (continued)

Churchill	NV	3.8	0.96
Clark	NV	4.5	3.0
Douglas	NV	0.41	0.14
Elko	NV	16	3.3
Esmeralda		3.1	1.4
Eureka	NV	6.0	1.2
Humboldt	NV	3.7	0.93
Lander	NV	2.6	0.75
Lincoln	NV	31	15
Lyon	NV	1.2	0.38
Mineral	NV	3.2	0.72
Nye	NV	32	24
Ormsby	NV	0.084	0.028
Pershing	NV	2.9	0.58
Storey	NV	0.15	0.051
Washoe	NV	4.2	1.2
White Pine	NV	7.7	2.2
Harney	OR	2.0	2.9
Malheur	OR	1.9	3.8
Beaver	UT	4.0	0.99
Box Elder	UT	4.6	1.4
Cache	UT	1.9	0.56
Carbon	UT	1.6	0.43
Daggett	UT	0.87	0.20
Davis	UT	0.66	0.17
Duchesne	UT	4.0	0.62
Emery	UT	6.4	1.7
Garfield	UT	15	4.0
Grand	UT	5.3	1.4
Iron	UT	1.9	0.55
Juab	UT	5.2	0.98
Kane	UT	7.1	5.3
Millard	UT	12	2.6
Morgan	UT	1.3	0.35
Piute	UT	1.0	0.22
Rich	UT	1.8	0.59
Salt Lake	UT	1.5	0.29
San Juan	UT	8.9	3.0
Sanpete	UT	2.0	0.46
Sevier	UT	2.2	0.55
Summit	UT	3.6	0.71
Tooele	UT	7.0	2.6
Uinta	UT	6.0	1.3

Table 2 (concluded)

Utah	UT	4.4	0.97
Wasatch	UT	2.2	0.46
Washington	UT	14	7.0
Wayne	UT	2.6	0.47
Weber	UT	1.2	0.27
Carbon	WY	9.1	1.5
Fremont	WY	17	5.3
Lincoln	WY	5.5	2.0
Sublette	WY	7.0	2.8
Sweetwater	WY	14	4.0
Uinta	WY	2.8	0.60
	Total	560	35

FIGURE LEGENDS

- Fig. 1. A map of the United States indicating the domain of the study, which includes the NTS and the Phase I and Phase II areas. Other cities indicated were briefly examined during the course of the study, but were not included in the domain. Historical data on gummmed film deposition for the Phase III cities was used in deriving data for the Phase II area.
- Fig. 2. Isopleths of ^{137}Cs deposition on the NTS. The indicated isopleths have units of kBq m^{-2} .
- Fig. 3. Isopleths of ^{137}Cs deposition in the Phase I and II areas.





