Fallout from U.S. atmospheric nuclear tests in New Mexico and Nevada (1945-1962)

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Abstract

One hundred and one atmospheric nuclear weapon tests were conducted between 1945 and 1962 in the United States, resulting in widespread dispersion of radioactive fallout, and leading to environmental contamination and population exposures. ^{1,2,3,4,5,6} Accurate assessment of the extent of fallout from nuclear weapon tests has been challenging in the United States and elsewhere, due to limited monitoring and data accessibility. ^{1,4,5,6}

Here we address this deficit by combining U.S. government data,^{2,3} high-resolution reanalyzed historical weather fields,⁷ and atmospheric transport modeling to reconstruct radionuclide deposition across the contiguous United States, ⁸ with 10-kilometer spatial and one-hour temporal resolution for five days following detonation, from all 94 atmospheric tests detonated in New Mexico and Nevada with fission yields sufficient to generate mushroom clouds. Our analysis also includes deposition estimates for 10 days following the detonation of Trinity, the first ever nuclear weapon test, on July 16, 1945.

We identify locations where radionuclide deposition significantly exceeded levels in areas covered by the U.S. Radiation Exposure Compensation Act (RECA).⁹ These findings include deposition in all 48 contiguous U.S. states. They provide an opportunity for re-evaluating the public health and environmental implications from atmospheric nuclear testing.

Finally, our findings also speak to debates about marking the beginning of the Anthropocene with nuclear weapons fallout.^{10,11} Our deposition estimates indicate that direct fallout from Trinity, a plutonium device, reached Crawford Lake in Canada, the proposed "golden spike" site marking the beginning of the Anthropocene epoch,^{12,13} starting on July 20, 1945.

MAIN

Atmospheric nuclear weapon testing beginning in 1945 led to unrestrained releases of radioactive materials in the environment. These materials were transported and dispersed in the atmosphere by prevailing winds and have historically been the most significant cause of exposure of the world population to human-made sources of radiation.¹ The deposition of these materials, including plutonium 239 and 240, is now considered a potential geological marker for the beginning of the Anthropocene Epoch.^{10,11}

Among the one hundred and one atmospheric nuclear weapon tests carried out in the contiguous United States between 1945 and 1962, ninety-four generated radioactive mushroom clouds.^{2,3} The first test, Trinity, took place in New Mexico on July 16, 1945, and the other ninety-three in Nevada starting in January 1951. Monitoring of U.S. radioactive fallout across the contiguous United States was limited in time and scope, and as a result, efforts to reconstruct its extent have had to rely on reanalysis of historical data, remodeling, and interpolation.^{4–6} This has had consequences for an understanding of population doses and eligibility for compensation under the 1990 Radiation Exposure and Compensation Act (RECA).⁹ For example, the Trinity test, which is now believed to have been about 24.8 kilotons (kt) of TNT equivalent in yield,¹⁴ is not included as a source of possible exposure in this legislation.

Here, we compute the atmospheric transport, dispersion, and deposition of fallout across the contiguous United States from all 94 atmospheric tests that took place in New Mexico and Nevada between 1945 and 1962 and generated a radioactive mushroom cloud. Our analysis uses U.S. government data about the location, time, and yield of U.S. atmospheric tests, ^{2,3} a stabilized radioactive mushroom cloud source term, ^{15,16} the U.S. National Oceanic and Atmospheric Administration (NOAA)'s HYSPLIT atmospheric transport and dispersion model, ⁸ and ERA5, a high spatial and temporal resolution dataset of reanalyzed historical weather fields developed by the European Centre for Medium-Range Weather Forecasts for 1940-onwards, updated in March 2023.⁷

We produce the first long-range radionuclide ground deposition estimates for the first ten days after the 16 July 1945 Trinity test. For the 93 atmospheric tests exploded in Nevada, we produce long-range radionuclide ground deposition estimates for the first five days after each test. Thirty of these 93 Nevada tests were not included in previous fallout studies. These 30 tests had yields spanning 0.0002 to 22 kt, with 73.4 kt cumulative and 2.4 kt mean yields. Overall, the results cover deposition of all fission products from all mushroom cloud producing atmospheric tests conducted within the contiguous United States with higher spatial and temporal resolution than previously available.

Our estimates indicate that there are locations in New Mexico and other states, including federally recognized tribal lands, where radionuclide deposition reached levels higher than that in counties covered by RECA. This analysis lays a basis for more directed re-evaluation of contamination and population exposure and its impact on public health and the environment. The tools and approach presented here may also facilitate similar modeling of atmospheric testing programs in other nuclear weapon states for which little to no deposition density data may be available.

Finally, our findings contribute to broader debates about marking and locating the beginning of the Anthropocene using radionuclide deposition from nuclear weapon tests fallout. Our deposition estimates indicate that direct fallout from Trinity reached Crawford Lake in Canada, the proposed site for the Anthropocene Global boundary Stratotype Section and Point (GSSP), 12,13 on July 20, 1945 before peaking on July 22, 1945.

FALLOUT MODELING

Our fallout simulation model uses the HYSPLIT Lagrangian atmospheric particle transport code integrated with weather fields from the ERA5 reanalysis project to track the dispersion and deposition of radioactive particles from a stabilized radioactive mushroom cloud source term. The cloud particle composition is based on a model from the Department of Defense Fallout Prediction System (DELFIC) with assumed log-normal size distributions of micron-size silicate and metallic particles broken down into one hundred particle-size bins with equal activity such that the total cloud activity is normalized to 1 (unit release).¹⁷ Two sets of particle distribution parameters were used depending on whether each detonation was low (surface and tower) or high altitude (balloon or airdrop) (see methods).

The spatial extents and directions of fallout are dependent on daily and hourly changes in surface and high-altitude wind patterns aloft, as well as local precipitation. The ERA5 reanalysis data set (1940-onwards) provides all the atmospheric parameters, including geopotential height, pressure, temperature, relative humidity, wind speed and direction, precipitation, and others, required to run HYSPLIT. ERA5 combines historical observations into globally complete estimates of the weather state using advanced modeling and data assimilation systems. To our knowledge, following its March 2023 update, it is the only reanalysis data set including upperair atmospheric observations that covers the entire 1945-1962 period. For the month of July 1945, it leverages ~2 million global observations (about 60,000 per day), split about equally between surface and upper air measurements (see extended data figure 1 for a map of the observations included for July 16, 1945). The reanalysis fields are provided on a 0.25-degree grid with a 1-hour temporal resolution on 37 pressure and one surface level.

Particle deposition via gravitational settling or wet removal is computed on a 0.1-degree resolution grid spanning the entire contiguous United States (20 by 60 degrees centered at 37.0° N, 95.0° W). For each test, we tracked hourly particle deposition up to 5 days after detonation. Given its historical significance, we also simulated the fallout from Trinity for 5 additional days (total of 10 days). The results are then post-processed to obtain radionuclide deposition density.

Local deposition density is obtained for each test in two steps. The first step decays the activity generated from fission (assuming plutonium-239 fuel for each test) from the time of detonation to the time of arrival in each 0.1-degree latitude x 0.1-degree longitude grid cell, summed over all particle sizes. The second applies a correction factor as a function of the grid cell distance from ground zero, such that long-range deposition density estimates using DELFIC particle-size parameters can reproduce available reanalyzed experimental data, produced by the U.S. Department of Energy and the National Cancer Institute (NCI), which is based on limited ground station measurements. The factors were obtained by benchmarking HYSPLIT estimates of iodine-131 deposition to the NCI reconstruction of nationwide (county-specific) total iodine-131

fallout deposition data from the Nevada Test Site at distances of 1500 to 3500 km from ground zero, 6,18,19 covering the contiguous United States (see methods).

RESULTS

Fallout deposition density from U.S. atmospheric nuclear tests in New Mexico and Nevada

We computed the dispersion and deposition of radionuclides produced by 94 non-zero yield atmospheric nuclear weapon tests across the contiguous United States. Six other atmospheric tests had zero yield and an additional one generated a yield of only ~36 grams of TNT, which did not generate a mushroom cloud. These seven tests were not simulated.

The first test, Trinity, was a tower test in New Mexico on July 16, 1945. The other 93 in Nevada consisted of 48 ground or tower tests and 45 airbursts, all between 1951 and 1962. Figure 1 shows the cumulative radionuclide deposition density map following the first 5 days after each of the 94 atmospheric tests included in this study. Our map shows similarities to previously known features seen in past deposition density estimates that were based on only Nevada tests and limited measurement data gathered by the U.S. Department of Energy and the National Cancer Institute in the 1990s. ^{4,18,20} Unlike previous studies, our higher spatial resolution captures the deposition tracks produced by tower or surface explosions and some apparent influence of the Rocky Mountains.

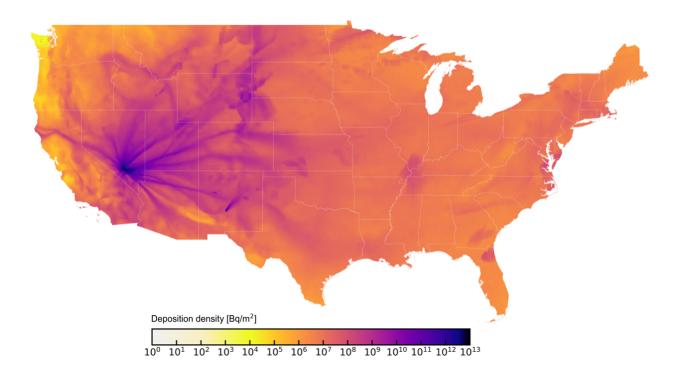


Figure 1. Estimated deposition density (Bq/m⁻²) of fission products from 94 non-zero yield atmospheric nuclear tests conducted in New Mexico and Nevada, across the contiguous United States. The highest deposition points indicate the ground zeros of the Trinity test in New Mexico and of the 93 atmospheric tests in Nevada.

Trinity test

Our map also includes the contribution of the Trinity test to the cumulative deposition density across the United States. Our results show the significant contribution of the Trinity fallout to the total deposition density across the contiguous U.S. (reaching 46 states within 10 days) and in New Mexico in particular. This result is consistent with the low altitude of the detonation (~30 meters) and the yield of the Trinity test recently re-evaluated at 24.8 kilotons of TNT explosive equivalent (representing ~5% of the total yield from all surface and tower shots in the contiguous U.S.).

Figure 2 shows a time sequence of maps of the Trinity deposition over the first 10 days following detonation. Our reconstruction suggests that radioactive fallout from the Trinity explosion led to significant deposition on a north-east primary axis before reaching 46 states within 10 days. Only Washington state and Oregon show no deposition. Deposition also occurred south and west of ground zero within the first 48 hours, and after.

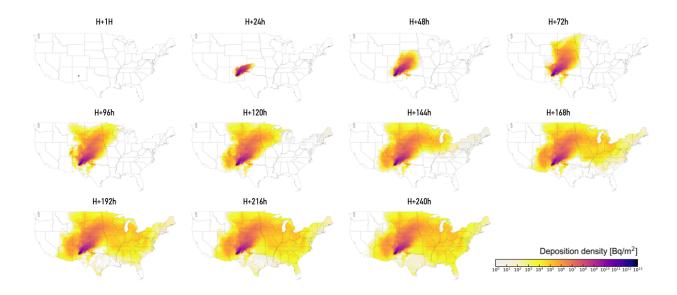


Figure 2. Estimated radionuclide deposition density from the Trinity test for the first 10 days after detonation on July 16, 1945 at 05:29 AM local time.

We find these results to be consistent with the few radiological and meteorological data available in the literature for this test. For example, our results for the first 24 hours agree with local fallout estimates produced as part of a 1987 NOAA analysis of Trinity also covering the first 24 hours (see figure 3).²¹ Our results are also consistent with the long-range contemporary detection of radioactive contaminants from Trinity in strawboard material for packaging sensitive photographic films, manufactured in Indiana and Iowa (see extended data figure 2).²²

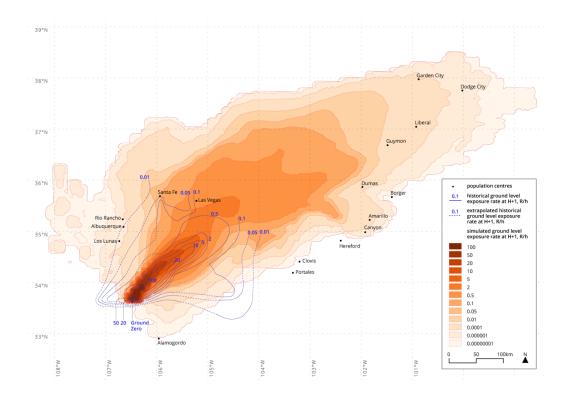


Figure 3. Historical and simulated Trinity fallout dose rate contours for ground level at H+1 hour.

Finally, our deposition estimates also indicate that direct fallout from the Trinity test arrived at Crawford Lake in Ontario, Canada, on July 20, 1945 with a peak deposition on July 22, 1945 (see extended data figure 3 for a time series of plutonium deposition estimate). This would mark the first-time plutonium-249 and 240 deposited in the lake that is now proposed as the Global boundary Stratotype Section and Point to define the Anthropocene as a geological epoch – five years before the proposed base dated at 1950 CE. 12,13

Deposition density and the Radiation Exposure Compensation Act

Our total deposition density estimates across the contiguous United States have implications for public health and discussions about the 1990 Radiation Exposure and Compensation Act. Aggregated by counties and federally recognized tribal lands, our total deposition density estimates show that there are locations in New Mexico, and in other parts of the United States, including Utah, Nevada, Wyoming, Colorado, Arizona, and Idaho, where radionuclide deposition reached levels larger than those we estimate in some counties covered by RECA. Total deposition density is a metric that reflects external exposure to radiation without accounting for internal contamination via the ingestion of contaminated water, fresh milk, and other foodstuffs.

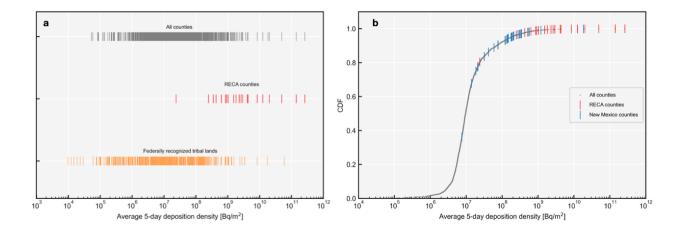


Figure 4. Deposition density distribution for counties and federally recognized tribal lands in the United States. (a) Deposition density for all counties (grey), RECA counties (red), and 549 federally recognized tribal lands, including tribal trust lands (orange). **(b)** Cumulative distribution function of county deposition density, with RECA and 33 the New Mexico counties.

Figure 4a shows the deposition density distribution for the 3108 counties and 549 federally recognized tribal lands (including tribal trust lands) in the United States and how they compare to deposition in areas covered by RECA. There are 38 federally recognized tribal land areas where estimated deposition levels are higher on average than the lowest county included in RECA. There are 27 higher than the second lowest county included in RECA. There are six in Nevada, Utah, Arizona, and New Mexico with levels comparable to the top 10 RECA counties.

Figure 4b shows how New Mexico counties lie on the county cumulative distribution function compared to RECA counties, given that ground zero for the Trinity test was in New Mexico and that no counties in New Mexico are covered by that Act. Our estimates indicate that there are locations in New Mexico where radionuclide deposition reached levels on par with Nevada, with levels in 28 of the 33 counties in New Mexico experiencing higher deposition levels on average than the lowest deposition level county covered by RECA. The New Mexico county within which the Trinity explosion took place – Socorro County – has the 5th highest deposition per county of all counties in the U.S. All other counties in the U.S. with this level of deposition are included in RECA. Overall, the results indicate that there are a significant number of locations that experienced levels of deposition higher than areas covered in RECA.

Sources of uncertainties

There are multiple sources of uncertainties associated with our deposition density estimates that can be grouped in four categories: uncertainties about nuclear test data (fission fuel, yield, cloud dimensions), uncertainties about the particle source term, uncertainties about modeling and post-processing, and uncertainties about the meteorological data.

For the available nuclear test data, we are restricted to public information available in government reports and the literature. There are unknown uncertainties about yield. For example, the Trinity yield was recently reevaluated from 21 kt to 24.8kt of TNT equivalent. The exact composition of each test device remains unknown (except for Trinity, a plutonium

device). We have assumed that all tests were performed with plutonium-239. This assumption does not, however, significantly impact the overall fission activity generated by the tests.

Several factors influence the HYSPLIT results. For the source term, the particle size distribution and the cloud dimensions have the most influence on the HYSPLIT results. The DELFIC particle size parameters combined with the U.S. government cloud parameters that we used produce conservatively low long range deposition estimates. Because of the lack of experimental data on particle sizes and corresponding ground deposition density measurements in the literature, a systematic exploration of the particle-size parameter space is beyond the scope of this study. Beyond the source term, underprediction may also be the result of multiple assumptions and models included in HYSPLIT, which have been noted elsewhere. 23,24 For example, HYSPLIT typically overestimates wet deposition from light rain. This would deplete the debris cloud more rapidly as it travels for several days and therefore cause an underestimation of deposition at corresponding distances downwind. In addition, HYSPLIT assumes particle sizes and densities to remain constant over time and may be underestimating their settling velocity once they reach lower altitudes. These two factors led us to develop a two-step post-processing approach that included correcting for the long-range underestimation of fallout deposition as described in the method section. Our estimates likely remain conservatively low, however. For example, we do not include deposition from activation products and unfissioned fissile materials.

DISCUSSION

This study presents an analysis of fallout for the first five days and first ten days after the Trinity test in New Mexico on July 16, 1945, and the first five days from each of the 93 atmospheric nuclear weapon tests conducted in Nevada between 1951 and 1962 that generated a mushroom cloud. It provides fission-product deposition-density estimates across the contiguous United States. The findings have implications for population exposure, contamination, public health, and the environment.

The analysis identifies locations in New Mexico and other states, including in federally recognized tribal lands, where radionuclide deposition exceeded levels in some counties covered by the Radiation Exposure Compensation Act (RECA). Our results demonstrate the significant impact of Trinity, the first nuclear weapon test, on the overall deposition density in New Mexico and across the contiguous U.S. They also indicate that fallout from Trinity crossed the Canadian border and reached Crawford Lake in Ontario, the proposed site marking the beginning of the Anthropocene epoch, less than a week after detonation.

While uncertainties remain in the nuclear test data, particle source term, modeling, and historical weather data, the results align with available information, including short-range measured and reanalyzed fallout patterns and contemporary observations of radionuclide contamination at long distances.

Overall, this research contributes to a better understanding of the extent of radioactive fallout from 94 atmospheric nuclear weapon tests in the United States and provides a methodology for similar studies of all 528 atmospheric nuclear tests that took place worldwide between 1945 and 1980. Finally, it also contributes to a better understanding of the processes, events, and places that are to possibly mark the beginning of the Anthropocene epoch.

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Data availability: All data generated or analyzed during this study are either included or cited in the published article and are available from the corresponding author upon reasonable request. Nationwide (county-specific) total iodine-131 fallout deposition data from the Nevada Test Site is available from the U.S. National Cancer Institute. The ERA5 gridded meteorological data can be downloaded from the Copernicus Climate Change Service (C3S) (2023).

Code availability: The source code for the HYSPLIT transport and dispersion model is available upon request from the NOAA Air Resources Laboratory (https://www.ready.noaa.gov/HYSPLIT linux.php).

Competing Interest Statement: The authors declare no competing interests.

Authors contributions: SP conceptualized the research with SA and MS. SP conducted the source term evaluations, the atmospheric transport modeling, and the data processing. GP conducted the meteorological data analysis with inputs from SP and SA. SP and MG performed data aggregation, cleaning, and analysis. MG, SA and SP developed data visuals. All authors contributed to the manuscript.

METHODS

Source term, transport, dispersion, and deposition of fallout particles

We modeled the dispersion and deposition of fallout from a stabilized nuclear debris mushroom cloud using the U.S. NOAA Hybrid Single-Particle Integrated Trajectory (HYSPLIT) particle transport and dispersion model (Linux version 5.2.0, January 2022),^{8,15} U.S. government data on key parameters for each test,^{3,14} and meteorological fields from the ERA5 reanalysis project (1940 – present, March 2023 update).⁷

Initial particle clouds were assumed to be stabilized \sim 10 minutes after detonation. They were represented as a segmented vertical linear source with activity distributed among the cap, skirt, and stem of the mushroom cloud as 0.775/0.15/0.075 for surface and tower tests and 0.9712/0.0283/0.0005 for all aerial tests (e.g., balloon, airdrop, ...).

Geographical coordinates, time, and yield of detonation as well as dimensions of the stabilized cloud were obtained from U.S. government reports (see Extended Data Table 1). In general, the base of the mushroom cap is \sim 0.7 of the altitude of the top of the cap. The base of the skirt is 1/2 and 2/3 the altitude of the base of the cap for ground/tower bursts and air bursts respectively.

The cloud particle sizes were assumed to be log-normally distributed using standard parameters from the U.S. Defense Land Fallout Interpretative Code for ground and tower tests (d=0.407 μ m, s=4) and for aerial tests (d=0.15 μ m, s=2), where *d* is the mean particle diameter and *s* the standard deviation of the diameter's natural logarithm.¹⁷ Particles were distributed in 100 diameter bins of equal activity (according to the 2.5 and 3rd moment respectively) and summed to a unit release. For ground and tower tests, the 2.5 moment of the distribution was used to model the first-order effect of fractionation between refractive and volatile nuclides which are typically located within the particle volume and on the particle surface, respectively. ^{25,26} No fractionation was assumed for aerial tests.

In HYSPLIT, the particle density is kept constant over time. We assumed particle density to range from 2.5 to 4.8 g/cm3 for tower and aerial tests respectively and used the default scavenging coefficient for wet removal, applied both to below- and within-cloud scavenging, covering a wide range of particle sizes. ²⁷ (In HYSPLIT, the wet removal rate constant is defined as $\beta_{wet} = 8x10^{-5} \ P^{0.79} \ s^{-1}$ with P the precipitation rate in mm/h).

The results presented in this study were obtained by running 95 HYSPLIT computations (including 94 120-hour runs for all tests and one 240-h run for Trinity), with 9,000,000 particles each — requiring ~1 year of CPU time. To speed up computations, fallout from individual detonations was run in parallel on 128 threads (AMD Ryzen Threadripper PRO 5995WX, 64 cores) with 1-TB of RAM. The number of particles to track as well as the size of the deposition grid (20 by 60 degrees with 0.1 x 0.1-degree cells centered at 37.0° N, 95.0° W) required significant computational and memory resources. The grid size did not allow us to comprehensively study the impact of the atmospheric tests on Canada and Mexico but our estimates suggest fallout did cross the Canadian and Mexican borders in several instances, including after Trinity. Deposition density estimates beyond the United States could be the focus of future studies.

Post-processing of particle deposition data

Our deposition density and dose rate estimates were produced in two steps. First, radionuclide density in Bq/m² was computed using the con2rem HYSPLIT routine. The source code of con2rem was modified to allow for the use of more than 500 nuclides in the source term and to account for the beginning of decay at the time of the explosion and not at the beginning of the simulation. To produce the deposition density map, decay was stopped for particles at their moment of deposition on the surface. Different source terms were used for deposition density and dose rate contour calculations normalized at H+1 hour, where H is the detonation time, using plutonium-239 ENDF8 fission product yields at 500 keV fission neutron energy. Decay of the source term was conducted at different time intervals with Onix, an open-source depletion code developed at Princeton University.²⁸

Second, a correction factor was applied to deposition density as a function of the distance from ground zero to account for the lack of well-defined semi-empirical particle sizes for tower shots (where only partial interaction between the ground and the fireball occur)¹⁹ and for what we identified as the underestimation of long-range deposition with standard DELFIC particle size parameters. The important challenge is the absence of consistent deposition density data for all radionuclides at short, medium, and very long ranges in the literature. This contributes to the need for a correction factor. A systematic exploration of the particle-size parameter space based on the paucity of semi-empirical data is beyond the scope of this study.

Instead, HYSPLIT estimates of iodine-131 deposition were benchmarked using the NCI reconstruction of nationwide (county-specific) total iodine-131 fallout deposition data from the Nevada Test Site at distances of 1500 to 3500 km from ground zero. The NCI dataset provides iodine deposition densities in 3094 United States counties from 54 atmospheric tests conducted at the Nevada test site. It was built from the reanalysis and interpolation of experimental deposition data, measured at ground stations across the United States. These measurements were carried out from October 1951 to November 1958 and involved between 40 and 95 stations spread throughout the country.

Two different correction factors C_{tower} and C_{air} were computed for ground/tower and aerial tests, using NCI data from 23 aerial and 31 ground and tower Nevada tests. For tower tests, we assumed a linear model, $C_{tower} \propto d_{GZ}$ with d_{GZ} the distance from ground zero, to capture the dominant effect of dry deposition via gravitational settling for large particles at short ranges. For aerial tests, we found the correction factor to vary as $exp(-\beta d_{GZ})$, consistent with the higher residence time of small airburst-generated particles, which are primarily removed from the atmosphere via wet scavenging. The parameters providing the best fit were found to be $C_{tower} = 0.1493 \times d_{GZ}$ and $C_{air} = 4.0518 \times 10^4 \times exp(-6.647 \times 10^{-4} \times d_{GZ})$ with d_{GZ} in kilometers.

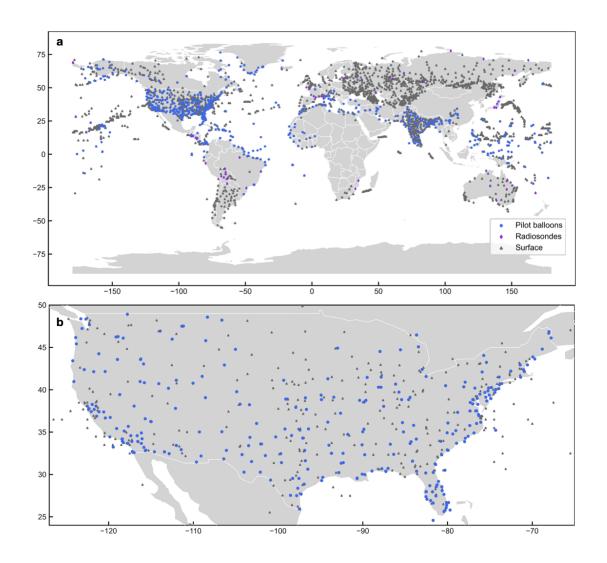
Additional Data and Figures

Extended Data Table 1. List of atmospheric nuclear tests with key parameters used in this study. Time in GMT, height, cloud top and bottom are in meters above ground level.

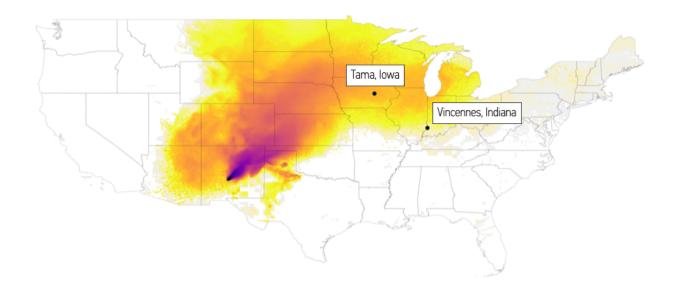
U.S. #	Operation	Name	Date	Туре	Time	Latitude	Longitude	Height [m]	Yield [kt]	Cloud top [m]	Cloud bottom [m]
1	MANHATTAN	Trinity	7/16/45	Tower	12:29	33.6773	-106.4754	30.5	24.8	9259	1822
7	RANGER	Able	1/27/51	Airdrop	13:45	36.8051	-115.9502	323.1	1	4225	2841
8	RANGER	Baker	1/28/51	Airdrop	13:52	36.8051	-115.9502	329.2	8	9711	6531
9	RANGER	Easy	2/1/51	Airdrop	13:47	36.8051	-115.9502	329.2	1	2853	1919
10	RANGER	Baker-2	2/2/51	Airdrop	13:49	36.8051	-115.9502	335.3	8	7577	5096
11	RANGER	Fox	2/6/51	Airdrop	13:47	36.8051	-115.9502	437.4	22	12149	7273
16	BUSTER	Able	10/22/51	Tower	14:00	37.0833	-116.0247	30.5	0.1	1168	771
17	BUSTER	Baker	10/28/51	Airdrop	15:20	37.0850	-116.0211	340.8	3.5	8384	5732
18	BUSTER	Charlie	10/30/51	Airdrop	15:00	37.0850	-116.0213	345	14	11219	6952
19	BUSTER	Dog	11/1/51	Airdrop	15:30	37.0846	-116.0209	431.9	21	12743	8171
20	BUSTER	Easy	11/5/51	Airdrop	16:30	37.0919	-116.0253	400.5	31	13953	9381
21	JANGLE	Sugar	11/19/51	Surface	17:00	37.1315	-116.0394	1.2	1.2	3287	2068
23	TUMBLER- SNAPPER	Able	4/1/52	Airdrop	17:00	36.7980	-115.9364	241.7	1	4000	2690
24	TUMBLER- SNAPPER	Baker	4/15/52	Airdrop	17:30	37.0841	-116.0203	338	1	3507	1770
25	TUMBLER- SNAPPER	Charlie	4/22/52	Airdrop	17:30	37.0844	-116.0211	1050.7	31	11524	8171
26	TUMBLER- SNAPPER	Dog	5/1/52	Airdrop	16:30	37.0841	-116.0211	317	19	12133	7256
27	TUMBLER- SNAPPER	Easy	5/7/52	Tower	12:15	37.0530	-116.1035	91.4	12	9044	5711
28	TUMBLER- SNAPPER	Fox	5/25/52	Tower	12:00	37.0955	-116.1036	91.4	11	11184	7062
29	TUMBLER- SNAPPER	George	6/1/52	Tower	11:55	37.0955	-116.1036	91.4	15	10050	6347
30	TUMBLER- SNAPPER	How	6/5/52	Tower	11:55	37.1384	-116.1183	91.4	14	11372	7181
33	UPSHOT- KNOTHOLE	Annie	3/17/53	Tower	13:20	37.0955	-116.1036	91.4	16	11270	7307
34	UPSHOT- KNOTHOLE	Nancy	3/24/53	Tower	13:10	37.0955	-116.1036	91.4	24	11336	6611
35	UPSHOT- KNOTHOLE	Ruth	3/31/53	Tower	13:00	37.0853	-116.0221	93	0.2	2926	2042
36	UPSHOT- KNOTHOLE	Dixie	4/6/53	Airdrop	15:30	37.0846	-116.0207	1835.5	11	12489	8832

37	UPSHOT- KNOTHOLE	Ray	4/11/53	Tower	12:45	37.0989	-116.0933	30.5	0.2	2674	1120
38	UPSHOT- KNOTHOLE	Badger	4/18/53	Tower	12:35	37.1384	-116.1183	91.4	23	9604	5642
39	UPSHOT- KNOTHOLE	Simon	4/25/53	Tower	12:30	37.0530	-116.1035	91.4	43	12119	8157
40	UPSHOT- KNOTHOLE	Encore	5/8/53	Airdrop	15:30	36.7979	-115.9298	738.5	27	11864	7597
41	UPSHOT- KNOTHOLE	Harry	5/19/53	Tower	12:05	37.0403	-116.0262	91.4	32	11733	7161
42	UPSHOT- KNOTHOLE	Grable	5/25/53	Airburst	15:30	36.7979	-115.9298	159.7	15	9730	6073
43	UPSHOT- KNOTHOLE	Climax	6/4/53	Airdrop	11:15	37.0875	-116.0192	406.6	61	11788	9441
50	TEAPOT	Wasp	2/18/55	Airdrop	20:00	37.0865	-116.0227	232.3	1	5275	3141
51	TEAPOT	Moth	2/22/55	Tower	13:45	37.0955	-116.1036	91.4	2	6149	3619
52	TEAPOT	Tesla	3/1/55	Tower	13:30	37.1254	-116.0484	91.4	7	7918	4352
53	TEAPOT	Turk	3/7/55	Tower	13:20	37.1384	-116.1183	152.4	43	12256	9330
54	TEAPOT	Hornet	3/12/55	Tower	13:20	37.0403	-116.0262	91.4	4	10056	7252
55	TEAPOT	Bee	3/22/55	Tower	13:05	37.0948	-116.0246	152.4	8	10807	7698
57	TEAPOT	Apple-1	3/29/55	Tower	12:55	37.0955	-116.1036	152.4	14	8440	5575
58	TEAPOT	Wasp Prime	3/29/55	Airdrop	18:00	37.0865	-116.0227	225.2	3	8475	5700
59	TEAPOT	НА	4/6/55	Airdrop	18:00	37.0287	-116.0587	9931.1	3	15533	10446
60	TEAPOT	Post	4/9/55	Tower	12:30	37.1221	-116.0353	91.4	2	3433	2366
61	TEAPOT	MET	4/15/55	Tower	19:15	36.7979	-115.9298	121.9	22	11345	8755
62	TEAPOT	Apple-2	5/5/55	Tower	12:10	37.0530	-116.1035	152.4	29	14254	9225
63	TEAPOT	Zucchini	5/15/55	Tower	12:00	37.0948	-116.0246	152.4	28	10898	6387
67	Project 56	Project 56 No. 4	1/18/56	Surface	21:30	36.9713	-115.9554	0.9	0.001	914	610
87	PLUMBBOB	Boltzmann	5/28/57	Tower	11:55	37.0948	-116.0245	152.4	12	8768	5720
88	PLUMBBOB	Franklin	6/2/57	Tower	11:55	37.0955	-116.1036	91.4	0.14	3863	3040
89	PLUMBBOB	Lassen	6/5/57	Balloon	11:45	37.1347	-116.0416	152.4	0.0005	722	486
90	PLUMBBOB	Wilson	6/18/57	Balloon	11:45	37.1347	-116.0416	152.4	10	9379	6331
91	PLUMBBOB	Priscilla	6/24/57	Balloon	13:30	36.7979	-115.9298	213.4	37	12169	6378
93	PLUMBBOB	Hood	7/5/57	Balloon	11:40	37.1347	-116.0416	457.2	74	13341	9379
94	PLUMBBOB	Diablo	7/15/57	Tower	11:30	37.1502	-116.1095	152.4	17	8392	4734
95	PLUMBBOB	John	7/19/57	Rocket	14:00	37.1604	-116.0538	4520.2	2	12104	7644
96	PLUMBBOB	Kepler	7/24/57	Tower	11:50	37.0955	-116.1036	152.4	10	7221	4783
97	PLUMBBOB	Owens	7/25/57	Balloon	13:30	37.1347	-116.0416	152.4	9.7	9383	4811
99	PLUMBBOB	Stokes	8/7/57	Balloon	12:25	37.0865	-116.0248	457.2	19	10002	6954
101	PLUMBBOB	Shasta	8/18/57	Tower	12:00	37.1279	-116.1073	152.4	17	8417	3540
102	PLUMBBOB	Doppler	8/23/57	Balloon	12:00	37.0865	-116.0248	457.2	11	10293	5721

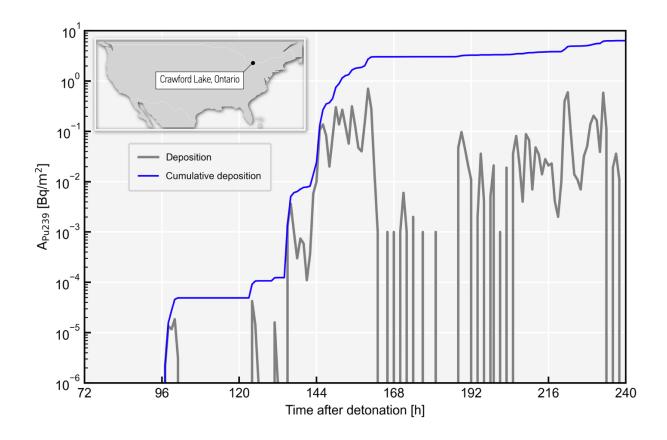
104	PLUMBBOB	Franklin Prime	8/30/57	Balloon	12:40	37.0865	-116.0248	228.6	4.7	8478	5125
105	PLUMBBOB	Smoky	8/31/57	Tower	12:30	37.1872	-116.0687	213.4	44	10217	6452
106	PLUMBBOB	Galileo	9/2/57	Tower	12:40	37.0530	-116.1035	152.4	11	9982	3886
107	PLUMBBOB	Wheeler	9/6/57	Balloon	12:45	37.1347	-116.0416	152.4	0.197	3892	2978
108	PLUMBBOB	Coulomb-B	9/6/57	Surface	20:05	37.0429	-116.0271	0.9	0.3	4257	2688
109	PLUMBBOB	Laplace	9/8/57	Balloon	13:00	37.0865	-116.0248	228.6	1	4820	2991
110	PLUMBBOB	Fizeau	9/14/57	Tower	16:45	37.0334	-116.0322	152.4	11	10964	7001
111	PLUMBBOB	Newton	9/16/57	Balloon	12:50	37.0865	-116.0248	457.2	12	8478	4515
113	PLUMBBOB	Whitney	9/23/57	Tower	12:30	37.1384	-116.1183	152.4	19	7777	4119
114	PLUMBBOB	Charleston	9/28/57	Balloon	13:00	37.1347	-116.0416	457.2	12	8469	4811
115	PLUMBBOB	Morgan	10/7/57	Balloon	13:00	37.1347	-116.0416	152.4	8	10908	6640
117	PROJECT58	Coulomb-C	12/9/57	Surface	20:00	37.0482	-116.0252	0	0.5	2728	1723
160	HARDTACKII	Eddy	9/19/58	Balloon	14:00	37.0865	-116.0248	152.4	0.083	2077	1010
165	HARDTACKII	Mora	9/29/58	Balloon	14:05	37.0865	-116.0248	457.2	2	4363	1772
166	HARDTACKII	Hidalgo	10/5/58	Balloon	14:10	37.0865	-116.0248	114.9	0.077	2382	1163
169	HARDTACKII	Quay	10/10/58	Tower	14:30	37.0948	-116.0245	30.5	0.079	1754	992
170	HARDTACKII	Lea	10/13/58	Balloon	13:20	37.0865	-116.0248	457.2	1.4	3906	2382
172	HARDTACKII	Hamilton	10/15/58	Tower	16:00	36.8023	-115.9331	15.2	0.0012	890	433
174	HARDTACKII	Dona Ana	10/16/58	Balloon	14:20	37.0865	-116.0248	137.2	0.037	2077	705
175	HARDTACKII	Vesta	10/17/58	Surface	23:00	37.1226	-116.0354	0	0.024	1760	1111
176	HARDTACKII	Rio Arriba	10/18/58	Tower	14:25	37.0409	-116.0268	22.3	0.09	2893	2131
178	HARDTACKII	Socorro	10/22/58	Balloon	13:30	37.0865	-116.0248	442	6	6649	4820
179	HARDTACKII	Wrangell	10/22/58	Balloon	16:50	36.7979	-115.9298	457.2	0.115	2110	1196
181	HARDTACKII	Rushmore	10/22/58	Balloon	23:40	37.1347	-116.0416	152.4	0.188	457	307
182	HARDTACKII	Catron	10/24/58	Tower	15:00	37.0428	-116.0278	22.3	0.021	1364	297
183	HARDTACKII	Juno	10/24/58	Surface	16:01	37.1233	-116.0387	0	0.0017	393	248
184	HARDTACKII	Ceres	10/26/58	Tower	4:00	37.1813	-116.0695	7.6	0.0007	479	303
185	HARDTACKII	Sanford	10/26/58	Balloon	10:20	36.7979	-115.9298	457.2	4.9	6987	2872
186	HARDTACKII	De Baca	10/26/58	Balloon	16:00	37.0865	-116.0248	457.2	2.2	4058	1772
187	HARDTACKII	Chaves (Chavez)	10/27/58	Tower	14:30	37.0446	-116.0307	15.8	0.0006	754	476
190	HARDTACKII	Humboldt	10/29/58	Tower	14:45	37.0476	-116.0254	7.6	0.0078	1058	601
191	HARDTACKII	Santa Fe	10/30/58	Balloon	3:00	37.0865	-116.0248	457.2	1.3	4211	2687
194	HARDTACKII	Titania	10/30/58	Tower	20:34	37.1772	-116.0701	7.6	0.0002	487	307
265	SUNBEAM	Little Feller II	7/7/62	Surface	17:00	37.1191	-116.3037	0.9	0.022	1790	1130
271	SUNBEAM	Small Boy	7/14/62	Tower	18:30	36.8025	-115.9259	3	1.65	4853	3065
272	SUNBEAM	Little Feller I	7/17/62	Surface	17:00	37.1096	-116.3182	0.9	0.018	1770	1118



Extended Data Figure 1. ERA5 surface and upper air (pilot balloons and radiosondes) observations for July, 16, 1945. (a), World-wide observations. (b), Details for the region of interest in this study.



Extended Data Figure 2. Trinity deposition density map six days after detonation showing the contamination of two mills manufacturing strawboard material for photographic film storage in 1945.



Extended Data Figure 3. Plutonium-239 deposition density estimates at Crawford Lake (43.468 N, 79.949 W) in Ontario, Canada, following the detonation of Trinity in New Mexico, United States. These estimates assume that 5.2kg out of 6 kg of plutonium-239 (specific activity of 2.27 10¹² Bq/kg) did not fission during the explosive chain reaction.²⁹ Estimates show that small amounts of plutonium could have arrived at Crawford Lake as early as 4 days after detonation and that peak deposition happened between 6 and 7 days after detonation.

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