

Accounting for Unfissioned Plutonium from the Trinity Atomic Bomb Test

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INTRODUCTION

Abstract—The Trinity test device contained about 6 kg of plutonium as its fission source, resulting in a fission yield of 21 kT. However, only about 15% of the ²³⁹Pu actually underwent fission. The remaining unfissioned plutonium eventually was vaporized in the fireball and after cooling, was deposited downwind from the test site along with the various fission and activation products produced in the explosion. Using data from radiochemical analyses of soil samples collected postshot (most many years later), supplemented by model estimates of plutonium deposition density estimated from reported exposure rates at 12 h postshot, we have estimated the total activity and geographical distribution of the deposition density of this unfissioned plutonium in New Mexico. A majority (about 80%) of the unfissioned plutonium was deposited within the state of New Mexico, most in a relatively small area about 30–100 km downwind (the Chupadera Mesa area). For most of the state, the deposition density was a small fraction of the subsequent deposition density of ²³⁹⁺²⁴⁰Pu from Nevada Test Site tests (1951–1958) and later from global fallout from the large US and Russian thermonuclear tests (1952–1962). The fraction of the total unfissioned ²³⁹Pu that was deposited in New Mexico from Trinity was greater than the fraction of fission products deposited. Due to plutonium being highly refractory, a greater fraction of the ²³⁹Pu was incorporated into large particles that fell out closer to the test site as opposed to more volatile fission products (such as ¹³⁷Cs and ¹³¹I) that tend to deposit on the surface of smaller particles that travel farther before depositing. The plutonium deposited as a result of the Trinity test was unlikely to have resulted in significant health risks to the downwind population.

Health Phys. 119(4):504–516; 2020

Key words: ²³⁹Pu; fallout; nuclear weapons; plutonium

THE TRINITY test device was reported to have contained about 6 kg (US DOE 2002) of plutonium as its major fission source. However, based on the reported fission yield of 21 kT (US DOE 2000), and the fact that about 1/3 of the yield was from fission of ²³⁵U in the thick natural uranium tamper surrounding the plutonium core, only about 15% of the ²³⁹Pu actually underwent fission.⁵ The remaining unfissioned plutonium was instantaneously vaporized in the fireball and after cooling, was deposited downwind from the test site along with the various fission and activation products produced in the explosion. In this paper, we estimate the deposition density of this unfissioned plutonium at various distances downwind from the test site as well as the total cumulative activity deposited within the state of New Mexico. The amount of plutonium contamination of the New Mexico environs has understandably become an issue of concern to some residents of the state, particularly those residing at locations near the White Sands test site (TBDC 2017).

The total unfissioned plutonium can be estimated from the reported amount of plutonium in the device, the estimated ratio of ⁹⁰Sr to ¹³⁷Cs in the deposited fallout, and the reported explosive yield. According to Glasstone and Dolan (1977), 1.45×10^{23} fissions of either ²³⁹Pu or ²³⁵U results in a yield of 1 kT. If all the reported yield of 21 kT were from plutonium fission, 1.197 kg of ²³⁹Pu would have fissioned ($[21 \text{ kT} \times 1.45 \times 10^{23} \text{ fissions kT}^{-1}] / [2.52 \times 10^{24} \text{ plutonium atoms kg}^{-1}]$), leaving $6 - 1.2 = 4.8$ kg of Pu unfissioned. However, because $\sim 1/3$ of the fissions were actually from fission of ²³⁵U, the amount of unfissioned plutonium was actually ~ 5.2 kg.

Although the unfissioned ²³⁹Pu from nuclear tests has generally been of less concern to knowledgeable experts in regard to the risk of health effects (compared to the risks from deposited fission products), there is a perception by

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The authors declare no conflicts of interest.

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(Manuscript accepted 25 June 2019)

0017-9078/20/0

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DOI: 10.1097/HP.0000000000001146

⁵Because the ratio of the fission yields for ⁹⁰Sr to ¹³⁷Cs differs considerably for ²³⁹Pu and ²³⁵U fission (3.21 vs. 1.14), the fraction of the total fissions from ²³⁵U can be estimated from the ratio of ⁹⁰Sr and ¹³⁷Cs deposition densities of Trinity fallout (2.04) estimated by Hicks (1981) (Beck 2001a). Although the actual fraction of the Trinity yield from ²³⁵U has not been officially reported, our estimate is in good agreement with unofficial estimates.

the general public that plutonium is especially hazardous. It is, therefore, worthwhile to attempt to document exactly how much and where this plutonium was deposited and to discuss the possible impact on the residents of New Mexico—past, present, and future.

To estimate the amount of plutonium deposited in various areas of New Mexico, we relied on data from analyses of postshot soil samples for $^{239+240}\text{Pu}$ activity supplemented by model-based estimates of $^{239+240}\text{Pu}$ activity in soil derived from postshot exposure-rate monitoring data. The use of a model to supplement the soil analyses was necessary because the available soil sample data were limited to areas relatively close to the test site and to the fallout pattern axis, as well as, in general, being very imprecise.

Using the combination of soil measurements and estimates from models, we estimated plutonium deposition density at ~1,000 sites covering the entire state of New Mexico. We then interpolated those data to obtain estimates on a 2 km × 2 km grid allowing for a fairly precise numerical integration of activity with increasing distance from ground zero (GZ). The specifics of the methodology and results are detailed in the following sections of this paper.

METHODS

Estimation of deposition density from soil sample data

A number of investigators and institutions collected soil samples downwind from GZ for plutonium measurement. Table 1 lists the various sampling programs and the approximate number of unique sites sampled. Unfortunately, some of these samples were obtained in a manner that made their use in estimating deposition density unreliable, leading us to determine they were not suitable for use in estimating the total plutonium deposited. Most of the other samples required corrections to account for insufficient depth of sampling and/or unspecified soil density. Fig. 1 shows the location of all the sampled sites.

Most of the soil samples were taken only to a depth of 5 cm and some only as deep as 2.5 cm. For samples taken many years after the test, the plutonium is known to have

Table 1. Summary of soil samplings.

Reference	Date of sampling	# Unique sites	# Profiles (total depth ≥ 15 cm) ^b
Olafson et al. (1957)	1948	17	0
Hakonson et al. (1973)	1972	8	8
Douglas (1978)	1973, 1974	88	11
Nyhan et al. (1976)	1976	4	2
Hansen and Rodgers (1985)	1977	54	17
McArthur and Miller (1989) ^a	1982	14	14

^aMost of these samples were remote from the areas impacted by Trinity fallout and served as control samples.

^bMost of the profile samples were taken in 5 cm increments; of the 38 profile samples, excluding the McArthur and Miller samples, 20 reached to only 15 cm while only 13 extended to ≥ 25 cm.

penetrated much deeper. Based on limited data, Hansen and Rodgers (1985) found that plutonium inventory was uniform in the top 2.5 cm of soil and decreased exponentially with further depth. Based on the cores collected at 17 sites by Hansen and Rodgers (1985), about 1/2 the plutonium collected down to a depth of 15 cm was in the top 2.5 cm in the mid-1970s when most of the soil data were collected (Fig. 2). Even the samples collected closer to the time of the test (Olafson et al. 1957) are suspect because the sample depth was sometimes only 2.5 cm or even less, and rain and natural processes would have caused some of the plutonium to move below the sampling depth. In their 1972 study, Hakonson and Johnson (1973) observed that the plutonium concentration penetrated to a soil depth of at least 30 cm. Of 12 profile samples taken by the US Environmental Protection Agency (EPA) (Douglas 1978), 6 had detectable levels of plutonium down to at least 10–15 cm. Nyhan et al. (1976) noted that their soil samples reflected “considerable downward migration of plutonium into the soil” with time. McArthur and Miller (1989) collected soil samples at a number of sites in New Mexico in 1982 in conjunction with the US Department of Energy (DOE) Offsite Radiation Exposure Review Program (ORERP). Those samples were obtained under a more rigorous sampling strategy, and soil preparation and chemical analysis procedures were conducted with more strict quality assurance than many of the earlier Trinity sampling programs. Although the $^{239+240}\text{Pu}$ at the sites sampled was mostly from Nevada Test Site (NTS) and global fallout rather than from Trinity, on average 60% was found below 10 cm. However, while these samples were taken 5–10 y later than the Trinity samples, the NTS and global fallout was deposited from 6 to 17 y later than the Trinity fallout.

The amount of soil collected at each site varied as well. For some of the sites sampled, only three 12.8-cm-diameter cores were obtained (Hansen and Rodgers 1985), although for the samples collected by Douglas (1978), ~1,000 cm² (10 cores) were sampled at most sites. Thus, even for the Douglas samples, an individual sample may not be a true representation of the mean deposition density over the surrounding area, particularly considering that the samples in those surveys were usually not obtained in ideal terrain where the deposited activity might have been expected to have deposited uniformly over the general area and would have been expected to have remained in place from the time of deposition to the time of sampling. It is well known (US EPA 1980) that in sparsely vegetated environs windblown fallout in surface soil tends to preferentially collect at the base of desert brush, and sampling in open areas may thus result in an underestimate of the true deposition density.

Some analyses were reported only as activity per mass of soil rather than per unit area. In that case, the specific bulk density of the soil is required to estimate deposition

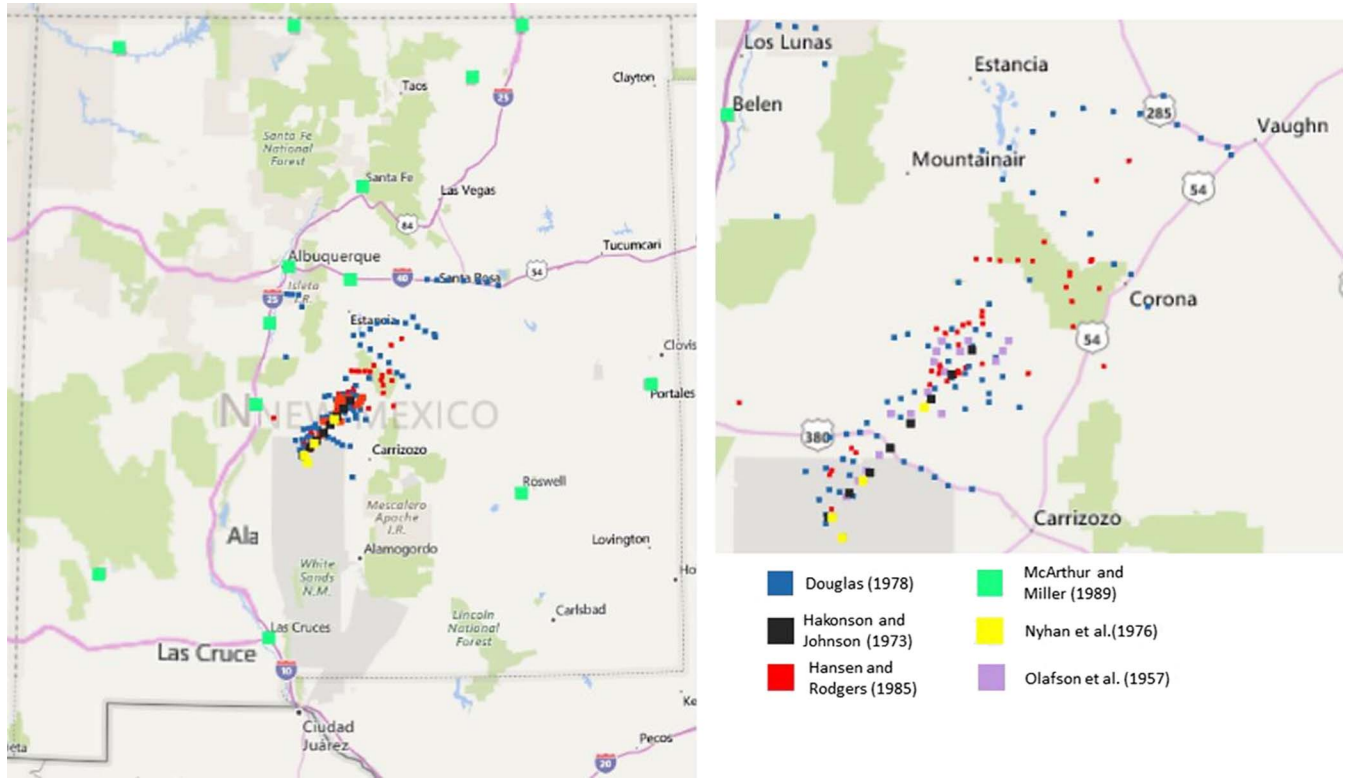


Fig. 1. Soil sampling locations.

density (Bq m^{-2}). To correct the samples where only activity per mass was reported, we assumed an average bulk density of 1.2 g cm^{-3} based on the mean density reported by Douglas (1978) for the samples they collected.

To address the problems with the limited depth sampled at most of the sites, we applied corrections based on

the reported sample depth to attempt to account for the plutonium likely not collected (Table 2). These correction factors are based on the observed depth distributions at sites where profiles were obtained, the McArthur and Miller (1989) soil data, and our best judgement. Because the number of complete profiles were relatively few, as shown in Table 1, and the depth

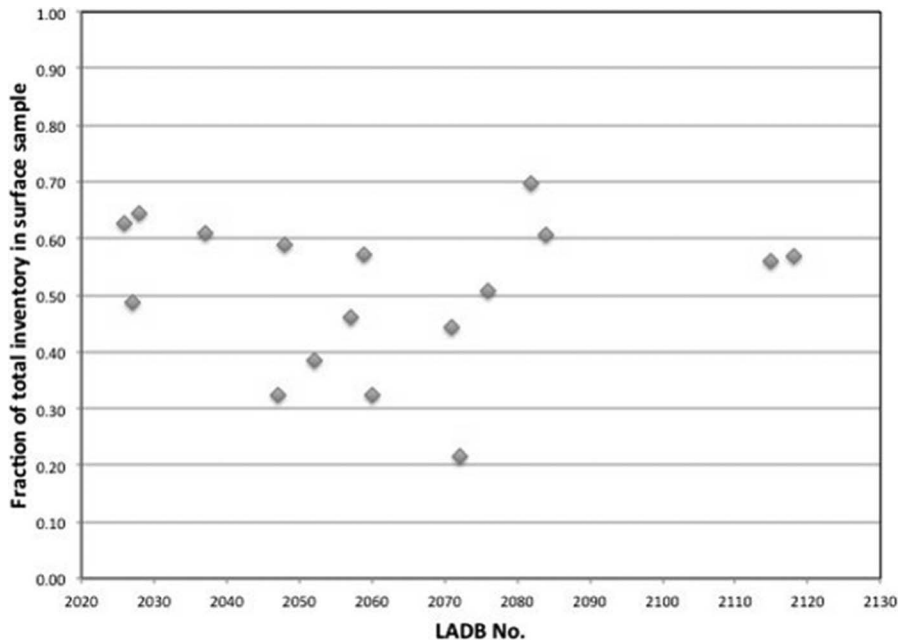


Fig. 2. Fraction of plutonium activity in top 5 cm, based on 17 profile samples 0–15 cm taken in 1977. LADB refers to sample number in the Los Alamos database, reproduced in Appendix A of Hansen and Rodgers (1985).

profiles varied from profile to profile, these correction factors may not be strictly accurate for any specific site, but on average, they should provide more reasonable estimates of the total plutonium deposited over the entire area than the estimates based on the uncorrected data.

As shown in Fig. 1, the available soil sample data covers only a limited geographical area relatively close to the test site and to the fallout pattern axis (center line of the trajectory). Some of these data, in our judgement, were anomalous or not suitable for estimating deposition density due to insufficient sample depth. The remaining soil data, notwithstanding the uncertainty due to lack of representativeness and particularly to measurement imprecision, are far too few to interpolate and extrapolate for estimating the cumulative deposition over the entire state. Thus, it was necessary to use an alternate methodology to extend the fallout pattern out to farther distances as well as to fill in the areas with a limited number of sites with good measurement data.

Estimation of $^{239+240}\text{Pu}$ from the reported exposure rate pattern

The model used to estimate plutonium deposition in this study is based on a joint US-Russian semiempirical model for estimating the deposition density of fission products at sites relatively close to a test site where fractionation affects the relative deposition of refractory vs. volatile radionuclides as a function of distance from GZ. The details of this model are summarized in the Appendix.

In brief, we estimated the plutonium deposition density at a large number of sites throughout New Mexico from the reported exposure rates at 12 h postshot (E12) from Quinn (1987) using conversion ratios of $^{239+240}\text{Pu}$ activity to E12 ($\text{Bq m}^{-2} \text{ mR h}^{-1}$; abbreviated as Pu/E12), corrected for fractionation as described in the Appendix.

Pu/E12 for unfractionated Trinity fallout was estimated to be $2.7 \text{ Bq m}^{-2} (\text{mR h}^{-1})^{-1}$ from the fission yields for ^{137}Cs (6.58% for ^{239}Pu and 3.22% for ^{235}U ; England and Ryder 1994), the number of fissions ($21 \text{ kT} \times 1.45 \times 10^{23} \text{ fissions kT}^{-1}$), the estimated amount of unfissioned plutonium (5.2 kg), the estimated fraction of the yield due to ^{235}U fission (32%), the specific activities of ^{239}Pu and ^{137}Cs (2.27×10^{12} and $3.21 \times$

$10^{15} \text{ Bq kg}^{-1}$, respectively), and the ratio of ^{137}Cs activity in deposited fallout normalized to E12 for Trinity (29 Bq m^{-2} ; Hicks 1981).

However, corrections are required to account for fractionation, i.e., the phenomenon whereby refractory radionuclides such as plutonium tend to be incorporated into larger particles that fall out more rapidly, and thus closer, to the test site than volatile nuclides such as ^{137}Cs or ^{131}I . The volatile nuclides condense later and attach preferentially to smaller particles that travel farther distances before depositing (Hicks 1981; Freiling 1961). Thus, the ratio of refractory nuclides to E12 is greater than the ratio for unfractionated fallout at locations close-in to the detonation site and along the trace⁶ axis than for fallout characteristic of deposition at greater distances and less than the unfractionated value at distances far removed from the detonation site or far off the axis.

Using the calculations of Hicks (1981), we can calculate the activity ratio R/V (of a refractory radionuclide R such as plutonium to a volatile radionuclide V such as ^{137}Cs) for $\text{E12} = 1.0 \text{ mR h}^{-1}$ and for different values of R/V.⁷ Using the joint US-Russian deposition density model, we can estimate R/V as a function of fallout time-of-arrival (TOA) and distance from the fallout pattern axis to correct the value of Pu/E12 and thereby, account for fractionation at each specific location. Table 3 gives our estimates of Pu/E12 vs. R/V⁸ and illustrates that the correction required can be quite significant, particularly for sites close to GZ, i.e., with low TOA values and at locations close to the trace axis.

The required estimates of E12 and TOA were obtained by interpolation of the published fallout pattern (Fig. 3) that was constructed from an analysis of all postshot monitoring data supplemented by meteorological data (Quinn 1987). Unfortunately, because the acquisition of monitoring data was limited to locations with roads, and the precision and accuracy varied depending on the accuracy of the particular instruments used, the required corrections for radioactive decay and consequently, the published fallout pattern itself is somewhat uncertain. Furthermore, the contours provided are fairly broad, i.e., the spatial resolution is poor, particularly close-in to GZ where the E12 changes rapidly with distance. This made precise interpolation of both E12 and TOA difficult.

Table 2. Corrections applied for insufficient sample depth.

Sample depth (cm)	Correction factor
<2.5	Not used
2.5	3.0
5	2.0
10	1.6
15	1.4
22.5	1.1
30	1.0

⁶We use the term trace to refer to the pattern of fallout downwind from GZ. Conventional units are used for E12 to be consistent with historical literature on deposition of fallout from nuclear testing.

⁷The Pu/E12 ratios in Table 3 include a small correction to account for ^{240}Pu in the original fuel. According to Douglas (1978), ~2.3% of the Trinity plutonium mass deposited was ^{240}Pu . This amount of ^{240}Pu is consistent with the fraction of ^{240}Pu used in early nuclear tests (Hicks 1990). Thus, based on the relative half-lives of ^{240}Pu (6,600 y) to ^{239}Pu (24,000 y), ~8% of the deposited activity was from ^{240}Pu . The fraction of ^{241}Pu in early devices was only about 0.05% (Hicks 1990).

Table 3. Estimated Pu/E12 vs. R/V.

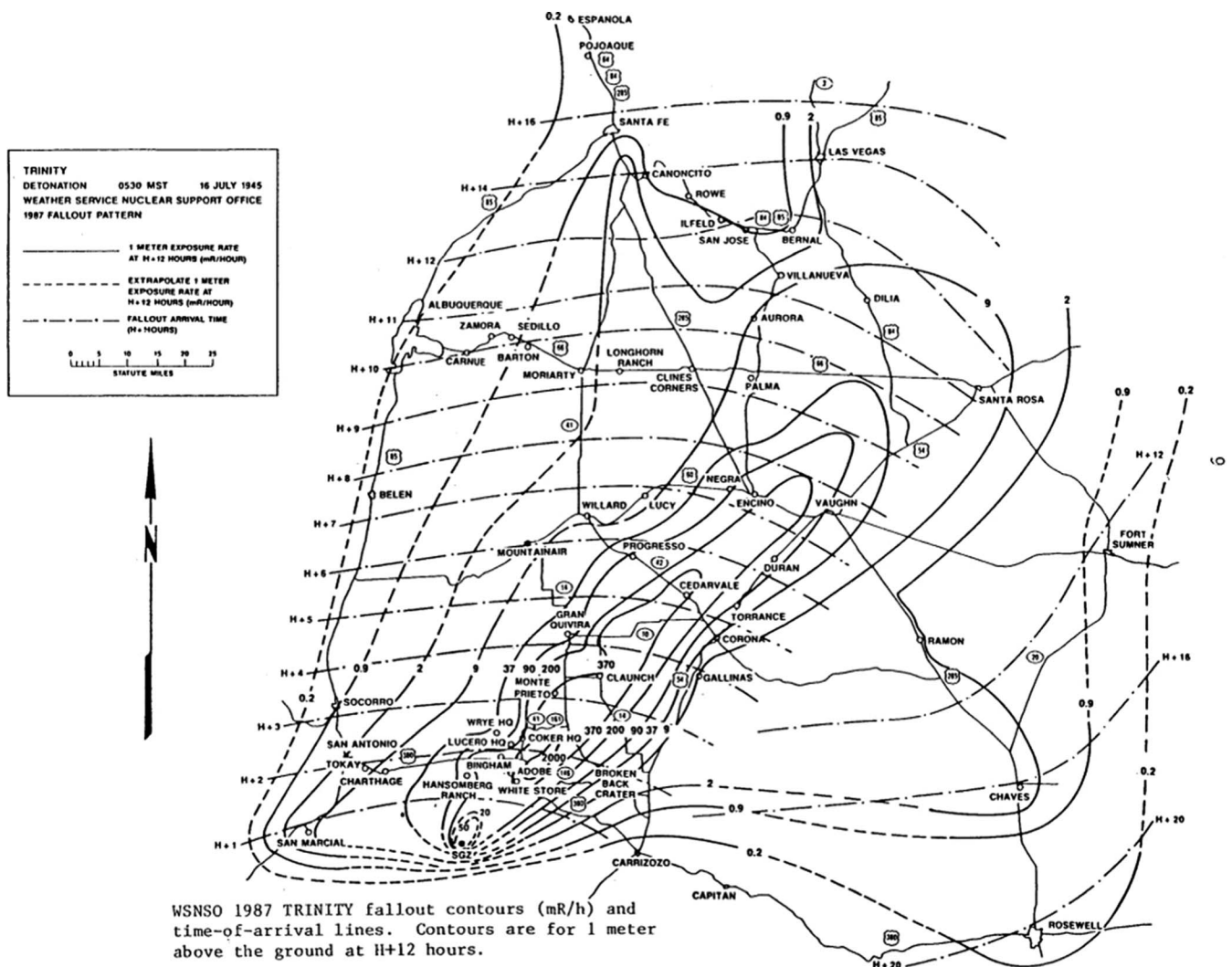
R/V	Pu/E12 ($\text{Bq m}^{-2} [\text{mR h}^{-1}]^{-1}$)
0.5	1.7
1.0	2.7
1.5	3.3
2.0	3.7
3.0	4.3
4.0	5.1

Nevertheless, we estimated E12 and TOA at all the sample sites as well as at the centroids of all the 1945 voting precincts for which Simon et al. (2020) calculated organ doses from fallout radionuclides and activation products. We then applied the R/V corrected Pu/E12 conversion based on the estimated TOA and E12 and the calculated distance from the trace axis to estimate a plutonium deposition density. The locations of these sites are shown on Fig. 4

which can be compared with the limited coverage of the soil sites shown in Fig. 1.

Although the model estimates are uncertain, primarily as a consequence of the uncertainty in the estimates of E12 and TOA but also due to the uncertainty in the estimated R/V and the exact amount of unfissioned plutonium, a comparison of model calculated vs. measured deposition density (Fig. 5) exhibits a fairly strong correlation ($r^2 = 0.7$), particularly if we restrict the comparison to calculated-to-measured (C/M) ratios within a factor of 5-fold.

We have assumed that ratios outside a factor of 5-fold indicate either that the soil data is anomalous (most likely, for the reasons discussed earlier regarding the various sampling and analysis uncertainties) or the model calculations are in error (considered less likely, except very close to the trace axis and to GZ where large corrections for R/V were required). The average ratio of C/M was found to be 1.18 (standard error [SE] = 0.10) suggesting that calculated ratios

**Fig. 3.** Fallout contours (E12, TOA) (Quinn 1987).

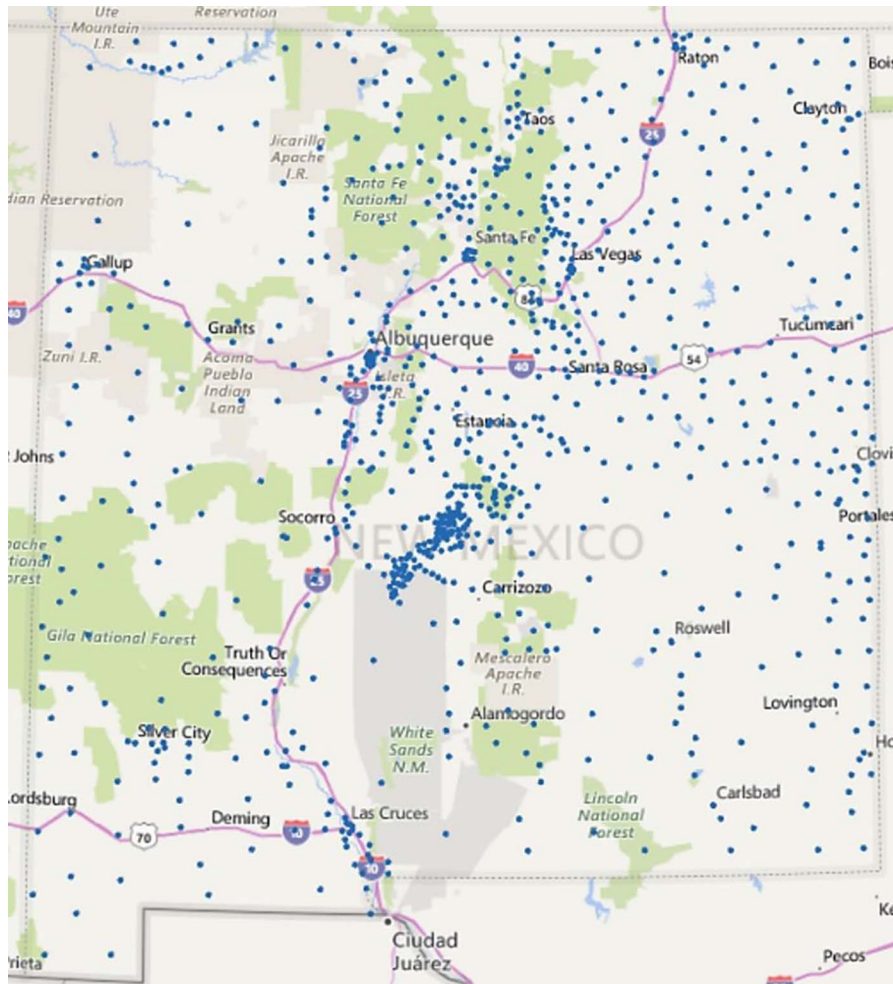


Fig. 4. Locations where deposition density was calculated from E12, TOA.

for data deemed reliable were generally within about 25% of the measured ratios. Furthermore, the C/M ratio varies little with R/V, suggesting the estimates of Pu/E12 vs. R/V are reasonably accurate. Considering, as discussed earlier, that the soil sampling carried out many years after the event would tend to underestimate the deposition, a C/M ratio greater than unity is not unexpected.

However, as can be seen from Fig. 5, there is a slight trend toward increasing C/M as the measured plutonium decreases. For example, the ratio of C/M for measured plutonium $<1,000 \text{ Bq m}^{-2}$ is about 1.4, while C/M for $>1,000 \text{ Bq m}^{-2}$ is about 0.9. Thus, either the model overestimates the plutonium at lower activities or underestimates the plutonium at high activities, the measured plutonium tends to be progressively more underestimated at lower activities, or more likely, some combination of the above. However, considering the multiple sources of uncertainty discussed in the preceding paragraphs, the correlation between the measured and calculated plutonium is quite satisfactory, and we believe it demonstrates that the model estimates can be reliably used to extend the deposition density estimates to all

of New Mexico as well as to fill in the gaps at close-in distances.

Estimation of plutonium deposition density using a combination of soil data and model estimates

Because of the limited number of soil samples and the spatial gaps in geographic coverage (Fig. 1), it was not possible to obtain a credible estimate of total deposition from the soil data alone. However, the reasonably strong correlation between the soil data and the model calculations allowed us to calculate the deposition density at sites without measurement data and estimate the total deposition in New Mexico two different ways. First, we used a combination of the soil data deemed credible ($C/M = 0.2\text{--}5$) supplemented by model calculations at additional sites. This method minimizes any potential error due to having to estimate R/V because the soil data are used for most of the sites where the R/V values are highest. Second, we used only the model-calculated deposition density under the assumption that this might provide better overall precision without affecting the estimated geographical precision. To allow a

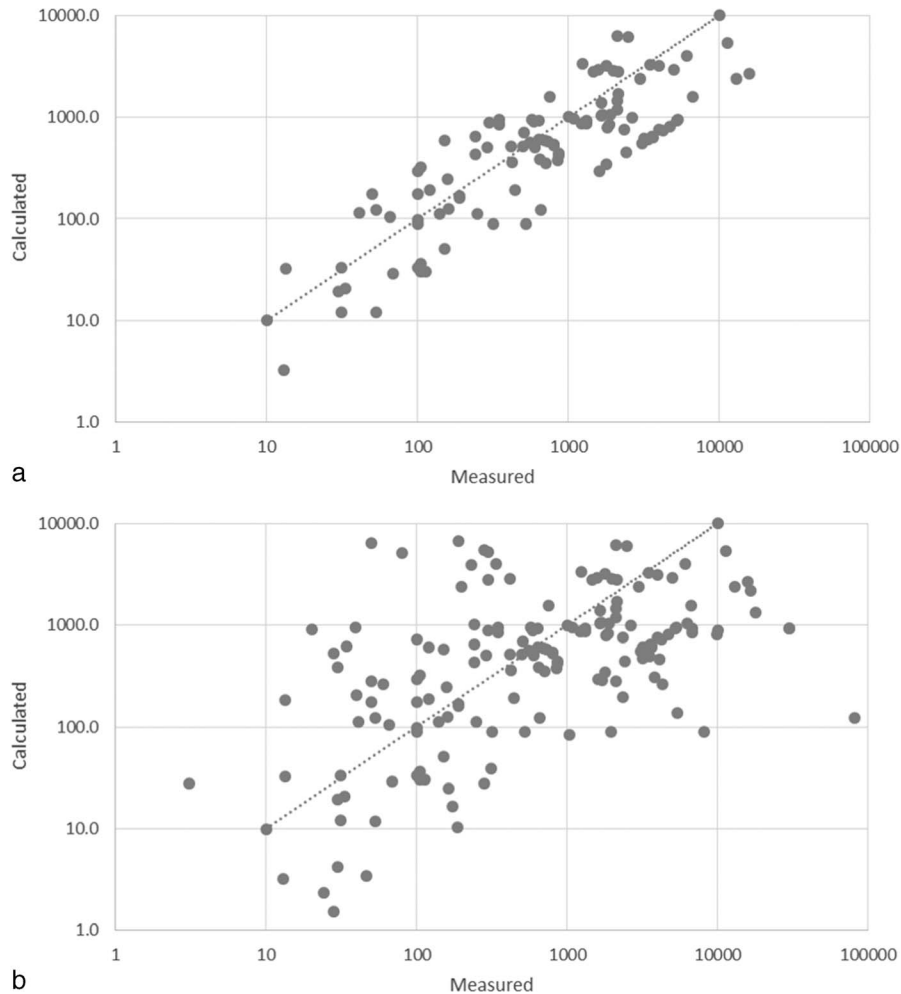


Fig. 5. Calculated vs. measured deposition density (Bq m^{-2}): (a) only sites with calculated-to-measured ratios between 0.2 and 5; (b) all soil-sampling sites.

precise numerical integration vs. distance, we used kriging in both cases to estimate (interpolate) the deposition density on a $2 \text{ km} \times 2 \text{ km}$ grid.

RESULTS

Fig. 6 is a plot of the interpolated deposition density estimates of $^{239+240}\text{Pu}$ activity throughout New Mexico. Fig. 6 is based on using only calculated (model) data because we found the interpolation plot using a combination of model and soil data to be almost identical. However, as expected, the data values using model data alone appeared to be slightly more precise as indicated by less scatter. This is not unexpected given that individual soil estimates are not very representative of the local area compared to the estimated E12, as any site can have been unknowingly disturbed or eroded.

Table 4 shows the calculated total deposition (total plutonium activity) as a function of distance from GZ for both methods along with the fraction of unfissioned plutonium (mass or activity).⁹ As indicated by both methods, about 80% of the unfissioned plutonium was likely deposited

within a distance of $<400 \text{ km}$ downwind. Given that a line from Trinity along the trace intersects the eastern border of New Mexico at about 350 km, most (if not all) of the plutonium deposited within 400 km was deposited within the state of New Mexico.

Our estimate of the total unfissioned plutonium deposited in New Mexico is considered somewhat uncertain, while the fraction deposited within a range of distances (the pattern of fallout) is believed to be more precise. Because R/V is only significantly >1 over a small area close to GZ and within a few tens of kilometers from the axis of the fallout trace, any uncertainty in R/V is expected to have had only a relatively small effect on the estimated distribution of plutonium vs. distance and the fraction of unfissioned plutonium deposited in New Mexico. This conclusion is supported by the overall relatively good correlation shown in Fig. 5 between calculated and measured

⁹The measured and calculated deposition densities are in Bq m^{-2} of $^{239+240}\text{Pu}$. The mass of plutonium deposited per unit area is directly proportional to the activity of $^{239+240}\text{Pu}$ deposited.

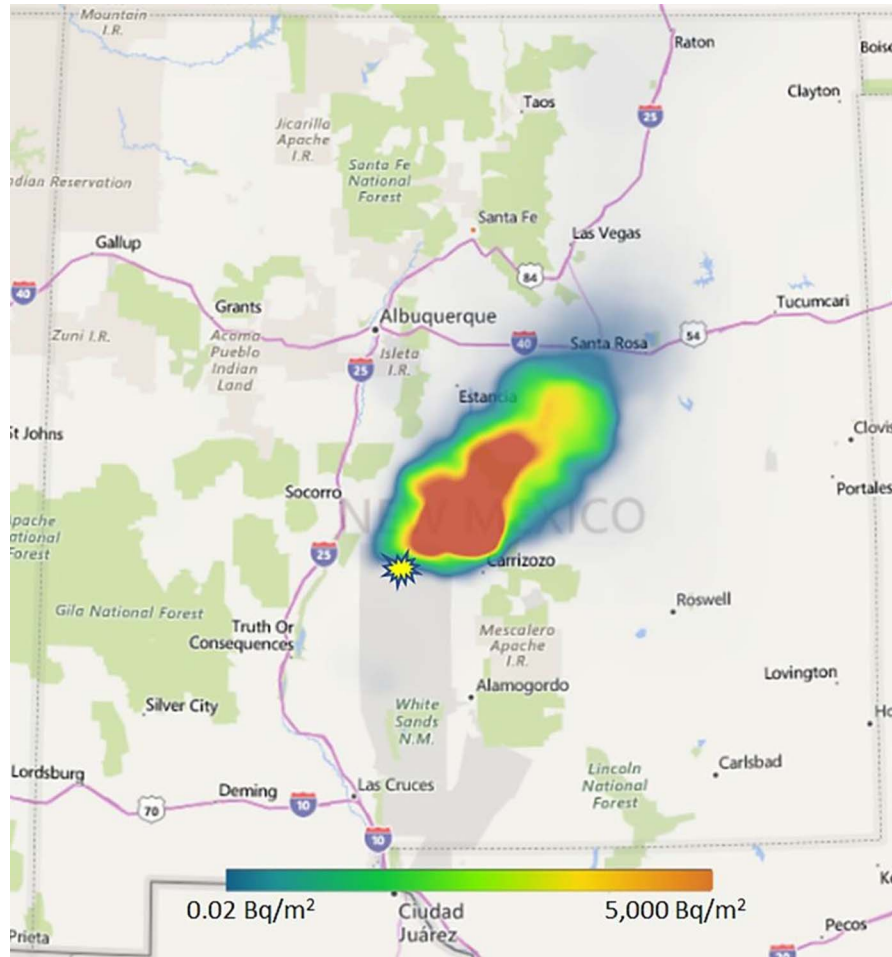


Fig. 6. Calculated deposition density of $^{239+240}\text{Pu}$.

plutonium deposition density and the fact that the C/M ratio did not vary significantly with R/V.

The reasons for the significant uncertainty in total deposition are several. First, the exact amount of plutonium used in the Trinity device is not known precisely. US DOE (2002) reported the fuel to have been “about” 6 kg of plutonium, which is the value used in our model. In comparison, the Defense Special Weapons Agency (DSWA 1997) estimated 6–7 kg was used in the first Soviet test, reputed to have been “very similar” to Trinity in its construction. In that test, only about 15% of the ^{239}Pu was reported to have fissioned. Other reported estimates range from ~5.5 kg to 6.5 kg. Thus, because only a small amount of plutonium actually fissioned, if there was 10% more or less plutonium in the Trinity device than the nominal 6 kg that we used for our calculations, the amount of unfissioned plutonium would have been ~10% higher or lower. The yield of the device is also uncertain to ± 2 kT (Young and Kerr 2005), which could have resulted in about 7% more or less unfissioned plutonium having been produced.

In addition, ^{239}Np was produced in the blast by neutron activation of the ^{238}U tamper surrounding the plutonium core. Based on the ^{239}Np activity per mR h^{-1} estimated for Trinity by Hicks (1981), as much as an additional 0.8 kg of ^{239}Pu might have been produced from the beta decay of this ^{239}Np . This extra source of plutonium is not included in our primary calculations because it does not represent the unfissioned remainder of the device’s core. Including this source of plutonium would have increased our estimate of the deposition density at each location and the total deposition in New Mexico, and would have increased the observed C/M ratio, by about 10%.

The amount of plutonium deposited very close to the test site is also very uncertain. Based on sparse available data, we crudely estimated ~5% of the total unfissioned plutonium to have been deposited within 10 km from GZ. The available soil activity data at distances <10 km, i.e., on the Trinity test site, ranged widely, from a few very high values to no alpha activity. Unfortunately, we could not use our model to estimate the plutonium on-site because the E12 measured near GZ was mostly from activation of the soil

Table 4. Fraction of unfissioned plutonium deposited vs. distance

a. Using soil data supplemented by model estimates of deposition density.		
Distance (km)	Unfissioned ^{239}Pu deposited (%)	Cumulative (%)
0–10	5.0	5.0
10–30	3.9	8.9
30–100	53	62
100–200	19	81
200–300	1.4	82
300–500	0.4	83
>500	17	100
b. Using model estimates of plutonium deposition density only.		
Distance (km)	Unfissioned ^{239}Pu deposited (%)	Cumulative (%)
0–10	5	5.0
10–30	3.6	8.6
30–100	52	61
100–200	17	78
200–300	1.2	80
300–500	0.4	80
>500	20	100

rather than from deposited fission products, and the available soil analysis data was too unreliable to include in the interpolations of deposition density vs. distance.

Finally, any systematic bias in the reported E12 would result in a corresponding bias in the total plutonium deposited.

Implications for health risk

Two possible modes of intake of plutonium from Trinity are most important with respect to potential health effects: inhalation of descending fallout and inhalation at later times from the resuspension of activity on the surface of the ground. Due to plutonium's low transfer from gut to blood, plutonium is not considered a significant hazard from ingestion relative to inhalation (ICRP 1993, 1995; Burley 1990).

The concern is that inhalation of plutonium could lead to an increased risk of lung, bone, or liver cancer (Burley 1990). The radiation dose would be a consequence of inhaling respirable particles of descending fallout or of contaminated soil that was resuspended by wind, human activity, or other activity. Previously, the US EPA (1977), using conservative models to relate surface soil activity to surface air activity and inhalation of those airborne particles containing plutonium to organ doses, recommended action levels for plutonium surface soil activity that would insure that activity in surface soil below these levels would result in minimal risk from either inhalation or ingestion. Those action levels are based on the level below which doses (particularly lung doses) would be well under the suggested annual radiation dose limits to the public recommended by national and international organizations such as the National Council on Radiation Protection

and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP).

The activity levels in New Mexico soils that we have estimated can be compared to these US EPA recommended action levels. The US EPA action level for ^{239}Pu is $7,400 \text{ Bq m}^{-2}$ in the top 1 cm of soil, which is considered the depth from which soil particles containing plutonium could be resuspended into the air. Even with the uncertainties discussed earlier, for areas off the site of the Trinity detonation, the plutonium soil activity was well below these action levels, even for the Chupadera Mesa region and even shortly after deposition. Note that our estimated plutonium deposition densities include the small contribution from ^{240}Pu . The subsequent penetration of activity to deeper levels in the soil was such that the activity in the top 1 cm is now far below these action levels at all locations. In fact, based on our estimates of the depth distribution in 1976 (Table 2), the current levels in the top 1 cm are a factor of 3–4 times lower than the levels shown in Fig. 6.

Measurements of plutonium activity in air carried out by the EPA in 1973–1974 in one of the highest soil activity areas were a factor of 25 less than the EPA recommended action level for airborne activity (Douglas 1978). Undoubtedly, the potential inhalation hazard was greatest shortly after the test when the activity was closer to the surface, and there was a possibility of inhaling descending fallout by those living in the fallout areas. However, the hazard during fallout would be from inhalation of small respirable particles (Simon et al. 2020). Because of the refractory nature of plutonium, most of the plutonium in the descending fallout would have been on nonrespirable large particles so the potential hazard was limited. As discussed, over time the plutonium penetrated deeper into the soil, thus greatly reducing the chance in the years after Trinity of inhaling airborne plutonium particles, and thereby, little risk would be expected to persons living today or in past years even in the highest fallout areas.

Analyses for the Trinity dose reconstruction (Simon et al. 2020) indicate that there are other radionuclides in Trinity fallout that contribute more effectively to the exposure of the lung, especially in the first year when doses are the highest. Those radionuclides include ^{239}Np , ^{140}Ba , and ^{237}U .

SUMMARY AND CONCLUSION

Based on the soil data and our model calculations, about 80% of the plutonium from the Trinity detonation was deposited in New Mexico, primarily in a region from 50–150 km from GZ in a northeast direction. While the geographical distribution of the deposited plutonium is believed to be fairly accurate, the estimates of the total unfissioned plutonium and the total deposited in New Mexico are acknowledged to be uncertain for the reasons discussed

earlier. The plutonium fallout pattern is generally consistent with the exposure rate pattern, though there is more plutonium along the trace axis and close-in than fission product activity due to fractionation.

The estimated fraction of plutonium deposited within a few hundred kilometers from GZ is consistent with the expected higher deposition of refractory radionuclides close-in due to fractionation. Hicks (1982) estimated that about 1/2 the refractories, on average, deposit locally, while Freiling (1962) suggested that, for the most refractory nuclides, this fraction would be even greater. Based on the Joint US-Russian model (see Appendix), we interpret close-in to be the distance in which all particles >50 μm diameter will deposit. The time at which this occurs, T_{max} , is based on the maximum height of the stabilized debris cloud from Hawthorne (1979) and the average gravitational settling velocity (see Appendix) of 50 μm particles. For Trinity, T_{max} is 14.6 h. Based on our interpolated deposition densities, about 65–70% of the total plutonium was deposited in less than 14.6 h, in reasonably good agreement with the Hicks and Freiling fractionation estimates considering the uncertainties discussed earlier. Although about 80% of the unfissioned plutonium was deposited within New Mexico, the fraction of more volatile radionuclides deposited in New Mexico would be expected to have been much less than 80% as a result of the volatile radionuclides being concentrated on the smaller particles that travel longer distances before depositing. As for the unfissioned plutonium and fission products deposited outside New Mexico, we note that fallout from Trinity was detected as far away as Indiana where it caused fogging of film produced in a Kodak film factory (Webb 1949).

Based on soil data obtained far from the pattern axis (Douglas 1978; Hansen and Rodgers 1985), as well as data reported by Beck (2001a and b), the mean deposition density in New Mexico from NTS and global fallout was about 30 Bq m^{-2} . So, as can be seen from Fig. 6a, only a relatively small geographical area in New Mexico has Trinity plutonium activity levels appreciably higher than the plutonium deposited by either NTS or global fallout and, for most of the state, the levels are at most a small fraction of the NTS and global fallout levels (Beck and Bennett 2002). In fact, due to the low annual precipitation in New Mexico, global plus NTS plutonium deposition density levels there are far less than the levels in most of the continental United States that range from 30–150 Bq m^{-2} (Beck and Bennett 2002). The areas shown in Fig. 6a as 0–10 Bq m^{-2} are areas where the Trinity plutonium, if any, is indistinguishable from global and NTS fallout.

Based on our review and analysis of all the historical monitoring data on plutonium in New Mexico from the detonation of the Trinity test, we believe we have reasonably

accounted for the unfissioned plutonium produced by the Trinity test. While the residual plutonium in New Mexico from the Trinity test is unquestionably a man-made contaminant and is understandably a source of apprehension to many, it does not technically differ from the larger amount of plutonium deposited in New Mexico from global and NTS fallout. Furthermore, most of this plutonium has now penetrated to depths well below the ground surface due to natural weathering processes.

Acknowledgments—Publication costs for this paper were supported by Intramural Research Program of the National Cancer Institute (NCI), National Institutes of Health (NIH), and the intra-agency agreement between the National Institute of Allergy and Infectious Diseases (NIAID) and the National Cancer Institute, NIAID agreement Y2-AI-5077 and NCI agreement Y3-CO-5117.

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APPENDIX

Model for estimating Pu/E12 vs. R/V (fractionation)

The ratio of Pu/E12 for unfractionated fallout, as described earlier, was calculated to be $2.7 \text{ Bq m}^{-2} (\text{mR h}^{-1})^{-1}$ but to vary with the degree of fractionation (Table 3). R/V is known to be >1 close to the Trinity test site where most of the activity that was deposited would be on relatively large particles, compared to $R/V < 1.0$ at distances where most of the activity would be on small particles. Thus, we need to estimate R/V at each location to estimate the Pu/E12 ratio at that location to estimate the plutonium deposition density at that site. Using a semiempirical model based on the work of Gordeev¹⁰ as modified by Beck,¹¹ in conjunction with the calculated relative radionuclide activities in Trinity fallout vs. E12 from Hicks (1981), we can accomplish this using the measured E12 and fallout TOA reported by Quinn (1987).

The predictive model for Pu/E12 is based on estimating the fraction of radioactive fission products on particles $<50 \mu\text{m}$ in diameter. This fraction allows one to estimate the fraction of activity that would be deposited and retained on vegetation and available for transfer from animals such as cows to milk consumed by humans (Land et al. 2015). The predictive model reflects the fact that refractory nuclides condense from the nuclear debris plasma earlier than volatile nuclides and thus, tend to be incorporated in larger particles (Freiling 1961, 1962; Hicks 1982). As the debris cloud cools, the more volatile nuclides condense and tend to deposit on the surface of smaller particles. Due to gravitational settling, the larger particles deposit earlier after the detonation than smaller particles. Hence, the earlier the TOA, the larger the proportion of large particles deposited as well as a greater proportion of total activity deposited that is on large particles and conversely, the smaller the fraction on small particles. This phenomenon is termed fractionation and describes the phenomenon where the ratio of refractory to volatile radionuclides (R/V) in the deposited fallout differs from the ratio of refractory to volatile fission products in the debris cloud. This implies that R/V is higher at locations close to the detonation site and lower at more distant locations. At some time after detonation, depending on the

maximum height of the debris cloud, all particles $>50 \mu\text{m}$ will have deposited, and all activity subsequently deposited will be on particles $<50 \mu\text{m}$.

N_{50} , the fraction of particles less than $50 \mu\text{m}$, is directly related to the average R/V, i.e., to the average ratio of refractory nuclide activity to volatile nuclide activity. Because plutonium is a highly refractory element, an estimate of the relationship between R/V and N_{50} allows us to estimate R/V and thus, the ratio of plutonium activity to the activity of nuclide Z (Pu/ Z), where Z is a volatile nuclide such as ^{137}Cs . Using the Pu/ ^{137}Cs ratio calculated from the amount of fuel in the device and the reported test yield and $^{137}\text{Cs}/\text{E12}$ ($\text{Bq m}^{-2} [\text{mR h}^{-1}]^{-1}$) vs. R/V based on Hicks (1981), we then can calculate Pu/E12 ($\text{Bq m}^{-2} [\text{mR h}^{-1}]^{-1}$) vs. R/V.

Using regression fits to actual measurements of N_{50} for a number of NTS and Russian tests (unpublished),¹¹ N_{50} is estimated by:

$$N_{50a} = (1-a) \times \text{EXP}[-(d \times t_r)^3] \text{ (on the axis)}$$

$$N_{50} = N_{50a} - 1.3 \text{ SQRT}(N_{50a}) \quad (\text{A1})$$

$$\times \ln(\text{E12}/\text{E12}_{\text{max}}) \text{ (off axis at same TOA),}$$

where $t_r = \text{TOA}/T_{\text{max}}$, $T_{\text{max}} = CT/0.73$, 0.73 km h^{-1} is the gravitational settling velocity of $50 \mu\text{m}$ particles, CT is the height of the cloud top in km, and E12_{max} is the exposure rate at $H + 12 \text{ h}$ on the axis at a given TOA.

Based on the regression fits to measured particle activity, the parameters a and d have been shown to vary slightly among nuclear tests depending on the height of burst (a) and the amount of wind shear (d). Based on these fits, we estimated $1 - a = 0.98$, $d = 1.8$ for Trinity based on the reported height of the burst and the observed width of the fallout pattern. As indicated by eqn (A1), N_{50} at a given TOA increases as one moves away from the fallout pattern axis.

The relationship between N_{50} and R/V was inferred from observations of $^{137}\text{Cs}/\text{E12}$ at the NTS and Russian nuclear testing test sites at various TOAs supplemented by published observations of the fraction of activity on small particles (Beck 2009; Hicks 1982; Freiling 1961, 1962; Freiling et al. 1965). It is predicated on the model assumption that N_{50} , by definition, approaches 1.0 as the TOA approaches T_{max} , i.e., that all particles less than $50 \mu\text{m}$ have

¹⁰ Gordeev KI. Radiation exposure to the population of the Semipalatinsk region from Semipalatinsk weapons tests. Part I. Experimental and theoretical investigation of the processes of radioactive contamination of grass resulting from local fallout from nuclear explosions and justification of the concept of "biologically active fraction" of fallout. Report to the National Cancer Institute, Bethesda, MD; 1999. Unpublished.

¹¹ Beck HL. Estimates of H+12 exposure rates and associated uncertainty received by the population of selected villages in the vicinity of the Semipalatinsk Test Site in Kazakhstan at the time of the Semipalatinsk Test Site atmospheric tests (1949–1962). Application of joint Russian/American methodology for fallout dose assessment to the estimation of internal doses and associated uncertainty. Final report to NCI in fulfillment of PSC #HHNSN261200800397P; 15 March 2009; unpublished. A peer-reviewed publication is being prepared for journal submission.

Table A1. Estimated relationship between N_{50} and R/V.

N_{50}	R/V
>0.83	0.5
0.43–0.83	1.0
0.23 to <0.43	1.5
0.09 to <0.23	2.0
<0.09	3.0

been deposited when $t = T_{\max}$. Based on Hicks' observations of R/V for fallout from NTS tests, R/V asymptotes to a value of 0.5 as N_{50} approaches 1.0. We have estimated an approximate, though simplistically modeled, relationship between N_{50} and R/V shown in Table A1.

For each location where plutonium deposition was calculated, we adjusted the unfractionated Pu/E12 value by the estimated R/V at that site, using Table 3, eqn (A1), and the above relationship between N_{50} and R/V, to estimate from the interpolated E12 corrected plutonium deposition density.

Although the semiempirical model for N_{50} described here has been shown to adequately reproduce measured N_{50} for both NTS and Russian tests,¹¹ the basis for the estimated relationship between N_{50} and R/V is less rigorous and thus somewhat more uncertain than the estimates of N_{50} .

