AN AERIAL RADIOLOGICAL SURVEY OF THE TRINITY FALLOUT AREA

WHITE SANDS MISSILE RANGE, NEW MEXICO

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ABSTRACT

An aerial gamma survey was conducted during May and June of 1992 to define the Trinity fallout field, which lies primarily in the White Sands Missile Range in the state of New Mexico. The field was mapped almost entirely from the gamma ray emissions of cesium-137 (^{137}Cs), a fission product. The field, as measured, extends from Trinity ground zero, over the Oscura Mountains, across the Chupadera Mesa, and thence past Cedarvale, New Mexico, a distance of more than 100 kilometers. An estimate of ^{137}Cs activity inventory is 100 Ci in an area covering 1,400 square kilometers. Another isotope, europium-152, is significant at ground zero. A ^{137}Cs concentration contour plot overlaid on a U. S. Geological Survey map indicates the location and intensity of the fallout field. A contour map of terrestrial exposure rate is presented in a similar fashion.

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1.0 INTRODUCTION

Trinity, the first nuclear explosion test, was detonated at 0530 on July 16, 1945 and was the culmination of the Manhattan Project.¹ The radioactive remnants, both from neutron activation and fission products, have been investigated by the Los Alamos National Laboratory² (LANL), the Department of Energy³ (DOE), and the Environmental Protection Agency⁴ (EPA). The initial and subsequent ground-based gamma exposure measurements show that the measurable fallout pattern extends more than 100 km from ground zero (GZ). The large size of the fallout field and the rugged and rather remote terrain suggested the use of DOE's Aerial Measuring System capability to complement the ground-based measurements.

The Remote Sensing Laboratory (RSL), operated by EG&G Energy Measurements (EG&G/EM) for DOE, conducted an aerial gamma survey during May and June of 1992. The gamma data were reduced to a map of the Trinity fallout pattern as well as a map of the external exposure rates in that area.

2.0 SITE DESCRIPTION

The Trinity site is located on the White Sands Missile Range (WSMR) in the state of New Mexico. Ground zero, coordinates N 33° 40.52', W 106° 29.48', is 161 km (100 mi) south of Albuquerque and 56 km (35 mi) southeast of Socorro, New Mexico. The base of operations was located at Alamogordo, New Mexico, 100 km (62 mi) south of GZ. The area surveyed (Figure 1) extends from 6 km (4 mi) south of GZ to 110 km (68 mi) in the northeast direction, which was the direction of the primary fallout cloud path. About two thirds of the survey (including GZ) is in Socorro County with the remaining one third in the counties of Lincoln and Torrance. The area includes the Oscura Mountains, 8 km (5 mi) to the east of GZ, and Chupadera Mesa, from 8 to 48 km (5 to 30 mi) northeast of GZ. The area beyond Chupadera Mesa is dominated by Gallinas Peak, 90 km (56 mi) from GZ. The survey area is sparsely populated, consisting mostly of desert and mountains. A few small villages are in the survey area: Bingham, Claunch, and Cedarvale. Ranching is the primary private land use outside the WSMR.

3.0 SURVEY PLAN AND EQUIPMENT

3.1 Survey Equipment Match

Comprehensive reports show the location and isotope concentration levels of the Trinity fallout field as measured from the ground² and as predicted from the zero time winds³ and early time ground monitoring data.³ These reports suggested that a survey area of some 4,000 km² (1,560 mi²) extending 100 km (62 mi) northeast of ground zero might be necessary.

Operational and gamma sensitivity parameters are well known for DOE aircraft and gamma data systems. However, a new navigation system was under test that would substantially aid the Trinity survey. This system, called the Global Positioning System (GPS), has worldwide coverage, whereas the long-used ultrahigh frequency ranging system (URS) has limited coverage and range, especially in mountainous areas. The URS system was also fielded in case difficulties with the GPS system required a fallback to a previous navigation system.

The DOE Beechcraft A-100 fixed-wing aircraft was chosen for the survey to accommodate the large, remote and mountainous area. The Messerschmitt-Bolkow-Blohm BO-105 helicopter, commonly used for gamma surveys, was not chosen because the time available per helicopter flight was too short to expeditiously cover the large survey area.

Descriptions of the survey aircraft system and the data van system are given in the following two sections. The survey parameters may be found in Appendix A.

3.2 Survey Aircraft

A Beechcraft A-100 fixed-wing aircraft was used as the aerial platform (Figure 2). The aircraft carried four detector pods, each containing two 4- × 4- × 16-in log-type NaI (Tl) detectors. Gamma ray signals from the NaI detectors were routed to the Radiation and Environmental Data Acquisition and Recorder IV (REDAR IV) system for pulse height analysis and storage on magnetic tape. Pressure, temperature, GPS data, and radar altitude transducer data were also acquired and stored by REDAR. Gamma ray energy spectra and the total count rates were displayed on a CRT as they were being acquired so that

FIGURE 1. TRINITY SURVEY AREA

the system operator could monitor them. The other two crew members were responsible for flying the aircraft.

FIGURE 2. BEECHCRAFT A-100 SURVEY AIRCRAFT

3.3 Data Van

A computer-based system (Figure 3), housed in a van, was used during the survey to evaluate the data immediately following each survey flight. The system contains hardware and software that operate on the stored data. The data analyst can plot gamma ray spectra from any portion of the gamma survey as well as contours of constant count rates scaled to a map or photograph. In this manner, the intensity and location of the isotope emitters can be identified within hours of each survey flight.

3.4 Action Plan

The actions required to prepare for, accomplish, and document the Trinity aerial survey were:

1. Configure the DOE A-100 aircraft to accept both GPS (satellite) and URS (ground-based) guidance. Test the A-100 aircraft for both guidance systems.
2. Test the A-100 gamma system for sensitivity to point sources and sensitivity to the documented Lake Mead Test Line (LMTL).
3. Test the A-100 aircraft over the Trinity fallout field as a presurvey mission. Since WSMR is within A-100 flight range of Las Vegas, Nevada, some technical questions could be

FIGURE 3. SURVEY DATA VAN

answered before committing a full complement of assets to the survey. Such questions as:

- a. To what extent or distance is the fallout field measurable?
- b. Will the GPS guidance system function adequately over long lines?
- c. Will WSMR radar or other electromagnetic background impair gamma system operation?

A two-day effort was planned and executed.

4. Perform the survey with closely spaced lines in the GZ area, then broaden the line spacing as Cedarvale, New Mexico, was approached. North-south flight lines were planned, because the geologic upthrusts generally lie north-south.

Flight safety was the first priority. Since the Trinity area is very rugged, altitudes of 91 m (300 ft) above ground level (AGL) were judged safe as a minimum altitude only. Flights within and adjacent to the WSMR were under continuous range control.

5. Update data reduction on a flight-by-flight basis. No flight would be launched before the current gamma data were judged satisfactory.
6. Complete the basic fallout contour map before concluding the field work.
7. Coordinate ground measurement locations with the field technician.⁵

8. Conclude the aerial survey and return the data to the DOE Remote Sensing Laboratory for further analysis.
9. Organize the aerial and ground-based measurements and maps into a survey report.

4.0 SURVEY CONDUCT

A standardized procedure was followed during the Trinity survey. Steps in the procedure are:

1. A water line (Elephant Butte Reservoir) was flown with several passes each at a different altitude. Then passes at the same altitude AGL were made over a test line (a relocatable line near or in the survey area).
2. A perimeter flight of roads in the survey area was then made. The GPS data from this flight were used to scale distances to a road map of the survey area. In this way, each subsequent gamma datum could be plotted on the map. The GPS positions were purposely degraded to ± 100 -200 m for nonmilitary use.
3. Following the perimeter and test line flights, routine survey flights began. All survey lines were flown at an altitude of 91 m (300 ft). Each flight, preceded by a preflight in which the system was calibrated and the data tape analyzed for proper system operation, consisted of:
 - a. A pass over the test line at survey altitude (91 m AGL) and again at 900 m AGL.
 - b. Passes in a north-south direction following preprogrammed adjacent lines over the survey area.
 - c. A repeat pass over the test line. Generally a water line is flown before or after the test lines, but Elephant Butte Reservoir was 70 km (43 mi) from GZ. Therefore, the reservoir was flown just three times during the survey.
4. Following each survey flight, the data were reduced to energy spectrum plots and parameter listings by a standard postflight computer program. These were examined by the survey scientist and data technician for integrity and quality. The reduced data were extrapolated to a common 91-m altitude above the ground and a contour map was drawn in count rate units.

A contour map also was drawn to show possible cesium-137 (^{137}Cs) gamma activity.

Military activity at WSMR precluded a simple order of data acquisition. As an example, the first flight lines were flown in the Claunch, New Mexico, area rather than near GZ, because planned WSMR aerial traffic would have jeopardized the gamma survey and flight crew.

5.0 DATA ANALYSIS

The data analyst has these basic stored data acquired each second:

1. A 256-channel gamma energy spectrum, 20 keV to 4 MeV
2. Atmospheric temperature and pressure
3. Altitude above ground level (AGL)
4. Geographic position which at Trinity was provided by GPS (the satellite Global Positioning System)

These data are further grouped into sets:

1. Calibration data such as system response to known gamma point sources and to a known test line in Nevada
2. Preflight or system test data
3. Test line data near or in the survey area
4. Over-water data near the survey area
5. Primary flight line data over the survey area
6. Postflight system test data
7. The written flight log as recorded by the system operator

All of these data were used to provide a best estimate of the position, magnitude, and isotopic content in the Trinity survey area.

5.1 Water Background and Test Lines

Elephant Butte Reservoir was flown on three different days over the Trinity reservoir at five altitudes. One of the three test lines (near Tularosa, Carrizozo, and GZ) was flown on the same day either just before or after the water passes. Elephant Butte reservoir is 71

km southwest of Trinity GZ, so the number of water passes was limited.

The over-water data were subtracted directly from the test line data to yield net terrestrial spectra and count rates. Subsequent increases or decreases in test line count rate were then interpreted as increases or decreases in airborne radon. Adding or subtracting the change in test line count rates to the original water count rate yields an effective water count rate. Water count rates or effective water count rates from test lines were subtracted from the total gamma count rate to yield terrestrial count rates in the survey line data:

$$GC = (TC - B) e^{\lambda(RA - 91)} \quad (1)$$

where

- GC = net gamma count rate at 91 m (cps)
- TC = total gamma count rate
- B = background (over-water count rate)
- λ = altitude coefficient, (1/m)
- RA = altitude above ground (m)

The altitude coefficient, λ , was determined as 0.00587 m^{-1} from GC versus altitude measurements over the test lines. This value agrees with the value over the LMTL near Las Vegas, Nevada. Background values (or effective water count rates) for GC averaged 2,500 cps with a standard deviation of 300 cps from the eighteen data flights at Trinity. Atmospheric radon variations, then, were normal (expected) and significant as compared to the normal terrestrial GC at 5,500 cps.

5.2 Gamma Energy Spectrum Stripping

Early flight line data from the Trinity survey were examined for isotopic content. Survey test line spectra were subtracted from survey line spectra to yield net anomalous gamma photopeaks and consequently the source isotopes. Cesium-137 and europium-152 (^{152}Eu) only were identified with this method.

Experience has shown that the photopeak stripping technique is the most sensitive for evaluating the

magnitude of a particular gamma photopeak superimposed on background spectra (Appendix B). Two different window arrangements were used to extract the predominant ^{137}Cs gamma photopeak. These include a two-window and a three-window arrangement. The net ^{137}Cs photopeak count rate was extracted from each of the 53,000 survey energy spectra using the following equation:

$$Cs = (A - KB) e^{\lambda_c(RA - 91)} \quad (2)$$

where

- Cs = net ^{137}Cs photopeak count rate (cps)
- A = count rate in the photopeak window from 554 keV to 770 keV
- K = ratio of photopeak window (A) to background window (B) over a test line
- B = count rate in the background window from 770 keV to 1,370 keV
- λ_c = altitude coefficient (1/m)
- RA = radar altitude (m)

The ratio, K , was determined from test line spectra at a 91-m altitude. The value of K ranged from 0.74 on the test line near GZ to 0.79 near Carrizozo. This coefficient was determined for each survey flight from test line data. The standard deviation for Cs , Equation 2 above, was about 30 cps.

The altitude coefficient, λ_c , was determined from the ^{137}Cs count rate versus altitude data over the cesium concentrations on Chupadera Mesa. The value was measured as 0.00935 m^{-1} .

Europium-152, a neutron activation product in the soil, was also evaluated in a manner similar to that for ^{137}Cs . A net spectrum was obtained and an extraction equation developed:

$$Eu = A - KB \quad (3)$$

where

- Eu = net ^{152}Eu count rate (cps)
- A = count rate in the signal window from 854 keV to 1,592 keV
- B = count rate in the background window from 1,592 keV to 3,026 keV
- K = ratio of A to B over the GZ test line

The value of K was 4.5 over the GZ test line and the standard deviation of ^{152}Eu was about 50 cps on the same line. The altitude coefficient was not developed for this window arrangement because ^{152}Eu was found only in the immediate GZ area.² The area west of the Oscura mountains was searched, however, for any other evidence of ^{152}Eu using both Equation 3 and net spectra.

Considerable effort was directed in a search for americium-241 (^{241}Am), generally associated with plutonium-239 (^{239}Pu), the Trinity fissile material. None was detected either with the photopeak (at 60 keV) spectral equation or with the net spectrum technique. Most of the data were examined with the following equation:

$$Am = (A - KB) e^{\lambda(RA - 91)} \quad (4)$$

where

- Am = net ^{241}Am photopeak count rate at 91 m (cps)
- A = count rate in the photopeak window from 50 keV to 70 keV
- K = ratio of A to B over a test line
- B = count rate in the background windows from 38 keV to 50 keV and from 70 keV to 82 keV
- λ = altitude coefficient (1/m)
- RA = radar altitude (m)

The value of K was about 1.00 and the standard deviation of Am about 30 cps from test line data at a 91-m altitude.

5.3 Counting Statistics and Detection Limit

The primary counting statistics resulting from limited count rates, varying natural isotope concentrations, and ground roughness were computed from test line data in the following manner:

$$\sigma(CR) = \left[\sum_{1}^N \frac{(CR - CR_a)^2}{N - 1} \right]^{1/2} \quad (5)$$

where

- $\sigma(CR)$ = standard deviation of the count rate of interest, CR
- CR_a = average count rate over the test line (cps)
- N = the number of data points along the test line (of order 100)

The standard deviation was also evaluated over survey flight lines or portions of flight lines where anomalous isotopes are absent.

The detection limit was set at three times the standard deviation, $3\sigma(CR)$, of the count rate of interest. This limit is called the critical level by Curie.⁶ All count rates above 3σ were included in the contour maps of specific isotopes such as the ^{137}Cs map of Trinity fallout. The expected rate of false alarms, then, is less than one percent, and the expected signal loss rate is 50% at 3σ .

From 21 to 84 data points (dependent on actual line separation) were averaged or accumulated to produce the Trinity ^{137}Cs contour map. This averaging of the data points reduces the 3σ minimum contour by the square root of the number of averaged data points, but produces a loss in spatial resolution.

Data averaging was generally carried out over square areas from 2,500 ft (762 m) on a side to 10,000 ft (3,000 m) on a side. The ^{137}Cs map chosen for publication was averaged over areas 5,000 ft (1,500 m) on a side or about 0.9 mi² (2.3 km²).

5.4 Map Verification with Energy Spectra

The ^{137}Cs contours may include false contours at low levels originating from the 609-keV bismuth-214 (^{214}Bi) photopeak. Bismuth-214 is a uranium-238 (^{238}U) daughter and is a naturally-occurring radio-nuclide. Net spectra were derived over most contoured areas in a search for false contours. Net spectra are obtained by subtracting a background spectrum from the total spectrum of a given area. If the ^{137}Cs photopeak is not evident, or the ^{214}Bi photopeak is the overwhelming predominant peak in the signal window, then the area is deleted from the map. The ^{137}Cs photopeak (in net spectra) was clearly visible at the minimum contour level (15 cps).

5.5 Exposure and Isotope Concentration Estimates

The gamma exposure rate at 1 m AGL was interpreted from the *GC* (Equation 1) at the 91-m altitude. The conversion of count rate to $\mu\text{R/h}$ was determined from the LMTL. The terrestrial exposure at 1 m AGL for the LMTL has previously been measured by several experimenters. The aerial gamma system was operated at several altitudes over the LMTL and the *GC* obtained at each altitude. The flight lines included the adjacent water in Lake Mead, so background and over-water count rates were available. Both the count rate versus altitude and the count rate per unit exposure rate were obtained.

$$R = \frac{10.4 e^{0.00587A}}{16152} = 0.0011 \quad (6)$$

where

- R = exposure rate ($\mu\text{R/h/cps}$)
- coefficient 10.4 = exposure rate over LMTL at 1 m AGL
- A = altitude, 91 m
- coefficient 16152 = count rate over LMTL at 1 m AGL

This experiment was repeated over the Trinity test line and yielded the same altitude coefficient, but ground level exposure rate measurements were not obtained on the Trinity test line.

Cesium-137 concentration estimates in the soil were computed from the ^{137}Cs count rates (Equation 2). The basic computation is outlined in Appendix B. The result is:

$$\text{cesium concentration} = 0.0019 \mu\text{Ci/m}^2/\text{cps}$$

where the vertical concentration distribution, S , is described by:

$$S = S_0 e^{-0.2D} \quad (7)$$

where

- D = depth in soil (cm)

Finally, estimates were made of the exposure rate due to cosmic rays in the Trinity area:

$$C = 2.7735 e^{0.0004523A} + 0.81305 e^{-0.0008A} \quad (8)$$

where

- C = cosmic exposure rate ($\mu\text{R/h}$)
- A = altitude (m)

The cosmic exposure equation is a fit to data reported by DOE's Environmental Measurement Laboratory in New York City.

6.0 RESULTS

The principal results of the Trinity aerial gamma survey are the contour maps that show the location and relative concentration of isotopes that comprise the Trinity fallout field. The only fallout isotope detectable was ^{137}Cs , a fission product. Other fallout isotopes have decayed to concentrations less than the limit of detection of the aerial system.

A large concentration of ^{152}Eu , from neutron activation in the soil, was found at GZ but not downwind in the fallout field.

Ground-based measurements of exposure and soil isotope concentrations are compared with exposure and concentration estimates from the aerial data.

6.1 Cesium Contour Map

6.1.1 General Characteristics

The ^{137}Cs contour map (Figure 4) defines most of the Trinity fallout field detectable by the aerial system. The map has been produced from ^{137}Cs count rates originating in the NaI(Tl) aerial detector package. Data points have been averaged in 5,000-ft blocks over the survey area. One point per block has been used to produce the contour map. The averaging process reduces the complexity and spatial resolution of the map but allows a lower minimum detection limit

LETTER LABEL	ESTIMATED TERRESTRIAL ¹³⁷ Cs CONCENTRATION (μCi/m ²)
A	0.03
B	0.03 - 0.08
C	0.08 - 0.11
D	0.11 - 0.23
E	0.23 - 0.46

*As computed from net ¹³⁷Cs photopeak count rates above background NaI(Tl) at 91 meters above the ground. The conversion coefficient used was 0.0018 μCi/m² per count per second. This assumes the vertical concentration decreases exponentially in the soil with a relation depth of 5 centimeters.

FIGURE 4. CESIUM-137 CONTOUR MAP OF TRINITY FALLOUT

versus nonaveraged data. Other maps with minimum averaging have been produced and are available.

The basic minimum detection limit has been set at 3σ (three standard deviations) of the background count rate algorithm. The detection limit is about 90 cps for the ^{137}Cs detection algorithm. The detection limit (the lowest contour) has been lowered by the factor $1/\sqrt{N}$ for N averaged points. The number of averaged points varies from 21 near Cedarvale, to 42 on Chupadera Mesa, and to 84 in the GZ area. The lowest contour at 15 cps approximates the detection limit over Chupadera Mesa.

Contour levels range from 15 cps to 120 cps as measured from the ^{137}Cs photopeak. Maxima occur near GZ at 270 cps (located 1 km from GZ and angle 7° east of north), and at 216 cps (33 km, 42.6°) on Chupadera Mesa. These are maxima of individual 1-second measurements, while Figure 4 includes the averaging effects discussed above. The total gamma energy spectrum and the ^{137}Cs spectrum obtained over Chupadera Mesa are shown in Figures 5 and 6.

The character of the cesium contours suggests a major fallout field extending from the GZ to beyond Cedarvale (105 km, 37° from GZ) and another fallout field extending to Bingham (30 km, 18°). These are consistent with cloud observations at zero hour in 1945.¹

The area bounded by the lowest contour level is close to 1,400 km². More coverage details are discussed in the following section.

6.1.2 Cesium Concentration

Estimates of ^{137}Cs concentrations in the soil may be computed from aerial data (Appendix B) if the vertical distribution of ^{137}Cs is known in this form:

$$C = C_0 e^{-\alpha z} \quad (9)$$

where

C = the ^{137}Cs concentration in the ground
 $\left(\frac{\text{pCi}}{\text{cm}^3}\right)$

C_0 = the ^{137}Cs concentration at the surface
 $\left(\frac{\text{pCi}}{\text{cm}^3}\right)$

α = distribution parameter (1/cm)

z = depth in soil (cm)

Reference 2 suggests a reasonable value is $\alpha = 0.2 \text{ cm}^{-1}$. Since α is not well known and is variable,² aerial estimates of ^{137}Cs concentration are necessarily uncertain. Some useful photopeak count rate to ^{137}Cs concentration conversion values are listed in Table 1.

FIGURE 5. TOTAL GAMMA ENERGY SPECTRUM OVER CHUPADERA MESA

FIGURE 6. CESIUM-137 GAMMA ENERGY SPECTRUM OVER CHUPADERA MESA

Table 1. Aerial Count Rate Conversions to Cesium-137 Concentration and to Exposure Rate

α (cm ⁻¹)	Area Concentration ^a ($\mu\text{Ci}/\text{m}^2/\text{cps}$)	Mass (surface) Concentration ^a ($\text{pCi}/\text{g}/\text{cps}$)	Mass (15-cm sample) Concentration ^a ($\text{pCi}/\text{g}/\text{cps}$)	Exposure Rate at 1m AGL ^b ($\mu\text{R}/\text{h}/\text{cps}$)
.2	0.0019	0.0242	0.0096	0.0068
.1	0.0028	0.0181	0.010	0.0067
.05	0.0045	0.0149	0.011	0.0067
.01	0.0183	0.0122	0.011	0.0068

^aThe concentration estimate is derived from both measurement and computation (see Appendix B).

^bExposure rates are derived from the concentration estimates combined with the work of Beck, DeCampo, and Gogolak (Reference 7).

Expected ¹³⁷Cs concentrations and external gamma exposure levels may be computed using values from Table 1 and an α value of 0.2 cm⁻¹.

1. The maximum ¹³⁷Cs concentration and external exposure rate near GZ at 270 cps are 0.5 $\mu\text{Ci}/\text{m}^2$ and 1.8 $\mu\text{R}/\text{h}$, respectively.
2. The maximum values on Chupadera Mesa at 216 cps are 0.41 $\mu\text{Ci}/\text{m}^2$ and 1.5 $\mu\text{R}/\text{h}$.
3. At the detection limit, 15 cps, concentration and external exposure are 0.03 $\mu\text{Ci}/\text{m}^2$ or 0.36 pCi/g at the surface and 0.10 $\mu\text{R}/\text{h}$.

6.1.3 Cesium Inventory

The total quantity or inventory of ¹³⁷Cs activity detectable by the aerial system may be evaluated from the data used to construct the map in Figure 4. The inventory is simply the sum of the product of the mean concentration in each block and the area of the block, where each block of data measured 5,000 ft or 1,524 m on a side. Table 2 lists the inventory of geographic sections of the fallout pattern as well as the totals.

6.2 Aerial and Ground-Based Exposure Measurements

6.2.1 Exposure Rate Map

The gamma exposure rate at 1 m AGL may be computed from the aerial total count rate data (GC in

Appendix B). An exposure contour map, Figure 7, at 3 $\mu\text{R}/\text{h}$ intervals shows the terrestrial exposure rate over the survey area. A smaller interval between contours yields a complex map that is difficult to read. More details are available, however, in a larger format.

Terrestrial exposure is due primarily to the natural gamma emitters in the soil (thorium-232 [²³²Th] and daughters, ²³⁸U and daughters, and potassium-40 [⁴⁰K]). Note that the significant cosmic contribution (6 $\mu\text{R}/\text{h}$ or more) is not included in the map.

The terrestrial exposure rate distributions show that much of the survey area is at about 4.4 $\mu\text{R}/\text{h}$ with a few exceptions. The most probable exposure west of GZ is 4.4 $\mu\text{R}/\text{h}$. Between GZ and the Oscura Mountains, two distinct exposure rates exist at 4.4 $\mu\text{R}/\text{h}$ and 9.9 $\mu\text{R}/\text{h}$. Apparently, alluvium at exposures above 15 $\mu\text{R}/\text{h}$ from the Oscura escarpment extends toward the GZ. These are visible at the base of the Oscura Mountains on the map. From the Oscura Mountains to the Chupadera Mesa 4.4 $\mu\text{R}/\text{h}$ is most probable, while the Chupadera Mesa itself is at 4.7 $\mu\text{R}/\text{h}$. In the Claunch area, the exposure rises to 6.8 $\mu\text{R}/\text{h}$. There is a small area about 5 km WSW of Gallinas Peak that approaches 21 $\mu\text{R}/\text{h}$. Energy spectra show enhanced thallium-208, a daughter of ²³²Th.

6.2.2 Ground-Based Exposure and Concentration Results

Ground-based ion chamber measurements and soil samples were gathered during the aerial survey.⁸

Table 2. Cesium-137 Inventory		
Section ^a	Inventory ^b (Ci)	Active Area (km ²)
A. GZ, Jornada Del Muerto (1.5 km west to 6.7 km east)	12.3	133
B. Oscura Mts. (6.7 km east to 10.0 km east)	3.9	69
C. Oscura Mts. to Chupadera Mesa (10 km east to 20 km east)	13.8	242
D. Chupadera Mesa (20 km east to 33 km east)	37.4	324
E. Claunch, NM and Gallinas Peak (33 km east to 73 km east)	32.4	628
Total	99.8	1,396

^aThe reference point is GZ for all sections. Distances are given in the west to east direction.

^bThe ¹³⁷Cs vertical concentration has been assumed as $C = C_0 \exp(-0.2Z)$. See Equation 9.

Sample locations are shown on the exposure map (Figure 7). The aerial exposure rates are compared to the ion chamber measurement and to the computed exposure from soil sample results in Table 3.⁹ The agreement appears quite close, though the aerial system evaluates as much as one-third of a square kilometer while the ion chamber and soil samples evaluate a much smaller area.

Soil moisture, and the concentrations of ²³⁸U and (radon-226), ²³²Th, and ⁴⁰K from soil sample measurements are given in Table 4. These agree within 10% of the natural isotope concentrations in the LMTL soil. Therefore, exposure rate conversion factors, derived from LMTL, should be applicable in the Trinity area.

A comparison of ¹³⁷Cs concentrations obtained from both soil samples and aerial data is given in Table 5. Only four of the aerial data locations were above the aerial detection limit, though the soil sample concentrations suggest that ten should have been. Note that five soil sample concentration values are just above the aerial detection limit of 0.15 pCi/g (average concentration in the top 15 cm of soil).

6.2.3 Cesium-137 Exposure Rates

Cesium-137 from international fallout contributes a very small exposure, perhaps 0.1 µR/h for the little remaining international fallout.³ The Trinity fallout, however, may contribute as much as 1.8 µR/h near GZ, and 1.5 µR/h on Chupadera Mesa. These fallout exposure rates do not appear clearly on the exposure rate map, perhaps because the geology is so variable.

6.2.4 Europium-152 Exposure Rate

Neutron activation in the soil during the Trinity event created significant ¹⁵²Eu at ground zero. The exposure rate from the many ¹⁵²Eu gammas is the largest measured by the aerial system in the survey area. The maximum 1-m exposure rate is estimated at 70 µR/h and is confined to a 500-m radius from GZ, as detected by the aerial system. The ¹⁵²Eu gamma energy spectrum as recorded at the 91-m (300-ft) altitude is shown in Figure 8.

7.0 DISCUSSION

The geographic coverage of the Trinity fallout field has been defined here by the fission product ¹³⁷Cs.

LEGEND

Soil sample sites are shown in boxed numerals.

CONVERSION SCALE	
LETTER LABEL	TERRESTRIAL EXPOSURE RATE ATT METER* ($\mu\text{R/h}$)
A	< 3
B	3 - 6
C	6 - 9
D	9 - 12
E	12 - 15
F	15 - 18
G	18 - 21

*Computed from aerial data obtained at an altitude of 91 meters. Cosmic exposure rates ranging from 6.2 $\mu\text{R/h}$ to 7.0 $\mu\text{R/h}$ are not included in the contour levels. Actual terrestrial gamma count rates from the detector may be computed by multiplying exposure rate by 910 cps per $\mu\text{R/h}$.

FIGURE 7. TERRESTRIAL GAMMA EXPOSURE RATES IN THE TRINITY FALLOUT AREA

Table 3. Trinity Area Gamma Exposure Rates			
Location	Soil Sample ^a ($\mu\text{R/h}$)	Ion Chamber ^a ($\mu\text{R/h}$)	Aerial ^b ($\mu\text{R/h}$)
1	12.5 ± 0.7	14.2 ± 0.7	12.8
2	10.0 ± 3.0	11.1 ± 0.6	12.0
3	12.8 ± 0.8	11.9 ± 0.6	14.2
4	14.0 ± 2.0	14.9 ± 0.7	13.0
5	14.5 ± 0.9	15.6 ± 0.8	14.3
6	14.4 ± 0.7	14.0 ± 0.7	15.1
7	13.2 ± 0.7	13.2 ± 0.7	11.1
8	12.4 ± 1.0	13.0 ± 0.7	13.7
9	10.3 ± 0.8	11.4 ± 0.6	10.9
10	11.2 ± 1.2	12.4 ± 0.6	12.6
11	13.4 ± 0.8	13.4 ± 0.7	10.0
Average	12.6 ± 1.5	13.1 ± 1.4	12.7 ± 1.6

^aSoil sample and ion chamber uncertainties are at one standard deviation.

^bThe aerial exposure uncertainty is about 1 $\mu\text{R/h}$.

Table 4. Isotope Concentrations and Soil Moisture Obtained from Soil Samples					
Average Isotope Concentration ^a in pCi/g $\pm$ SD					
Location	% Moisture	²²⁶ Ra	²³² Th	¹³⁷ Cs	⁴⁰ K
1	10 $\pm$ 1	0.8 $\pm$ 0.1	0.88 ± 0.06	0.08 ± 0.05	14.6 ± 0.4
2	14 $\pm$ 2	0.5 $\pm$ 0.3	0.5 $\pm$ 0.3	0.18 ± 0.09	10 $\pm$ 5
3	6.8 ± 0.7	0.69 ± 0.03	0.78 ± 0.09	0.2 $\pm$ 0.2	15 $\pm$ 2
4	7 $\pm$ 2	0.7 $\pm$ 0.2	0.9 $\pm$ 0.2	1.1 $\pm$ 0.3	18 $\pm$ 2
5	10 $\pm$ 1	0.89 ± 0.06	1.1 $\pm$ 0.1	0.8 $\pm$ 0.4	19 $\pm$ 1
6	10.9 ± 0.8	1.1 $\pm$ 0.2	0.99 ± 0.04	0.2 $\pm$ 0.1	17.8 ± 0.7
7	12.2 ± 0.7	0.75 ± 0.03	0.93 ± 0.02	0.2 $\pm$ 0.1	18.1 ± 0.5
8	13 $\pm$ 3	0.75 ± 0.07	0.8 $\pm$ 0.1	0.17 ± 0.06	15 $\pm$ 2
9	10 $\pm$ 1	0.7 $\pm$ 0.1	0.45 ± 0.05	0.7 $\pm$ 0.4	7.5 ± 0.5
10	9 $\pm$ 1	0.5 $\pm$ 0.1	0.40 ± 0.04	0.6 $\pm$ 0.4	14 $\pm$ 2
11	14 $\pm$ 2	0.93 ± 0.07	0.93 ± 0.08	0.3 $\pm$ 0.3	17.6 ± 0.9

^aUncertainties represent one standard deviation.

Table 5. Aerial/Soil Sample Cesium-137 Concentration Comparison		
Soil Sample Location ^a	Soil Sample ¹³⁷ Cs Concentrations ^b (pCi/g)	Aerial ¹³⁷ Cs Concentration ^c (pCi/g)
1	0.08 ± 0.05	d
2	0.18 ± 0.09	<0.15
3	0.20 ± 0.20	<0.15
4	1.10 ± 0.30	<0.15
5	0.80 ± 0.40	0.30
6	0.20 ± 0.10	0.30
7	0.20 ± 0.10	<0.15
8	0.17 ± 0.06	<0.15
9	0.70 ± 0.40	0.60
10	0.60 ± 0.40	1.20
11	0.30 ± 0.30	<0.15

^a Locations are shown on the Exposure Rate map, Figure 7.

^b Soil sample ¹³⁷Cs concentration uncertainties are given at one standard deviation.

^c Cesium-137 concentration uncertainties from aerial data are not known for concentrations less than 0.15 pCi/g. Uncertainties are expected within a factor of two for concentrations larger than 0.15 pCi/g.

^d No aerial data at this location.

Further, the lowest level at the edge of the fallout field, 0.15 pCi/g, (average in top 15 cm of soil) is consistent with the level of international fallout in New Mexico, 0.1 to 1.0 pCi/g.² No other man-made isotopes were visible or measurable in or near the fallout field other than at GZ. Ground zero contains appreciable ¹⁵²Eu. The ¹³⁷Cs contour map, then, is expected to represent the location and relative concentrations of much of the Trinity fallout, whether measurable or not.

The data points used to describe the cesium map have been averaged heavily such that the original 53,000 data points have been reduced to about 1,500. The advantage is a lower detection limit. The disadvantage is a loss of geographic resolution to about 1 km. The low detection limit does show the northerly Trinity fallout plume extending to the survey boundary, near Bingham, New Mexico. The flight lines in this area of the survey should have been longer in order to map all of the measurable fallout (cesium-137).

FIGURE 8. TERRESTRIAL GAMMA ENERGY SPECTRUM OVER TRINITY GROUND ZERO

Perhaps the most difficult technical problem in the aerial Trinity survey is the interpretation of the data over the Oscura Mountains and Gallinas Peak where survey altitude variations of 300 m or more occur. The

^{137}Cs survey count rates decrease by one-half for each 80-m increase in altitude, so that a substantial concentration is no longer measurable at the higher altitudes. There is ^{137}Cs on the Oscura Mountains, as analysis of gamma energy spectra indicate. But, the quantity is uncertain, because the aerial system is calibrated only for flat terrain.

The surface exposure rates at 1 m AGL on the Oscura escarpment are also suspect, because of the non-

standard measurement geometry. The exposure rate map shows very large exposure rate changes on the face of the escarpment. Certainly there are some highly radioactive, natural rock types in the layers exposed by the fault line of the escarpment. This material appears to have weathered and washed or fallen down the slopes leading to the escarpment. In support of the aerial measurement, though, the soil sample and ion chamber results agree with the aerial measurement over a large area.

APPENDIX A

SURVEY PARAMETERS

Survey Dates

Presurvey: May 6 and 7, 1992
Survey: May 11 through June 2, 1992

Hardware

Aircraft: Beechcraft A-100 fixed-wing
Detectors: Eight 4- × 4- × 16-in NaI(Tl)
Data Acquisition System: REDAR IV
Steering: GPS
Data Van: Data General MV7800XP Computer

Area Coverage

Area: 3,150 km² (1,216 mi²)
Number of Flight lines: 115
Average Line Length: 37 km (23 mi)
Flight Line Spacing: Variable: 381 m, 762 m, and 1,524 m
Line Direction: North/South

Data

Acquisition Rate: Once per second
Data Type: Gamma energy spectra, atmospheric pressure and temperature, radar altitude above ground, geographic position
Flight Altitude: 91 m (300 ft)

Results

Isotopes Detected: Primarily ¹³⁷Cs, ¹⁵²Eu, and ¹⁵⁴Eu
Deposition Extent: Ground Zero, WSMR, NM to Cedarvale, NM (0-100 km)
Area of Deposition: 1,400 km² (500 mi²) (as measured)
Quantity of Deposition: 100 Ci of ¹³⁷Cs (as measured)

APPENDIX B

GENERAL DATA ANALYSIS METHODS

A few useful methods to treat gamma energy spectra as measured by NaI(Tl) are discussed below.

B.1 GROSS COUNT RATE

The gross count (GC) rate is defined as the integral count in the energy spectrum (ES) between 38 keV and 3,026 keV.

$$GC = \sum_{E=38 \text{ keV}}^{3026 \text{ keV}} ES \quad (\text{B-1})$$

This sum includes all the natural isotope gammas from ^{40}K , ^{238}U , and ^{232}Th (KUT, the major terrestrial, natural gamma emitters). Other natural contributors are cosmic rays, aircraft background, and airborne radon daughters.

The response versus altitude of the aerial system to terrestrial gammas has been measured over a documented test line near Las Vegas, Nevada, for which the concentrations of KUT and the 1-meter exposure rates have been measured separately. From this calibration, the terrestrial gross count rate has been associated with the 1-meter exposure rate in micro-roentgens per hour ($\mu\text{R/h}$) for natural radioactivity. The conversion equation is:

$$E(1m) = \frac{[GC(A) - B]}{1553} \cdot e^{0.00587A} \quad (\text{B-2})$$

where

- $E(1m)$ = exposure rate extrapolated to 1 m AGL ($\mu\text{R/h}$)
- A = altitude in meters
- $GC(A)$ = gross count rate at altitude A (cps)
- B = cosmic, aircraft, and radon background (cps)

B is obtained from flights over bodies of water where the terrestrial count rate is absent.

The gross count has been used for many years in the aerial system as a measure of exposure. Its simplicity yields a rapid assessment of the gamma environment.

Anomalous or nonnatural gamma sources are found from increases in the gross count rate over the natural count rates. However, subtle anomalies are difficult to find using the gross count rate in areas where its magnitude varies with, for example, geologic or ground cover changes. Differential energy data reduction methods, as discussed in the next section, are used to increase sensitivity of the aerial system to anomalous gamma emitters.

B.2 SPECTRAL WINDOWS

The aerial system produces a gamma energy spectrum each second from which the GC is computed. Generally, the ratio of natural components in any two integral sections (windows) of the energy spectrum will remain nearly constant in any given area:

$$\sum_{E=a}^b ES / \sum_{E=b}^c ES = \text{Constant} = K \quad (\text{B-3})$$

where

- ES = energy spectrum
- E = energy
- $a < b < c$

The window, a - b , is placed where gamma rays from a man-made emitter would occur in the spectrum. The result of Equation B-3 could be expected to increase over the constant value, when anomalous

gammas appear in window a - b . Equation B-4 is routinely applied in the data reduction software when a search is made for specific isotopes.

$$S = \sum_{E=a}^b ES - K \sum_{E=b}^c ES \quad (B-4)$$

In this equation, K is defined in Equation B-3 and its value is determined over a region which does not contain the man-made emitter. The net signal, S , is zero unless anomalous gamma rays are measured in the window defined by a and b . A window arrangement is illustrated in Figure B-1.

FIGURE B.1. ENERGY WINDOW SET FOR CESIUM-137 PHOTOPEAK EXTRACTION

Equation B-4 is used to locate specific isotopes by setting a and b to enclose the photopeak of the particular gamma from the isotope. For the general case when any man-made isotope is sought, a , b , and c are set at 38 keV, 1,394 keV, and 3,026 keV, respectively. Because most long-lived, man-made isotopes emit gammas in the energy range 38 keV to 1,394 keV, Equation B-4 becomes a general search tool and is called the man-made gross count (MMGC).

B.3 ISOTOPE CONCENTRATION COMPUTATION

An estimate of a specific isotopic concentration in the soil may be computed from the isotope's photopeak count rate in the detector. In addition, a knowledge of the detector's basic probability for total gamma absorption, the isotopic vertical concentration distribution in the soil, and both the air and soil densities are required. The equation that approximates the photopeak count rate to isotope activity concentration is:

$$S_v^0 = \left[\frac{A_0}{2} \int_0^{\pi/2} \frac{R(\theta) \tan \theta e^{-(\mu/\rho)_a \rho_a h \sec \theta} d\theta}{\alpha + (\mu/\rho)_s \rho_s \sec \theta} \right]^{-1} \quad (B-5)$$

where

S_v^0 = activity per volume at the soil surface per photopeak count per second ($\gamma/\text{sec}/\text{cm}^3/\text{cps}$)

A_0 = effective area or probability of total absorption per unit gamma fluence (cm^2)

$R(\theta)$ = relative detector response as a function of incident gamma angle, θ , with respect to the vertical

μ/ρ = gamma mass attenuation coefficient (cm^2/g) in air (a) or soil (s)

ρ = air or soil density (g/cm^3)

α = vertical concentration distribution parameter in the equation

h = distance of detector above the ground (cm)

$$S = S_v^0 e^{-\alpha z} \quad (B-6)$$

where z is the depth in soil.

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AN AERIAL RADIOLOGICAL SURVEY OF THE
TRINITY FALLOUT AREA
WHITE SANDS MISSILE RANGE, NEW MEXICO
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