EGG-10617-1130
U/C-702
SEPTEMBER 1991

Received by GSTI

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OCT 18 1991
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EGG--10617-1130

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AN AERIAL RADIOLOGICAL SURVEY OF THE
**CENTRAL SAVANNAH
RIVER SITE**

AIKEN, SOUTH CAROLINA

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DATE OF SURVEY: FEBRUARY 1987

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**CENTRAL SAVANNAH
RIVER SITE**

AIKEN, SOUTH CAROLINA

SURVEY DATE: FEBRUARY 1987

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This work was performed by EG&G/EM under Contract Number DE-AC08-88NV10617 with joint funding provided by the United States Department of Energy and E.I. du Pont de Nemours & Company, Inc., operators of the Savannah River Site and Savannah River Laboratory at the time of the survey.

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ABSTRACT

An aerial radiological survey was conducted over a 194-square-kilometer (75-square-mile) area encompassing the central portion of the Savannah River Site (SRS). The survey was flown during February 10-27, 1987.

These radiological measurements were used as baseline data for the central area and for determining the extent of man-made radionuclide distribution. Previous SRS surveys included small portions of the area; the 1987 survey area was covered during the site-wide survey conducted in 1979.

Man-made radionuclides (including cobalt-60, cesium-137, protactinium-234m, and elevated levels of uranium-238 progeny) that were detected during the survey were typical of those produced by the reactor operations and material processing activities being conducted in the area. The natural terrestrial radiation levels were consistent with those measured during prior surveys of other SRS areas.

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1.0 INTRODUCTION

An aerial radiological survey was performed over a portion of the Savannah River Site which included 194 square kilometers (75 square miles) of the central portion of the site. The survey was conducted during February 10-27, 1987 by EG&G Energy Measurements, Inc. (EG&G/EM) for the U.S. Department of Energy and the E.I. du Pont de Nemours & Company, Inc., Savannah River Site.* The survey was part of the Comprehensive Integrated Remote Sensing (CIRS) program. The airborne radiation monitoring portion of the program is a continuing series of surveys designed to provide a data base for studying the transport of man-made radionuclides through the environment encompassing the Savannah River Site and the surrounding area. The CIRS program can also provide state-of-the-art remote sensing capabilities to support the needs of various DOE facilities.

The 1987 gamma survey is one of several such surveys conducted over the SRS land areas and facilities. Other surveys conducted near or over small segments of the same area include those conducted in 1974, 1979, 1982, and 1983.^{1,2,3,4}

The purpose of this survey was to determine the kind, relative intensity, and spatial extent of natural and man-made radiation over the central portion of the Savannah River Site. This area was covered during the site-wide survey in 1979.

2.0 SURVEY EQUIPMENT AND PROCEDURES

The aerial radiological survey consisted of flying the specially equipped AMS helicopter in a regular pattern over the survey site. The measurements performed permit mapping of radiation and selected radionuclides in addition to the location and identification of anomalous

* During the time of the survey, E.I. du Pont de Nemours & Company, Inc., operated the Savannah River Plant. The name of this facility has been changed and is now referred to as the Savannah River Site.

radioactivity. Specifically, spectra of gamma photon energy were measured on a second-by-second basis and recorded with the position of the aircraft. The spectra were obtained using an array of eight, 10.2-cm $\times$ 10.2-cm $\times$ 40.6-cm (4-in $\times$ 4-in $\times$ 16-in) sodium iodide (thallium-activated), NaI(Tl), scintillation detectors. Spectra, positional data, and other information were recorded in flight by a custom-engineered data acquisition system (REDAR IV) which provided multichannel analysis, navigation, and data logging. The aerial platform employed was a Messerschmitt-Bolkow-Blohm (MBB) BO-105 helicopter (Figure 1). The base of operations was at the U.S. Army Signal Corps Hangar at Bush Field in Augusta, Georgia. A brief description of the above system and survey procedures is given in Appendix A; a more detailed description can be found in a separate publication.⁵

The aerial survey of central Savannah River Site was conducted at an altitude of 46 meters (150 feet) with flight-line spacings of 76 meters (250 feet). The helicopter speed was 130

FIGURE 1. MBB BO-105 HELICOPTER WITH DETECTOR PODS

kilometers per hour (70 knots). Using these parameters, an area of approximately 194 square kilometers (75 square miles) was surveyed. A description of the operational parameters for the 1987 survey is contained in Appendix B.

3.0 DATA PROCESSING

The processing of the magnetic tapes with recorded data from each flight was begun in the field utilizing the Radiation and Environmental Data Analyzer and Computer (REDAC) system. This system consisted of a computer analysis laboratory mounted in a mobile van. During survey operations, the van and aircraft were based at Bush Field in Augusta, Georgia. The interior of the van is shown in Figure 2, and Figure 3 shows a block diagram of the REDAC processing system which consisted primarily of a Data General S-280 computer and peripherals. An extensive inventory of software routines was available for the preliminary data

FIGURE 2. INTERIOR OF THE MOBILE DATA ANALYSIS LABORATORY

FIGURE 3. BLOCK DIAGRAM OF THE REDAC SYSTEM

analysis (accomplished in the field) and the final analysis (accomplished in Las Vegas after the completion of field operations). Appendix C contains a general review of customary data analysis routines and procedures that have been used in SRS surveys. Using various portions of the gamma ray energy spectrum, algorithms were developed to extract contributions from selected gamma emitting radioactive materials and to suppress interference from other sources. The results presented were obtained solely by the matrix method algorithm. Due to a complex mix of radionuclides and the detector resolution, only algorithms derived using matrix mathematics could adequately isolate the activity of the source of interest. However, the matrix algorithms were less sensitive than those derived from other methods (*i.e.*, the level of uncertainty in the processed data was greater for the matrix algorithms).

4.0 RESULTS

Radiological data were collected and processed for the central portion of the Savannah River Site depicted in Figure 4. This figure is an aerial view of the surveyed area with the

SURVEY BOUNDARY

FIGURE 4. AERIAL VIEW OF SURVEYED AREA SHOWING FACILITIES AND WATERWAYS

facilities, roadways, and waterways labeled, and all processed data presented later in this section are superimposed on this base photograph. The surveyed area encompassed 194 square kilometers (75 square miles) of the Savannah River Site.

Results of the algorithms were combined with positional information to generate isopleth contour plots. These were then presented as isoradiation contour plots of annual dose contributions. The "Total" and "Man-Made" isoradiation contour plots are presented primarily to establish the spatial distribution and relative intensity of gamma radioactivity. Because these quantities cannot be simply related to a dose or concentration, no conversions were applied. The dose conversion for the "Natural" isoradiation contour plot is simply the measured exposure rate integrated for a year (8.766 mrem/yr/ μ R/h). Dose conversions for specific radionuclides were obtained by application of Beck's dose conversion factors to the radionuclide concentrations, which are estimated from a simple radiation transport model.⁶

The minimum contour values of the isoradiation contour maps of the listed sources are included in Table 1. The lowest contour level is derived from the statistical variability in the data for a particular source of radiation as described in Appendix C. Generally, the lowest contour interval is some multiple of the observed variance. Values less than the lowest level are considered undetectable because they are masked by statistical variation of the background at the accepted confidence level (typically 99.9%). Conversely, significant data, whose values are equal to or slightly greater than this lowest level, may be incorrectly dismissed as background (50% confidence at the lowest level). Therefore, selection of this lowest level is always a compromise between optimal sensitivity and minimal false indications. Appendix C briefly describes the statistical methods that establish levels of uncertainty in the data collected with the detector system used during this survey.

Gamma rays of both elevated, naturally occurring, and man-made radionuclides were detected over central area facilities, along creeks, branches, adjacent land areas, and in the air. The detected man-made sources were traceable to SRS operations which include reactor operations, material processing, material storage, material transfer, and waste burial.

Table 1. Figures and Parameters of Processed Isoradiation Contour Maps			
Figure	Radiation Source	Minimum Level	Units
5	Total	3,000	cps
6	Natural	24	mrem/yr
7	Man-Made	500	cps
8	Bi-214	2.0	mrem/yr
9	Cs-137	3.1	mrem/yr
10	Co-60	3.7	mrem/yr
11	Pa-234m	2.6	mrem/yr

Twenty-three locations are identified in Figure 12 depicting the centers of detected man-made activity. Spectral data were selected at these locations in an attempt to characterize the distribution of specific radionuclides. As indicated by the parameters in Table 2 and the gamma ray energy spectra in Figures 13-18, the primary contributors to the man-made activity were cobalt-60, cesium-137, excess bismuth-214, protactinium-234m, and argon-41.

Terrestrial gamma ray activity of elevated, naturally occurring uranium-238 daughters (bismuth-214) was detected along segments of Upper Three Runs, Mill, and Tinker Creeks. According to SRS officials, these creeks flow through an area with natural uranium-238 levels higher than those typically found elsewhere on the Savannah River Site.

Gamma ray activity detected in the air over the SRS survey area came from naturally occurring bismuth-214 daughters of radon-222 gas originating from the soil. Argon-41 (a man-made, gamma-emitting, gaseous by-product of reactor operations) was also detected in the air in plumes downwind of the operating reactors. Although argon-41 was detected over a significant portion of the surveyed area, an isoradiation contour map of this man-made source was not produced. The flight-to-flight variation was too drastic to spatially characterize this source for the complete survey. However, contour maps of these data were generated on a flight-to-flight basis to monitor these variations. An argon-41 gamma ray pulse-height spectrum is shown in Figure 17; a spectrum characteristic of airborne radon-222 is shown in Figure 18.

The annual dose computed for naturally occurring gamma emitters in the central area is consistent with that of other previously surveyed SRS areas. The inferred range is 50 to 70 mrem/yr, which includes an estimated cosmic contribution of approximately 33 mrem/yr.

FIGURE 5. ISORADIATION CONTOUR MAP OF TOTAL TERRESTRIAL ACTIVITY

FIGURE 6. ISORADIATION CONTOUR MAP OF NATURAL TERRESTRIAL ACTIVITY

FIGURE 7. ISORADIATION CONTOUR MAP OF MAN-MADE TERRESTRIAL ACTIVITY

FIGURE 8. ISORADIATION CONTOUR MAP OF BISMUTH-214 ACTIVITY

FIGURE 9. ISORADIATION CONTOUR MAP OF CESIUM-137 ACTIVITY

FIGURE 10. ISORADIATION CONTOUR MAP OF COBALT-60 ACTIVITY

FIGURE 11. ISORADIATION CONTOUR MAP OF PROTACTINIUM-234m ACTIVITY

FIGURE 12. SURVEY AREA SHOWING SPECTRAL EVIDENCE OF RADIATION SOURCES

Table 2. Man-Made Source Distribution in the Central Area					
Area	Spectrum^a Locations	Bi-214	Co-60	Cs-137	Pa-234m
700/300 A	21				X ^b
700 U/TC	19		X		X
F Area	16,17	X	X	X	X
H Area	10,11	X	X	X	X
R Reactor	2,3,4,5,6,7,8		X	X	X
Waste Burial	14	X	X	X	X
Drainage Basins	12,16,18		X	X	
Four Mile Branch	13		X	X	
Tim's Branch	20				X
Par Pond	1			X	
Steed Pond	20				X
Mill Creek	22	X			
Tinker Creek	9	X			
Upper Three Runs Creek	15	X			

^a Locations of centers of man-made activity depicted in Figure 12.

^b X indicates the presence of the particular source in a given area.

FIGURE 13. TYPICAL GAMMA RAY ENERGY SPECTRUM COLLECTED OVER AREAS WHERE URANIUM-238 DAUGHTERS WERE ELEVATED ABOVE NATURALLY OCCURRING LEVELS

FIGURE 14. TYPICAL GAMMA RAY ENERGY SPECTRUM COLLECTED OVER AREAS WHERE COBALT-60 WAS DETECTED

FIGURE 15. TYPICAL GAMMA RAY ENERGY SPECTRUM COLLECTED OVER AREAS WHERE CESIUM-137 WAS DETECTED

FIGURE 16. TYPICAL GAMMA RAY ENERGY SPECTRUM COLLECTED OVER AREAS WHERE PROTACTINIUM-234m (URANIUM-238) WAS DETECTED

FIGURE 17. TYPICAL GAMMA RAY ENERGY SPECTRUM OF AIRBORNE ARGON-41 DETECTED IN PLUME OVER THE CENTRAL AREA

FIGURE 18. TYPICAL GAMMA RAY ENERGY SPECTRUM OF AIRBORNE RADON-222 DAUGHTER ACTIVITY MEASURED OVER THE CENTRAL AREA

APPENDIX A

SURVEY EQUIPMENT AND PROCEDURES

The aerial radiological measurements were made with a detector array and a data acquisition system mounted in a Messerschmitt-Bolkow-Blohm (MBB) BO-105 helicopter. The detector package consisted of an array of eight sodium iodide (thallium-activated), NaI(Tl), detectors. Each detector was comprised of a photomultiplier tube coupled to an NaI(Tl) crystal which was 10.2 cm $\times$ 10.2 cm $\times$ 40.6 cm (16 in $\times$ 4 in $\times$ 4 in). Two equipment pods, each containing four detectors, were mounted on the exterior of the helicopter. The photomultiplier tube mounted to each NaI(Tl) crystal converted the scintillations of light in the crystal to electrical pulses. The electrical pulses from the eight crystals were normalized and combined in summing amplifiers to produce a single gamma ray energy spectrum useful for analyzing low intensity sources. A single 10.2-cm $\times$ 10.2-cm (4-in $\times$ 4-in) crystal in each pod provided a spectrum useful over highly active areas where the electronics that are driven by the eight-detector array would experience unacceptably large counting losses. Both spectra were simultaneously acquired and recorded, resulting in an increased dynamic range of sensitivity. Each pod also contained an upward-looking 7.6-cm $\times$ 7.6-cm (3-in $\times$ 3-in) crystal that was used in conjunction with the eight large detectors to compute the effects of background radiation due to nonterrestrial sources.

The outputs from the summing amplifiers were analyzed in separate multichannel analyzers (MCAs) in the Radiation and Environmental Data Acquisition and Recorder (REDAR) system, Model IV. The REDAR system is a multimicroprocessor, portable, data acquisition and real-time analysis system. It was designed to operate in the demanding environments associated with helicopters and fixed-wing aircraft. A block diagram of the REDAR system is shown in Figure A-1.

The inputs to the MCAs were adjusted so that the photopeaks due to calibration sources appeared in preselected channels. Each MCA collected a 1,024-channel gamma ray energy spectrum once every second. The collected spectrum was scaled to 4 keV per channel. The

FIGURE A-1. BLOCK DIAGRAM OF THE REDAR IV SYSTEM

1,024-channel spectrum was compressed into 256 channels, as summarized in Table A-1, before storage on magnetic tape. The energy resolution of the NaI(Tl) crystals varies with energy so that the spectral data can be compressed without compromising photopeak identification and data analysis techniques. This spectral compression technique reduced the data storage requirement by a factor of four.

Other information acquired and recorded by the REDAR system each second included aircraft positional data, system live-time information, and environmental conditions, *i.e.*, absolute barometric pressure and outside air temperature.

The helicopter position was established by two systems: an ultrahigh-frequency ranging system (URS) and a radar altimeter. The URS consisted of two remotely located transponders and an on-board interrogator that used the transit time of an ultrahigh-frequency radio pulse to obtain the distance from the aircraft to each remote unit. The radar altimeter similarly

Table A-1. REDAR IV Spectral Data Compression Scheme			
E_{γ} (keV) At Input Channel Center	Input Channel (linear @ 4 keV/channel)	Output Channel (compressed)	Output Channel Energy Coefficient ΔE (keV/channel)
0 - 300	0 - 75	0 - 75	4
304 - 1,620	76 - 405	76 - 185	12
1,624 - 4,068	406 - 1,017	186 - 253	36
4,072 - Cutoff	1,018 - 1,023	254	N/A
		255 (always zero)	

measured the time delay for the return of a pulsed signal and converted this delay to aircraft altitude above ground level. In addition to being recorded on magnetic tape, position and altitude information were also processed in real time by the steering microprocessor. These data provided steering information to the pilot for flying predetermined flight lines at the desired altitude.

APPENDIX B

SURVEY PARAMETERS

Site: Central Savannah River Site
Location: Aiken, South Carolina
Survey Date: February 10-27, 1987
Base of Operation: Bush Field, Augusta, Georgia
Survey Coverage: 194 km² (75 mi²)
Lines Surveyed: 110
Line Spacing: 76 m (250 ft)
Survey Altitude: 46 m (150 ft)
Project Scientist: E.L. Feimster
Survey Aircraft: MBB BO-105 Helicopter
Acquisition System: REDAR IV
Detector Array: Eight 10.2-cm wide × 10.2-cm thick × 40.6-cm long NaI(Tl) detectors (Cd-Pb shielded upper surface and sides).
Two 10.2-cm diameter × 10.2-cm thick NaI(Tl) detectors.
Two 7.6-cm diameter × 7.6-cm thick upward-looking NaI(Tl) detectors.

Data Processing:

Source: Cesium-137
Photopeak Energy Window: 590 to 734 keV
Conversion Factor: 0.036 mrem/yr/cps
Source: Cobalt-60
Photopeak Energy Window: 1,046 to 1,466 keV
Conversion Factor: 0.058 mrem/yr/cps
Source: Protactinium-234m
Photopeak Energy Window: 890 to 1,106 keV
Conversion Factor: 0.067 mrem/yr/cps
Source: Bismuth-214
Photopeak Energy Window: 1,586 to 1,946 keV
Conversion Factor: 0.067 mrem/yr/cps
Source: Natural Terrestrial Activity
Energy Window: 1,394 to 3,026 keV normalized to 38 to 3,026 keV
Conversion Factor: 0.008 mrem/yr/cps (natural terrestrial)
Cosmic Ray Contribution: 33 mrem/yr

APPENDIX C

REVIEW OF DATA ANALYSIS TECHNIQUES

This appendix is designed to illustrate some of the methodologies used for analyzing multi-channel spectral data collected with airborne detector systems. Analysis is conducted to resolve, identify, and quantify radionuclides present in the environment. Methods discussed in this appendix are those that have been typically applied to multichannel spectral data collected over areas such as those of the SRS facilities. The primary focus of the analysis is to extract photopeak counts per unit time (count rate) of the source(s) of interest. This count rate is then plotted as a function of position to provide an isoradiation contour map of a given area. Secondary processing involves extrapolating the aerially measured count rate to ground level activity using various source distribution models.

The radiation profile is analyzed, generally, using some or all of the following:

1. Total count rate
2. Nonterrestrial count rate
3. Natural terrestrial count rate
4. Total man-made source count rate
5. Specific radionuclide count rate

Items 1-4 are derived from summing photopeak and Compton scatter counts that lie within specified energy ranges. These ranges are discussed in this appendix. Generally, a conversion factor is applied to some of the derived quantities listed above to generate estimates of quantities such as annual dose, exposure rate, and concentration. This estimate may contain large uncertainties which are difficult to quantify because the estimate is based on a model of the three-dimensional distribution of radiation activity. The distribution, as well as other pertinent parameters (soil moisture, terrain cover, etc.), may be unknown or highly variable. Often, ground sampling and analysis is utilized to corroborate aerial survey results.

TOTAL TERRESTRIAL EXPOSURE RATE AND NONTERRESTRIAL BACKGROUND

An isoradiation contour map showing the spatial distribution of exposure rates is routinely generated for major survey areas. Maps of this type represent the exposure rate due to all gamma rays of terrestrial origin (gross count) plus the contribution due to cosmic ray interactions with the earth's atmosphere.

Customarily, exposure rates at 1 meter above ground level are estimated from gross count rates measured over the survey area minus the component due to nonterrestrial sources. An estimated cosmic ray contribution based on the elevation of the survey area is also added to that exposure rate if an isoradiation contour map of the total exposure rate is desired or practical.

During each flight, the airborne system was flown over a calibration line near the Savannah River Site. The background radiation contributions from all nonterrestrial sources were estimated from measurements made in two ways: flights over L Lake near SRS ("water line") and by a new technique using flights over the calibration line. These data enabled the removal of nonterrestrial background contributions from the aerial measurements and provided a check on flight-to-flight variations in the levels of airborne radon activity.

The gross count energy window included gamma rays with energies between 38 and 3,026 keV, which includes all significant gamma rays due to natural sources of radiation. Several corrections were applied to the measured gross counting rates before converting them to exposure rates:

$$GC = [(A_e \cdot W_{GC}) \cdot LT - C] \cdot AH \quad (C-1)$$

where

GC = Normalized gross counting rate corrected for system live-time and altitude variations

A_e = Detector effective area normalization

W_{GC} = Measured gross counting rate

LT = Live-time counting loss correction

C = Nonterrestrial contributions to the gross count rates

AH = Correction for altitude variations

The nonterrestrial counting rates (C in Equation C-1) include contributions from: sources of radiation on board the helicopter, airborne radon and daughter products, and cosmic rays. As previously mentioned, these combined contributions were determined in two ways in the SRS data analysis:

1. Water Line Method – The nonterrestrial component was measured directly by flying the detector system over a large body of water, *i.e.*, a water line. Since the radiological activity from water is usually negligible, the total count rate measured over the water would be due only to nonterrestrial sources. This method is preferred, but is used only whenever a large body of water is available. Lake Mead near SRS was used en route to and from the survey area.
2. Upward-Looking Detector Method – Additional upward-looking detectors were added to the system to estimate contributions due to nonterrestrial sources. This technique must be employed if there are no nearby bodies of water available that will accommodate the flying of water lines. The following is a detailed description of the procedure and algorithm:
 - a. Calibration flights of the upward-looking detector were made over a test line at Lake Mead, Nevada, and Calvert County, Maryland. The system consisted of two detector pods, each containing one 7.6-cm $\times$ 7.6-cm (3-in $\times$ 3-in) upward-looking NaI(Tl) detector and four 10.2-cm $\times$ 10.2-cm $\times$ 40.6-cm (4-in $\times$ 4-in $\times$ 16-in) downward-looking NaI(Tl) detectors. The upward-looking capability was achieved by placing each 7.6-cm $\times$ 7.6-cm (3-in $\times$ 3-in) detector over the four log detectors with 1/16-in lead and cadmium sheets inserted between the detectors and along the sides of the pods surrounding the upward-looking detectors.

Two assumptions were made during calibration flights over the test lines:

- (1) Airborne radon was uniformly distributed in the air over the land and water lines.
- (2) Aircraft and cosmic contributions to the total activity at the survey altitude were constant values.

- b. An algorithm was derived from data collected over the test range that calculates the nonterrestrial component of the total activity as a function of the ratio of the gross count rate in the upward-looking detectors to the gross count rate in the downward-looking detectors. The algorithm is written as follows:

$$NTC = \frac{gc}{R_w - R_L} - \frac{R_L GC}{R_w - R_L} \quad (C-2)$$

where

NTC = Computed count rate due to nonterrestrial sources in downward-looking detectors

gc = Gross count rate in the upward-looking detectors

GC = Gross count rate in the downward-looking detectors

$R_L = \frac{gc - (r + a + c)}{GC - (R + A + C)}$ over the land calibration line

$R_w = gc/GC$ over water calibration line. Where $gc = r + a + c$

and $GC = R + A + C$

$(R + A + C)$ and $(r + a + c)$ are the radon, aircraft, and cosmic radiation components that comprise the nonterrestrial component detected in the downward- and upward-looking detectors, respectively. The gc and GC were measured and adjusted for the altitude and meteorological conditions of a selected survey area.

The ratios, R_w and R_L , as illustrated in Figure C-1 and described in Equations C-3 and C-4 below, decrease slightly with effective survey altitude (ALT_{eff}) of the detectors.

$$R_w = 0.0938 - (2.15 \cdot 10^{-6} \cdot ALT_{eff}) \quad (C-3)$$

$$R_L = 0.0489 - (1.45 \cdot 10^{-5} \cdot ALT_{eff}) \quad (C-4)$$

FIGURE C-1. RATIO OF COUNT RATES IN THE UPWARD- AND DOWNWARD-LOOKING DETECTORS AS A FUNCTION OF EFFECTIVE ALTITUDE

where

$$ALT_{eff} = ALT_{mea} \cdot COR_P \cdot COR_T \quad (C-5)$$

and

COR_P and COR_T are factors that adjust pressures and temperatures measured in the survey area for standard conditions as described in Equations C-6 and C-7.

$$COR_P = P_{mea} / P_{std} \quad (C-6)$$

$$COR_T = (T_{std} + 273) / (T_{mea} + 273) \quad (C-7)$$

Pressure, P , is measured in pounds per square inch (14.69 for standard conditions) and temperature, T , in degrees centigrade (20°C at standard conditions).

The uncertainty, σ_{NTC} , in the computed nonterrestrial component of the background radiation (Equation C-2) is given by:

$$\sigma_{\text{NTC}} = \sqrt{\left(\frac{1}{R_W - R_L}\right)^2 \sigma_{\text{gc}}^2 + \left(\frac{R_L}{R_W - R_L}\right)^2 \sigma_{\text{GC}}^2} \quad (\text{C-8})$$

To test the accuracy of this method, the results of the algorithm (Equation C-2) were compared to data collected over large bodies of water where only the nonterrestrial component exists. Nonterrestrial count rates predicted by the algorithm were, in most cases, within 10% or less of the count rates measured over selected large bodies of water with widely varying radon concentrations and meteorological conditions.

The measured and computed gross count rates due to nonterrestrial background as a function of effective survey altitude collected over a test line near Lake Mead, Nevada, and Diablo Canyon, California, are presented in Figures C-2 and C-3, respectively, to illustrate performance.

The resulting net count rate (GC described in Equation C-1) was converted to exposure rate at the 1-meter level by applying a conversion factor of 127 counts per second per mrem/yr. This factor was derived from many measurements made over areas with known concentrations of naturally occurring radioisotopes. The total exposure rate at 1 meter above the ground level minus any contribution from the nonterrestrial component may be estimated by adding the estimated cosmic ray contribution of 33 mrem/yr. Contour lines of equal exposure rate were plotted utilizing the processed gross count data along with the recorded position information. The exposure rate contour map was scaled to overlay United States Geological Survey (USGS) maps. Thus, the spatial distribution and intensity of the exposure rates due to terrestrial gamma ray emitters within the survey area were defined.

The exposure rates inferred from aerial data are not valid in areas where other than typical mixes of naturally occurring radionuclides exist or where mixes are drastically different from those of the calibration range.

FIGURE C-2. GROSS COUNT RATE OF NONTERRESTRIAL BACKGROUND AS A FUNCTION OF ALTITUDE OVER A TEST LINE NEAR LAKE MEAD, NEVADA

NATURAL TERRESTRIAL EXPOSURE RATE

The total terrestrial exposure rate, described above, is sensitive to both natural and man-made gamma radiation. In fact, man-made radioactivity often will dominate and completely mask the natural contribution. But it is sometimes desirable to display the exposure rate due solely to naturally occurring radioactivity despite the presence of man-made radioactivity. This quantity is called the natural terrestrial exposure rate.

The natural terrestrial exposure rate is determined using a simple algorithm which samples a portion of the energy spectrum characteristic of the natural radiation background, but avoids interference by man-made radionuclides. Most common, long-lived, man-made radionuclides

FIGURE C-3. GROSS COUNT RATE OF NONTERRESTRIAL BACKGROUND AS A FUNCTION OF ALTITUDE OVER A TEST LINE NEAR DIABLO CANYON, CALIFORNIA

have photopeaks with energy less than or equal to 1,333 keV. The natural terrestrial count rate algorithm excludes these lower energies and includes only higher energy contributions, 1,394 to 3,026 keV. The algorithm for natural terrestrial count rate is nearly identical to the total count rate algorithm for exposure rate. The differences lie only in the definition of the measured count rate and addition of a normalization factor. The exposure rate conversion factor and all other terms remain the same as for the total exposure rate algorithm.

The natural terrestrial gross count rate can be expressed as:

$$NTGC = [(A_e \cdot R \cdot W_{NTGC}) \cdot LT - C] \cdot AH \quad (C-9)$$

where

NTGC = Effective gross count rate, due only to natural sources, corrected for live-time and altitude variations

R = Ratio of counts observed in the natural source window to those observed in the total energy window from a spectrum known to be free of man-made radioactivity

W_{NTGC} = Measured count rate in the natural source window (1,394 to 3,026 keV)

A_e, LT, C and AH are defined in Equation C-1.

MAN-MADE GROSS COUNT RATE

The man-made gross count (MMGC) algorithm is essentially the opposite of the natural terrestrial gross count. The MMGC algorithm is designed to exhibit the presence of only man-made radioactivity and to suppress natural background variations. It is meant only as a qualitative indicator of the magnitude and spatial distribution of man-made radioactivity. It cannot be simply related to exposure rate. The algorithm exploits changes in spectral shape. Large changes in gross counting rates from natural radiation usually produce only small changes in spectral shape because the natural emitters change in more or less a constant ratio as the detector moves from one location to another. The algorithm senses counts in the lower energy portion of the spectrum, in excess of those predicted, on the premise that these counts bear a constant ratio to counts in the upper energy portion. Since the algorithm is designed to be most sensitive to man-made nuclides, the spectrum dividing line is chosen at an energy (1,394 keV) above which most long-lived, man-made nuclides do not emit gamma rays. It is analytically expressed in keV as:

$$\text{MMGC} = \sum_{E=38 \text{ keV}}^{1,394 \text{ keV}} \text{counts}_E - K \sum_{E=1,394 \text{ keV}}^{3,026 \text{ keV}} \text{counts}_E \quad (\text{C-10})$$

The counts in the upper energy window (1,394 to 3,026 keV) are multiplied by a constant, K, to equal the counts in the lower energy window (38 to 1,394 keV) in areas containing only naturally occurring background radiation. Hence, the resultant average MMGC is equal to zero for areas containing normal background radiation and will become positive in areas containing man-made radionuclides.

Because the man-made gross count algorithm is general and will respond to a wide range of nuclides, its sensitivity to specific nuclides is less than optimum. If the search nuclide is known, more sensitive algorithms can be devised.

PHOTOPEAK SPECTRAL ANALYSIS

In addition to the total exposure rate (gross count), the ground-based computer system, REDAC, was used to process multichannel spectral data for activity due to specific radionuclides.

Software algorithms were used to:

1. Combine portions of the multichannel spectrum to suppress the natural background and enhance the presence of specific contaminants
2. Combine these results with position information to generate isoradiation contours of the quantity of interest
3. Convert photopeak count rate to activity in the soil

A gamma ray energy spectrum is comprised of a collection of photopeaks immersed in continuous background. The photopeaks are due to those photons which arrive at the detector without interaction or collision en route from their source. The energies associated with photopeaks are nearly unique signatures of individual radionuclides. The background is due to photons whose energy and direction have been garbled by interactions, principally Compton scattering. In the absence of man-made radioactivity, the photopeaks and Compton background are due to naturally occurring radionuclides (both uranium-238 and thorium-232 with daughters, plus potassium-40). Man-made radioactivity contributes additional photopeaks and

background. Algorithms have been devised to identify and isolate contributions of specific radionuclides which can be then mapped and used to infer concentrations (or dose).^{*} These "spectral stripping" algorithms, as they are called, are divided into three types: two-window strip, three-window strip, and matrix method. The following discussion develops and describes these three techniques.

As discussed in Appendix A, the detectors are calibrated with sources of known energy so that photopeaks of designated radionuclides are collected in predetermined channels of a multichannel analyzer. Although a photopeak has a very definite energy, the energy resolution of the detector system and associated electronics results in the broadening of the photopeak over a narrow energy window so that:

$$E_+ \leq E_\gamma \leq E_- \quad (C-11)$$

where E_γ is the discrete photopeak energy. E_+ and E_- are defined as the lower and upper energy resolution limits determined by:

$$E_\pm = E_\gamma \pm p \cdot E_\gamma \quad (C-12)$$

and p is the fractional detector resolution determined by laboratory measurements (about 10%).

The photon count rate (CR) in the photopeak can be estimated from the sum of counts in a source window per unit time less the approximate background contribution. The fundamental difference between stripping algorithms is the way in which the background contribution is estimated and removed. The photopeak count rate (A) is a sum of multichannel analyzer channels which span the corresponding window energy range so that:

$$A = \sum_{i=n_1}^{n_2} C_i \quad (C-13)$$

^{*} These are related to the photopeak count rate via published or easily computed conversion factors.

where

A = Total window counts

C_i = Counts per channel/unit time

n_1 & n_2 = Upper and lower channels actually summed

Note that the limits of the sum are n_1 and n_2 . Ideally, the limits would be n_+ and n_- , which would, in principle, then yield the “true” photopeak count rate. However, it may be necessary to select the actual window limits (n_1 and n_2) to be different from n_+ and n_- . This need typically arises to avoid interference from nearby photopeaks due to other than the radionuclide of interest, *e.g.*, Ar-41 (1,293 keV) and Co-60 (1,157 and 1,332 keV). Therefore, a photopeak correction (F) is required to estimate the “true” photopeak count rate. In fact, even if n_1 and n_2 are chosen to be n_+ and n_- , a small correction ($\leq 10\%$) may be necessary. Determination of F is described later as the algorithms are developed.

Energy windows of specific sources will have undesirable contributions from other sources of greater energy. These are mostly due to Compton scattering of the uncollided gamma rays between the source and the detector and Compton scattering inside the detector. Algorithms have been developed to remove components of other sources from the total counts measured in the energy window of the source of interest. The total source window count rate may then be described as in Equation C-13.

Table A-1 of Appendix A lists the energy ranges and the associated analyzer channels. The energy ranges used to measure counts of uncollided gamma rays of sources typically detected at the SRS site are listed in Table C-1.

TWO-WINDOW STRIP

The two-window strip is the simplest and most sensitive algorithm, but it has limited validity and is the most vulnerable to interference by other photopeaks. This algorithm exploits the fact that background contribution can only arise from photons whose photopeak energy is greater than the photopeak of interest. This algorithm approximates the background as a

Table C-1. Energy Windows Used to Sum the Counts of Uncollided Gamma Rays of Detected Radionuclides Using the Two- and Three-Window Algorithms			
Source	Window	Nominal Energy Range (keV)	Analyzer Channels
Bi-214	A	1,574 - 1,946	182 - 194
	B	2,342 - 2,882	206 - 220
Co-60	A	1,094 - 1,394	142 - 166
	B	1,394 - 3,026	167 - 224
Cs-137	A	590 - 722	100 - 110
	B	518 - 590	94 - 99
	B'	722 - 794	111 - 116
Pa-234m	A	890 - 1,106	125 - 142
	B	1,106 - 1,394	143 - 166

constant magnitude per channel throughout the source window. The magnitude is estimated from a single background window (B) which lies at some greater energy than the source window. The equation describing this strip is:

$$CR = A_e \cdot LT \cdot F \cdot (A - KB) \quad (C-14)$$

where

CR = Net count rate due to the source of interest

A = Window count rate due to source plus contributions

B = Window count rate of other sources that contribute to the window of the source of interest, typically referred to as the background window

K = A/B, a constant when no man-made sources are present and the typical mix of naturally occurring sources is constant

F = Photopeak correction factor

Generally, the typical mix of naturally occurring gamma emitters in the soil is relatively constant for most areas; *i.e.*, radiological surveys conducted over most of the United States have shown that the ratios, U-238/K-40, Th-232/K-40, U-238/Th-232, or the ratio of any

combination of multichannel spectral windows in a spectrum of a typical mix of these sources is a constant value. Therefore, the counts A and B from selected windows of a composite spectrum of these sources compare so that $K = A/B$ is a constant value for a given survey area. The energy window width used to obtain A counts for a specific source is determined from Equations C-11 and C-12.

THREE-WINDOW STRIP

Though the two-window stripping method is the most sensitive, it does not remove the contributions of other sources that were not present in the data from which K was derived. Therefore, the three-window strip algorithm was established. It employs two background windows (depicted in Figure C-4) so that:

$$CR = A_e \cdot LT \cdot F \cdot [A - (B + B')] \quad (C-15)$$

where

CR = Net source count rate

A = Total counts in the central/source window

$B + B'$ = Total counts in two windows straddling the central window as illustrated in Figure C-4 so that $A - (B + B') = 0$ regardless of other detected man-made sources or changes in natural soil mix

As described in Appendix A, the energy channel edges and widths are fixed; therefore, the energy limits of the desired windows are not always attainable. In this case, the windows are chosen for A, B, and B' as near the desired limits as possible and are adjusted by a factor, K, to yield a result equivalent to Equation C-15. This algorithm is:

$$CR = A_e \cdot LT \cdot F \cdot [A - K(B + B')] \quad (C-16)$$

FIGURE C-4. THE SOURCE AND TWO BACKGROUND WINDOWS USED WITH THE THREE-WINDOW ALGORITHM METHOD

where

$$K = \frac{A}{B + B'} \quad (\text{C-17})$$

and K is dependent upon the widths of the windows used to acquire A , B , and B' . The variation in K is insignificant and generally depends on the Compton shape of the portion of the spectrum where the windows are selected.

This method is very useful in stripping low energy sources in whose windows are included Compton-scatter components of higher energy from natural and man-made sources that occur in the same location. A source such as cesium-137 occurs in portions of the energy spectrum where it is convenient to use the three-window method.

The photopeak correction factor (F) is determined analogously for both the two- and three-window strips. It is the ratio of the true photopeak count rate to that generated by the algorithm. Note that the "true" photopeak was defined as n_+ and n_- . This can be estimated from a background-free spectrum of the radionuclide of interest as:

$$F = \frac{\bar{A}}{A - KB} \text{ or } \frac{\bar{A}}{A - K(B + B')} \quad (C-18)$$

where

$$\bar{A} = \sum_{i=n_-}^{n_+} C_i \quad (C-19)$$

Generally, F is negligible for most two-window strips, but may be as large as 2, particularly for three-window strips.

The uncertainty of CR from both algorithms is defined as the observed variance, Equation C-18.

In Equations C-14 and C-16, K was assumed constant in areas where no man-made contamination existed. Note that this definition considers both real variations in K and counting statistics. A three-second sliding interval average was applied to the results of Equation C-11 to increase the data sensitivity for low level distributed sources.

$$\sigma_{CR} = \sqrt{\frac{A + K^2 B}{s}} \quad (C-20)$$

where

s = Number of points used in a sliding interval average (3 seconds).

A significant anomaly was declared when the count rate produced by Equation C-14 or Equation C-16 exceeded a preset multiple (n) of uncertainty ($n\sigma_{CR}$) in Equation C-20. Since the

values of Equation C-14 were normally distributed, various $n\sigma_{CR}$ were chosen to provide a range of sensitivities to accurately evaluate the man-made contamination.

MATRIX METHODS

Due to the photopeak resolution of NaI(Tl) detectors and depending on photopeak location, sources may contribute (by overlapping window or Compton scatter) to the total counts $W_1, W_2, \dots, W_i$ in the source window of interest. When such window interference occurs and the previously described algorithm cannot adequately strip the source of interest, a multiwindow algorithm is employed. Generally, in a composite spectrum with a finite number of source photo peaks (*i.e.*, n), the equation of the measured total counts, W_i , in a spectral window of the *i*th source of interest is written as:

$$W_i = K_{i,1}S_{i,1} + K_{i,2}S_{i,2} + \dots + K_{i,j}S_{i,j} + \dots + K_{i,n}S_{i,n} \quad (C-21)$$

$K_{i,j}$ is the fraction of the *j*th source count, $S_{i,j}$, that contributes to the total window counts, W_i , of the *i*th source of interest in a net spectrum of the contributing source.

Algorithms can be derived for specific sources by writing a system of these equations for the sources and using matrix solutions to extract a desired source activity ($S_{i,j}$, with $i = j$ representing the source activity of interest, $S_{1,1} \dots S_{n,n}$). A system of linear equations can be written as follows:

$$W_1 = K_{1,1}S_{1,1} + K_{1,2}S_{1,2} + \dots + K_{1,j}S_{1,j} + \dots + K_{1,n}S_{1,n} \quad (C-22a)$$

$$W_2 = K_{2,1}S_{2,1} + K_{2,2}S_{2,2} + \dots + K_{2,j}S_{2,j} + \dots + K_{2,n}S_{2,n} \quad (C-22b)$$

$$W_i = K_{i,1}S_{i,1} + K_{i,2}S_{i,2} + \dots + K_{i,j}S_{i,j} + \dots + K_{i,n}S_{i,n} \quad (C-22c)$$

$$W_n = K_{n,1}S_{n,1} + K_{n,2}S_{n,2} + \dots + K_{n,j}S_{n,j} + \dots + K_{n,n}S_{n,n} \quad (C-22d)$$

In order to properly determine the coefficients, $K_{i,j}$, the following are necessary:

1. Net spectra must be obtained for the detected radionuclides, either from the survey area or from calibration sources.
2. Photopeak counts for uncollided gamma rays of detected sources must be obtained from the net spectra using windows described in Equations C-11 and C-12. In some cases, a window width is chosen that eliminates a fraction of the true source counts; it is then necessary to correct these data to the true window data. Table C-2 lists the spectral windows of the sources of interest.

Table C-2. Compensation for Differences Between the Actual Spectral Windows Used During Processing and the True Spectral Window				
Source	Energy (keV)	Energy Window (keV Range Used)^a	Energy Window (keV Range True)^b	F^c
Ar-41	1,293	1,238 - 1,370	1,154 - 1,430	1.20
Bi-214	1,764	1,574 - 1,946	1,586 - 1,946	.97
Co-60	1,253 ^d	1,094 - 1,238	1,046 - 1,466	2.15
Cs-137	662	590 - 734	590 - 734	.95
Pa-234m	1,001	890 - 1,094	890 - 1,106	1.018

^a Energy windows chosen for the algorithm to optimally extract source counts when other sources contribute to this window

^b The desired energy range is based on detector resolution. The resolution of NaI(Tl) detectors is approximately 8% up to 300 keV and 10% for greater energies.

^c Count rate correction for narrow windows

^d The average energy and source window used for cobalt-60 was chosen to characterize the activity of its 1,173- and 1,333-keV gamma rays.

The $K_{i,j}$'s in Equations C-22a through G-22d are ratios determined as follows:

$$K_{i,j} = S_{i,j}/W_i \quad (C-23)$$

As the number of contributing sources increase, the number of $K_{i,j}$'s becomes large. In this case, computerized matrix techniques, specifically Cramer's rule and Laplace expansions, can be employed. The photopeak counts from Item 2 (above) can be used to find the $K_{i,j}$'s using the computerized matrix solution to the following:

$$K_{i,j} = \frac{\begin{vmatrix} S_{1,1} & S_{1,2} & \cdots & W_1 & \cdots & S_{1,n} \\ S_{2,1} & S_{2,2} & \cdots & W_2 & \cdots & S_{2,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ S_{i,1} & S_{i,2} & \cdots & W_i & \cdots & S_{i,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ S_{n,1} & S_{n,2} & \cdots & W_n & \cdots & S_{n,n} \end{vmatrix}}{\begin{vmatrix} S_{1,1} & S_{1,2} & \cdots & S_{1,j} & \cdots & S_{1,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ S_{i,1} & S_{i,2} & \cdots & S_{i,j} & \cdots & S_{i,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ S_{n,1} & S_{n,2} & \cdots & S_{n,j} & \cdots & S_{n,n} \end{vmatrix}} \quad (C-24)$$

Once the $K_{i,j}$'s have been computed for Equations C-22a through C-22d, algorithms can be written for the activity of specific sources as:

$$S_j = \frac{\begin{vmatrix} K_{1,1} & K_{1,2} & \cdots & W_1 & \cdots & K_{1,n} \\ K_{2,1} & K_{2,2} & \cdots & W_2 & \cdots & K_{2,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ K_{i,1} & K_{i,2} & \cdots & W_i & \cdots & K_{i,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ K_{n,1} & K_{n,2} & \cdots & W_n & \cdots & K_{n,n} \end{vmatrix}}{\begin{vmatrix} K_{1,1} & K_{1,2} & \cdots & K_{1,j} & \cdots & K_{1,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ K_{i,1} & K_{i,2} & \cdots & K_{i,j} & \cdots & K_{i,n} \\ \vdots & \vdots & & \vdots & & \vdots \\ K_{n,1} & K_{n,2} & \cdots & K_{n,j} & \cdots & K_{n,n} \end{vmatrix}} \quad (C-25)$$

Where S_j is the activity of the j th source of interest. The solution of the matrix reduces to the form:

$$S_j = k_1 W_{1,j} \pm k_2 W_{2,j} \pm \cdots + k_j W_{j,j} \pm \cdots + k_n W_{n,j} \quad (C-26)$$

where

$$k_i = f(K_{i,j}) \quad (C-27)$$

with the value and sign of the k_n 's determined by the solution of Equation C-25.

In order to completely eliminate the interference of other photopeaks, it may be necessary to use a source window in the matrix solution that does not yield the "true" photopeak count rate. In cases such as this, the "true" photopeak count rate has to be inferred from the count rate generated by the algorithm. A photopeak correction factor that properly adjusts the observed photopeak count rate is defined as:

$$F = S_j \text{ expected} / S_j \text{ generated} \quad (C-28)$$

where

$S_j \text{ expected}$ = Source counts from gamma rays of the j th source of interest observed in a pure spectrum defined as $\bar{A}$ of Equation C-18

$S_j \text{ generated}$ = Source counts extracted from a window chosen so that sensitivity to the source of interest is empirically optimized yet avoids interference by other sources

Table C-2 lists windows chosen to extract the activity of sources detected during the 1987 survey and the factors that adjust the extracted activity to the expected activity. The uncertainty in the counts for the multiwindow extractions is written as:

$$\sigma_{S_j}^2 = S_j + k_1^2 W_{1,j} + k_2^2 W_{2,j} + \cdots + k_j^2 W_{j,j} + \cdots + k_n^2 W_{n,j} \quad (C-29)$$

The right side of the equation is divided by the number of points, s , in the sliding interval average discussed previously in this section.

ALGORITHM OUTPUT

Figure C-5 illustrates gross count rate as a function of time along a flight line. Figure C-6 illustrates the count rate with natural background removed, employing Equation C-11, along the same flight path. Away from the source, the net count rate oscillates about 0, indicating that the value of K does not vary greatly with location; the count rates were nearly normally distributed about 0. Figure C-5 includes a plot of 99% confidence level, three times the uncertainty ($n\sigma_{CR}$, where $n = 3$) described in Equation C-12 as a function of time along the flight line. Minimum detectable activities (MDA) for five sources compared between the 1985 and 1986 SRP surveys are listed in the results section. The data plotted in Figure C-5 are typical of data collected over the Steel Creek Corridor and the Savannah River Floodplain.

FIGURE C-5. GROSS COUNT RATE AS A FUNCTION OF TIME ALONG A FLIGHT LINE

FIGURE C-6. GROSS COUNT RATE WITH THE NATURAL BACKGROUND REMOVED

COUNT RATE CONVERSIONS

With the variety of terrain and moisture conditions found in areas such as the SRS site, it is impossible to characterize the source distribution accurately over the entire surveyed area. Conversion factors listed in Table C-3 were derived to bracket possible source distributions.

The distributions of a man-made source released to the environment can normally be found in the soil with an exponential vertical distribution of concentration. The exponential equation is in the form of $e^{-\alpha z}$, with alpha (α) being the inverse relaxation depth. At one relaxation depth, that volume of soil will contain 63% of the total activity. At a relaxation depth of two, that volume will contain 86% of the total activity, and at a relaxation depth of three, that volume will contain 95% of the total activity.

Table C-3. Factors that Convert Aerially Measured Count Rates to Annual Dose for Uncollided Gamma Rays									
Source	Aerial to Ground			HASL 258 Conversion			Aerial to 1-Meter Dose		
	$\gamma/\text{gm-s}^B/\text{cps}$	$\gamma/\text{cm}^2\text{-s}^B/\text{cps}$		$\mu\text{R/h}/\gamma/\text{gm-s}^B$	$\mu\text{R/h}/\gamma/\text{cm}^2\text{-s}^B$		$\mu\text{R/h}/\text{cps}$		
	Uniform	$\alpha = .1^C$	Surface	Uniform	$\alpha = .1^C$	Surface	Uniform	$\alpha = .1^C$	Surface
Bi-214	.00016	.020	.107	49.0	6.58	34.10	.008	.028	.062
Co-60	.00018	.0029	.060	38.4	1.28	5.90	.0069	.0065	.0104
Cs-137	.00022	.0023	.018	19.6	.68	3.38	.0043	.0041	.0058
Pa-234m	.00019	.0091	.082	41.7	1.38	6.92	.0080	.0075	.0115

^A H. Beck, J. DeCampo, C. Gogolak, Sept. 1972. *In Situ Ge(Li) and NaI(Tl) Gamma Ray Spectrometry*. Report No. HASL 258, TID-4500. Health and Safety Laboratory, U.S. Atomic Energy Commission.

^B s = Time in seconds

^C Conversion for sources exponentially distributed in the soil

Beginning with a vertical concentration distribution:

$$C(z) = C_0 e^{-\alpha z} \quad \gamma/\text{cm}^3 \cdot \text{s} \quad (\text{C-30})$$

where

C_0 = the surface concentration, $\gamma/\text{cm}^3 \cdot \text{s}$

α = exponential concentration factor, cm^{-1}

z = depth in soil, cm

the sensitivity of the pods to a monoenergetic gamma distribution may be written.

$$S_v^0 = \frac{C_0}{\text{cps}} = \frac{1}{X} \quad \gamma/\text{cm}^3 \cdot \text{s} \cdot \text{cps} \quad (\text{C-31})$$

where

$$X = \frac{A_0}{2} \int_0^{\theta=90^\circ} \frac{R(\theta) e^{-\mu_a h \sec \theta} \tan \theta d\theta}{\alpha + \rho \mu_g \sec \theta}$$

A_0 = detector effective area for monoenergetic gamma total absorption in the detector for fluence perpendicular to the ground surface, cm^2

$R(\theta)$ = relative effective area versus the angle, θ , measured from the ground perpendicular to the pod

μ_a = the air mass attenuation coefficient for the gamma energy in question, cm²/g

μ_g = the soil mass attenuation coefficient for the gamma energy in question, cm²/g

h = the detector (aircraft) altitudes in units of air thickness, g/cm²

ρ = soil density, g/cm³

The sensitivity, S_v^0 , may be used to convert a photopeak count rate from the detector or pod output to the soil surface concentration, C_0 .

In practice, the effective area, A_0 , is measured with known point sources of different energies. The angular factor, $R(\theta)$, is measured and approximated with unity, cosine θ , or a linear combination of these to fit an angular response at a given gamma energy.

Other useful conversions may be obtained from S_v^0 . These are:

1. The sensitivity per unit soil surface area

$$S_A = \frac{S_v^0}{\alpha} \quad \gamma/\text{cm}^2 \cdot \text{s} \cdot \text{cps} \quad (\text{C-32})$$

2. The sensitivity per unit soil surface mass

$$S_\rho^0 = \frac{S_v^0}{\rho} \quad \gamma/\text{g} \cdot \text{s} \cdot \text{cps} \quad (\text{C-33})$$

3. The sensitivity to a soil sample of depth z

$$S_\rho^z = S_v^0(1 - e^{-\alpha z})/\rho \alpha z \quad \gamma/\text{g} \cdot \text{s} \cdot \text{cps} \quad (\text{C-34})$$

It was assumed in Table C-3 that no additional shielding existed between the source and the detector array. It was further assumed that distributed sources were spread over an area comparable to several times the survey altitude.

Values were derived for surface, exponential (where the relaxation depth is 10 cm), and uniform volume source distributions. The value of the isoradiation contours in this report are in

annual dose (mrem/yr) with the source distribution in the soil assumed to be a uniform volume distribution. This distribution assumes an infinite half-space geometry; *i.e.*, the source is homogeneous over the surface plane and uniformly vertically distributed in the soil. Source concentration values computed per unit count rate, assuming a uniform surface distribution, will be overestimated in those areas where the distribution is other than that assumed. Values that convert count rate data measured by the airborne detector system to source concentration are a function of the following:

1. Source distribution
2. Detector angular response
3. Soil moisture
4. Soil and air attenuation

Extrapolation of aerially measured count rate data to concentration and exposure is discussed in detail in a separate publication.⁷

Count rate per unit concentration of the extracted man-made sources was further converted to exposure rate per unit count rate, microroentgens per hour per count/sec ($\mu\text{R/h/cps}$) using computations by Beck *et al.*⁶ A time adjustment of 8.76 $\mu\text{R/h/mR/yr}$ (8,760 h/yr and 10^{-3} $\mu\text{R/mR}$) and an adjustment that corrects exposure rate in air to dose rate in tissue were applied to the exposure rate to count rate conversion factors to yield annual dose, millirem per year per count/sec (mrem/yr/cps). The exposure rate in air to tissue dose rate corrections varies slightly with source energy. Tables C-3 and C-4 list the factors required to convert count rates of sources with either a uniform volume distribution, a surface distribution, or an exponential with a relaxation depth of 10 cm to annual dose. The listed sources are those usually detected in areas of the SRS site.

Table C-4. Factors that Convert Exposure Rate to Annual Dose					
Source	mrem per mR ^A	$\mu\text{R/h}^{\text{B}}$ per mrem/yr	mrem/yr/cps		
				Exp.	
			Uniform	$\alpha = .1$	Surface
Bi-214	.954	8.36	.067	.234	.518
Co-60	.956	8.37	.058	.054	.087
Cs-137	.957	8.38	.035	.035	.048
Pa-234m	.956	8.37	.067	.063	.096

^A These values are the product of time adjustment (8.76 $\mu\text{R/h/mR/yr}$) and factors that convert annual exposure in air to annual dose to muscle tissue.

^B *Physical Aspects of Irradiation, Recommendations of the International Commission on Radiological Units and Measurements*, Handbook 85, US Department of Commerce, p. 3, 1964.

APPENDIX D

BACKGROUND RADIATION

Natural background radiation originates from radioactive elements present in the earth (*i.e.*, the terrestrial component), airborne radon, and cosmic rays entering the earth's atmosphere from space. The terrestrial gamma radiation originates primarily from the uranium decay chain, the thorium decay chain, and radioactive potassium. Annual dose equivalents from the terrestrial component of background radiation are as low as 18 to 35 millirems (mrems) (2 to 4 μ R/h) for the Atlantic and Gulf Coastal Plains and as high as 79 to 140 mrems (9 to 16 μ R/h) on the Colorado Plateau.⁷

One member of both the uranium and thorium decay chains is an isotope of radon, a noble gas, which can both diffuse through the soil and travel through the air to other locations. Therefore, the level of airborne radiation due to these radon isotopes and their daughter products at any specific location depends on a variety of factors including meteorological conditions and soil permeability. Typically, airborne radiation contributes between 1% and 10% of the natural background radiation levels.

Cosmic rays interact with the elements of the earth's atmosphere and soil to produce an additional natural source of gamma radiation. The intensity of this radiation source depends on altitude and, to a lesser extent, on latitude. In general, the cosmic ray contribution to the natural background radiation is largest at high altitudes and high latitudes. Annual dose equivalents in the United States due to cosmic rays range from about 26 mrems (3 μ R/h) in southern Florida to about twice that value in Wyoming.

External radiation may also be received from radioactive elements in building materials. Naturally occurring radioactive materials can be concentrated in a particular location due to building or road construction. In structures made of stone, concrete, or brick, the radiation dose is generally higher than in nearby wooden buildings. Thus, radiation doses due to background sources are highly variable and depend upon a number of factors.

APPENDIX E

EG&G/EM GAMMA SURVEYS RELATED TO SRS ACTIVITIES

1. Boyns, P.K. May 1975. *Aerial Radiological Survey of the Savannah River Plant (Aiken, South Carolina)*, Date of Survey: June 1974. Report No. EGG-1183-1665. Las Vegas, NV: EG&G/EM.
2. Boyns, P.K., and D.B. Smith. July 1982. *An Aerial Radiological Survey of the Savannah River Plant and Surrounding Area, Aiken, South Carolina*, Date of Survey: June 1979. Report No. EGG-1183-1816. Las Vegas, NV: EG&G/EM.
3. Boyns, P.K. September 1983. *An Aerial Radiological Survey of the Beaufort-Jasper Water Treatment Plant and Canal, South Carolina*, Date of Survey: March 1983. Report No. DOE/ONS-8311. Las Vegas, NV: EG&G/EM.
4. Boyns, P.K. October 1983. *An Aerial Radiological Survey of the Cherokee Hill Water Treatment Plant, Georgia*, Date of Survey: March 1983. Report No. DOE/ONS-8315. Las Vegas, NV: EG&G/EM.
5. Boyns, P.K. December 1984. *An Aerial Radiological Survey of the Savannah River Floodplain*, Date of Survey: July-October 1983. Report No. EGG-10282-1049. Las Vegas, NV: EG&G/EM.
6. Feimster, E.L. October 1987. *An Aerial Radiological Survey of the Beaufort-Jasper Water Treatment Plant, Beaufort, South Carolina*, Date of Survey: July-August 1986. Report No. DOE(ONS-SRL)-8704. Las Vegas, NV: EG&G/EM.
7. Feimster, E.L. October 1987. *An Aerial Radiological Survey of the Cherokee Hill Water Treatment Plant, Port Wentworth, Georgia*, Date of Survey: August 1986. Report No. DOE(ONS-SRL)-8706. Las Vegas, NV: EG&G/EM.
8. Jobst, J.E. May 1987. *An Aerial Radiological Survey of the Savannah River Plant Drainage Basins*, Date of Survey: August 1982. Report No. DOE/ONS-8312, Rev. 1. Las Vegas, NV: EG&G/EM.
9. Jobst, J.E. September 1988. *An Aerial Radiological Survey of L Lake and Steel Creek, Savannah River Plant*, Date of Survey: August 1985. Report No. DOE(ONS-SRL)-8611. Las Vegas, NV: EG&G/EM.
10. Feimster, E.L. *An Aerial Radiological Survey of L Lake and Steel Creek, Savannah River Plant*, Date of Survey: July 1986. Report No. EGG-10617-1146. Las Vegas, NV: EG&G/EM.

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1. Boyns, P.K. May 1975. *Aerial Radiological Survey of the Savannah River Plant (Aiken, South Carolina)*. Date of Survey: June 1974. Report No. EGG-1183-1665. Las Vegas, NV: EG&G/EM
2. Boyns, P.K., and D.B. Smith. July 1982. *An Aerial Radiological Survey of the Savannah River Plant and Surrounding Area, Aiken, South Carolina*. Date of Survey: June 1979. Report No. EGG-1183-1816. Las Vegas, NV: EG&G/EM
3. Jobst, J.E. May 1987. *An Aerial Radiological Survey of the Savannah River Plant Drainage Basins*. Date of Survey: August 1982. Report No. DOE/ONS-8312, Rev. 1. Las Vegas, NV: EG&G/EM
4. Boyns, P.K. December 1984. *An Aerial Radiological Survey of the Savannah River Floodplain*. Date of Survey: July-October 1983. Report No. EGG-10282-1049. Las Vegas, NV: EG&G/EM
5. Boyns, P.K. July 1976. *The Aerial Radiological Measuring System (ARMS): System, Procedures and Sensitivity*. Report No. EGG-1183-1691. Las Vegas, NV: EG&G/EM.
6. Beck, H.L., *et al.* September 1972. *In Situ Ge(Li) and NaI(Tl) Gamma Ray Spectrometry*. Report No. HASL-258, TID-4500. New York, NY: US AEC Health and Safety Laboratory.
7. Klement, A.W., *et al.* August 1972. *Estimate of Ionizing Radiation Doses in the United States 1960-2000*. U.S. EPA Report No. ORD/CD72-1. Washington, D.C.: Environmental Protection Agency.

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