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RADIOLOGICAL ASSESSMENT REPORT
FOR THE
LANSLOWNE PROPERTY
105-107 EAST STRATFORD AVENUE
LANSLOWNE, PENNSYLVANIA

October-December 1984

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ABSTRACT AND EXECUTIVE SUMMARY

During the early part of this century, a University of Pennsylvania physics professor engaged in commercial production of radium sources for medical use; he conducted part of this activity in his home at 105 East Stratford Avenue in the Philadelphia suburb of Lansdowne, Pennsylvania. The work continued at this location until some time in the early 1940s.

The professor's residence comprised the western half of a duplex structure located in the approximate center of a 155-ft by 155-ft lot. As a result of the professor's radium-separation activities, the residence and surrounding land area became contaminated. Additionally, the adjoining residence at 107 East Stratford became contaminated, albeit to a lesser extent.

During May 1964, the Pennsylvania Department of Health and the U.S. Public Health Service conducted an initial decontamination of the 105 East Stratford premises. Some contaminated articles were removed and transported to a radioactive waste disposal site outside Pennsylvania. Accessible residual radioactivity was relatively stabilized with a heavy coat of paint.

In 1984, the Pennsylvania Department of Environmental Resources suggested that the U.S. Environmental Protection Agency (EPA) might wish to include the property at 105 East Stratford on its list of properties to be assessed for health hazards. Pursuant to this suggestion, the EPA requested the Argonne National Laboratory (ANL) Occupational Health and Safety Department (OHS) Health Physics Section (HP) to perform a radiological characterization of the site in order to determine the levels of contamination present and also to estimate the effort required to release the site for unrestricted use. The ANL-OHS/HP Radiological Survey Group (RSG) performed this radiological characterization during the period October-December 1984. At that time, all furnishings and personal items were removed from both residences (105 and 107 East Stratford) and surveyed for radioactive contamination. Subsequently, the entire site was subjected to a detailed radiological characterization, the results of which are presented in this report.

All the furniture removed from these premises was surveyed in its entirety. A significant number of items were found to be contaminated.

Attempts to clean these items rarely succeeded. Contaminated items were labeled and stored for future disposition.

Areas with elevated levels of radioactivity were found throughout both residences, as well as on the surrounding property. Contamination was also found in the garage behind the 105 East structure. The 105 East residence had substantially more contamination than the 107 East residence, as was expected. The chimneys, particularly the rear chimney, from the 105 East residence had extensive contamination, indicating that contaminated materials may have been burned at the site. The high background radiation emanating from this residence made it difficult to establish the relatively lower levels of contamination in the 107 East residence.

The property surrounding the 105 East residence was found to have substantial contamination scattered throughout, with the highest level occurring in the backyard. The soil surface contamination seemed to drop markedly (but not entirely) at the property lines. The property surrounding 107 East was found to be less contaminated, although the background radiation emanating from the adjoining area made it difficult to establish the degree of surface or near-surface contamination from surface surveys.

Subsurface investigation of the soil surrounding the structure indicated that radium contamination was widespread and extended to a depth of eight feet at some locations. There was evidence that some of this contamination extended onto adjoining properties and may have been transported off the site via subsurface migration. Additionally, analysis of samples from access points in the residence sewer system effluent established that the system was contaminated.

The radiological assessment was performed by the following Health Physics personnel of the Occupational Health and Safety Department, Argonne National Laboratory, Argonne, Illinois: W. H. Smith, C. M. Sholeen, K. F. Flynn, J. D. Thereon, and D. W. Reilly.

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INTRODUCTION

During the early part of this century, a University of Pennsylvania physics professor engaged in the commercial production of radium sources for medical use; part of this activity was reportedly conducted in his home, located at 105 East Stratford Avenue in Lansdowne, Pennsylvania, a Philadelphia suburb (see Figs. 1 and 2). This work continued at this location until some time in the early 1940s.

The professor's residence comprised the western half of a duplex structure (see Fig. 3) located in the approximate center of a 155-ft by 155-ft lot. As a result of the professor's radium separation activities, the residence and surrounding land area became contaminated. Additionally, the adjoining residence at 107 East Stratford became contaminated, albeit to a lesser extent.

During May 1964, the Pennsylvania Department of Health and the U.S. Public Health Service undertook an initial decontamination of the 105 East Stratford premises. Contaminated articles were removed and transported to a radioactive waste disposal site outside Pennsylvania. Residual radioactivity was relatively stabilized with a heavy coat of paint.

During 1984, the Pennsylvania Department of Environmental Resources suggested that the U.S. Environmental Protection Agency (EPA) might wish to include the property at 105 East Stratford Avenue on its list of properties to be assessed for health hazards. Pursuant to this suggestion, the EPA requested the Argonne National Laboratory (ANL) Occupational Health and Safety Department (OHS) Health Physics Section (HP) to perform a radiological characterization of the site in order to establish the levels of the contamination present and also to estimate the effort required to release the site for unrestricted use. The ANL-OHS/HP Radiological Survey Group (RSG) performed the radiological characterization during the period October-

December 1984. At that time, all furnishings and personal items were removed from both residences (105 East and 107 East) and surveyed for radioactive contamination. Subsequently, the entire site was subjected to a detailed radiological characterization, the results of which are presented here.

A photograph of the front view of the Lansdowne structure is shown in Figure 4. A rear view photograph is shown in Figure 5. The west side of the property is shown in Figure 6 and the east side of the property is shown in Figure 7. Interior views of the structure are shown in Figure 8 (first floor of 105 East looking from living room through dining room to kitchen), Figure 9 (second floor of 105 East, center bedroom) and Figure 10 (basement room of 105 East where the original radium work was reportedly conducted). As indicated from these photographs, the construction was standard for that era; with oak floors, plaster walls, plaster ceilings (subsequently covered in some areas with acoustical tile), heavy woodwork and central heating via a system of hot water radiators.

RADIOLOGICAL SURVEY PROCEDURES

GENERAL

The comprehensive radiological assessment of the Stratford Avenue site included interior and exterior surveys and collection and analysis of air, soil, and sewer system samples. The primary activity was the direct survey of all interior floors, walls, and overheads with portable instruments. Additionally, selected exterior surfaces (e.g., accessible roof and chimney areas) and the adjacent land surfaces were surveyed with portable instruments. Smear surveys were performed at randomly selected locations on all interior surfaces, as well as on areas where background radiation and/or radioactivity was higher than expected. Air samples were collected on each level of each residence, as well as in the backyard, to determine concentrations of radon daughters, thoron daughters, and airborne radioactive particulate material and to detect the presence of actinon daughters. Additionally, radon concentration was monitored at each of the 16 interior sampling locations for a 24-hour period. The ambient penetrating radiation field on each level of both residences was monitored with a pressurized ion

chamber for a 24-hour period. Soil samples were collected with a split-spoon sampler in one-foot increments at 11 locations on the property. Sampling depths ranged from 3 to 12 ft. The ensuing bore holes were logged with a sodium iodide gamma detector to ascertain any anomalies in the ambient gamma radiation levels. Environmental soil corings and offsite background soil corings were also taken to a 1-ft depth. Water and sludge samples were collected from two locations in the effluent sewer lines. Details of these procedures and the instruments used are given below and in Appendix 1. The appendices include generic information not only on instruments and procedures that were required for this particular survey, but also on other instruments and procedures that were available, if needed.

INSTRUMENTATION

Three types of portable survey instruments were used to conduct the direct radiological surveys: (1) gas-flow proportional detectors with window areas of 100 cm² and 325 cm² (using Eberline PAC-4G-3 electronics) were used to monitor for alpha and/or beta-gamma radiation; (2) NaI crystal detectors, 5 cm (2 in)* in diameter by 2 mm thick (Eberline PG-2 with Eberline PRM-5-3 electronics), were used to monitor for low-energy x-ray and gamma radiation; and (3) NaI crystal detectors, measuring 2.5 cm (1 in) in diameter by 2.5 cm (1 in) thick (Eberline PRM-7 μ R meter) and calibrated with a ²²⁶Ra standard source, were used to measure the ambient external penetrating radiation field in units of μ R/h. All floors, walls and overheads were surveyed in their entirety with the first two instruments. A general survey of the entire facility was performed with the third instrument to establish the general radiation field in units of μ R/h. The ambient penetrating radiation field was monitored continuously for a 24-hour period on each level of both residences using a Reuter-Stokes (RSS-111) pressurized ionization chamber calibrated with an NBS-traceable ⁶⁰Co source. These instruments and associated calibration procedures are detailed in Appendices 1 and 2.

Contaminants were identified in-situ or from samples by gamma-spectral analyses. These analyses were performed with a sodium iodide (NaI) or

*All measurements were originally taken using the English system. The Systems International (SI) units are to the nearest approximation.

hyperpure germanium (HPGe) detector coupled to a multichannel analyzer. This instrumentation is also described in Appendix 1.

SMEAR SURVEYS

Dry smears were taken at representative locations throughout each residence with 4.25-cm-diameter filter papers (Whatman #1). A standard smear sample is obtained by applying moderate pressure with the tips of the first two fingers to the back of the filter paper and wiping the surface over an area of approximately 900 cm². Smears were taken on original structures and components such as walls, floors, pipes, and vents. A smear of 100 cm² was taken from any area or object indicated by a portable survey instrument to have a radiation level notably above expected backgrounds. A smear of 100 cm² was also taken if the surface was extremely dusty.

To expedite the processing of the numerous smear samples collected, two counting techniques were employed with two types of counters. A large area, thin-window, gas-flow proportional counter, sensitive to alpha and/or beta-gamma radiation, was used to make an initial count on groups of smears. For confirmatory counts on individual smears noted to be above the expected background level, a Nuclear Measurement Corporation Model PC-5 or 3A, internal gas-flow proportional counter (PC counter) with a thin aluminized Mylar window (referred to as Mylar spun top) was used.

Initial counts were made with the large-area counter on groups of ten smears at a time. Smears from any group indicating a reading above the instrument background were then counted individually in the PC counter. In addition, at least two smears randomly selected from each group of ten were counted in the PC counter. All smears of the areas or objects with noted elevated direct survey readings were counted individually in the PC counter. More detailed descriptions of the counters and the counting and calibration techniques are presented in Appendix 1.

AIR SAMPLES

Air-particulate samples were collected using a commercial vacuum cleaner modified by ANL to pull air through a filter medium (Hollingsworth-Vose HV-70 or LB-5211).

A total volume of 26.7 m³ of air was sampled at a flow rate of 40 m³/h. A 10% portion (5 cm in diameter) of the filter medium was removed after collection and counted for both alpha and beta-gamma activity in the PC counter. Concentrations of radon (²²²Rn) daughters, thoron (²²⁰Rn) daughters, and the presence of any long-lived airborne radionuclides were determined based on the results of several counts of each sample at specified intervals.

Air-particulate samples were also collected on Millipore membrane filter medium for 90 minutes at a flow rate of approximately 1 m³/h. A portion of each filter sample was used for alpha spectral analysis to determine the actinon (²¹⁹Rn) daughter concentration. Additionally, the radon concentration and the "Working Level" were monitored for a 24-hour period at each of these 16 sampling locations. An Eberline Radon Gas Monitor (RGM-2) and an ANL Environmental Working Level Monitor (EWLM-II) were used to ascertain the variability of these quantities on a daily basis.

Details of air-sampling techniques and associated calculations are given in Appendix 3.

SEWER SAMPLES

The residence sanitary sewer system was sampled at two effluent locations exterior to the site. These samples were taken at the outfall immediately adjacent to the property and at the confluence of the local sewer line with the main city sewer line (see Fig. 11). Both sludge and water samples were extracted from each location.

The sludge and water samples were sent to the ANL Analytical Chemistry Laboratory for analysis. The sludge samples were filtered and dried. Both the filtrate and the dried residue were analyzed. The suspended solids in the water samples were filtered and the filtrate was evaporated to ascertain the dissolved solids content.

Each fraction of the water sample and the sludge solids were analyzed for uranium (uranium fluorometric) and ²²⁶Ra and ²³²Th decay chains (gamma spectrometric). Each sample was assigned three-part identification numbers; (1) the site number (19), (2) the sample type (SS for sewer sludge and SW for sewer water), and (3) a consecutive number.

SOIL BORINGS

A subsurface investigation of the area surrounding the duplex structure was conducted using soil-boring techniques. A total of 11 bore holes were drilled to depths up to 12 ft. Split-spoon (1½-in inside diameter) samples were taken from these bore holes at continuous 1-ft increments. Each bore hole was logged using a 2 x 2-in NaI(Tl) detector in conjunction with a Nuclear Data (ND-100) multichannel analyzer, a teletype printer as the hard copy readout, and punched paper tape storage. Readings were taken at grade level and at 2-ft increments thereafter. The bore-hole samples also were identified by a three-part number: (1) the site number (19), (2) the sequential bore hole number preceded by an S designating soil (e.g., S1), and (3) a number designating the maximum depth of the sample in feet (e.g., 2.0 equates to the sample taken from 1.0 to 2.0 ft below the surface). The 11 bore holes were identified as 19-S6 through 19-S16.

SOIL CORINGS

In addition to the soil borings, four environmental coring samples were taken from the site and two background corings were taken from selected locations in the Lansdowne area (see Fig. 11). These samples (4-in-diameter by 12-in-deep corings) were collected using a 4-in-diameter, 6-in-long right-circular-cylinder cutting tool, commonly used to cut holes on golf course greens. Each soil core was taken in four segments for analysis. Starting from the surface, three 2-in segments were cut, bagged, and marked A, B, and C, respectively; the final 6-in segment was marked D. The segmented coring technique was used to determine if contaminant migration might have occurred, to reduce the dilution of lower-level soil with the upper-level segments with respect to the surface deposition of the contaminants (or vice versa), and to reveal if any overburden or backfill had been added. The background samples were collected in order to establish the expected background concentrations for the contaminant radionuclides in this area. The four environmental corings were identified as 19-S2 through 19-S5. The background corings were identified as 19-SB21 and 19-SB22.

In preparation for analysis, each soil sample was weighed in its "as collected" state, dried for approximately 48 hours at 80°C, and then

reweighed to determine dry weight. Each sample was then put into a mill jar (8.7 l) and milled for up to two hours. At no time were any rocks in these samples crushed, ground or pulverized, since this would act to dilute, and hence lower the reported concentrations of deposited radioactive material. After sufficient milling, the sample material was sieved. Each fraction (rocks and dross vs. fines) was bagged and weighed separately (see Fig. 12). Additional details of sample processing are given in Appendix 4.

The soil samples were analyzed at ANL. Weighed aliquots of the milled material from the soil samples were loaded into screwtop plastic containers; aliquots of 100 g, if available, were prepared for gamma-spectral analysis, and aliquots of 5 g were utilized for radiochemical (fluorometric) analysis. Every effort was made during sample preparation to prevent cross-contamination. Soil samples suspected of containing elevated levels of radioactivity were processed in equipment separate from soil samples thought to contain background or near background levels. All processing equipment was scrubbed and air dried before introduction of the next sample.

RADIOLOGICAL SURVEY RESULTS

GENERAL

All the furniture designated for removal from the premises for further use was surveyed, and a significant number of items were found to be contaminated. Attempts to clean these items rarely succeeded. Contaminated items were appropriately labeled and stored for future disposition.

Areas with elevated levels of radioactivity were found throughout both residences, as well as throughout the surrounding property. Contamination was also found in the garage behind 105 East. As expected, the 105 East residence had substantially more contamination than did the 107 East residence. The chimneys, particularly the rear chimney, from the 105 East residence had extensive contamination, indicating that contaminated materials may have been burned at the site. The high background radiation emanating from this residence made it difficult to establish quantitatively the relatively lower levels of contamination in the 107 East residence.

The property surrounding the 105 East residence had substantial contamination scattered throughout, with the highest level occurring in the backyard. The surface contamination levels seemed to drop markedly at the property lines. The property surrounding 107 East was less contaminated, although the background emanating from the adjoining area made it difficult to establish quantitatively the degree of contamination from surface surveys.

Subsurface investigation of the soil surrounding the structure indicated that radium contamination was widespread and extended to a depth of 8 ft at one location. There was evidence that some of this contamination extended onto adjoining properties and might have been transported offsite via subsurface migration. Additionally, analysis of samples collected from access points in the sewer system revealed the presence of contamination within the sewer system. These samples were taken at the outfall immediately adjacent to the property as well as at the confluence of the local sewer line with the main city sewer line (see Fig. 11).

FURNITURE SURVEY

- 105 East - All the furniture and personal items from this residence were removed to the street, where the background was low, and surveyed for contamination. Items determined to be free of contamination were transported to a storage facility. Contaminated items were returned to the house for disposition. Thirteen items and three ledgers were found contaminated (levels up to 100,000 dis/min-100 cm² beta-gamma). These items are listed in Table 1.
- 107 East - All the furniture and personal items from this residence were removed to a separate location on Ardmore Street in Lansdowne, where they were subjected to instrument and smear surveys. Items determined to be free from contamination were transferred to various locations identified by the owner. Contaminated items were so identified and left for subsequent decontamination or were returned to the 107 East residence. Forty-four items (including nine books) were found to be contaminated. These items also are listed in Table 1. The contamination on the items that were successfully cleaned appeared to

be in the furniture polish and accumulated dust. The contamination that was not removed was, no doubt, more deeply embedded.

INTERIOR SURVEY

Instrument and Smear Survey

The measurements recorded with the gas-flow proportional-counter survey instruments were converted to surface contamination measurements according to the following method (also see Appendix 2). For gross readings taken in the beta mode, the alpha contribution was subtracted to determine the net beta-gamma count rate. The net count rate was then converted to disintegrations per minute (dis/min) by equating to ^{226}Ra and daughters (see Appendix 2) and normalized to a surface area of 100 cm^2 . Readings in the alpha mode also were converted to dis/min- 100 cm^2 as equivalent to ^{226}Ra and daughters. Two survey instruments were used. The first, identified as the floor monitor (FM), had a 325-cm^2 probe. The second, identified as a hand probe (HP), had a 100-cm^2 probe. Since instrument calibrations were to infinitely-thin, flat-plate standards, all reported readings should be regarded as minimal values; no corrections were made for absorption by surface media.

Low-energy x-ray and gamma exposures were measured with the PRM-5-3 instrument. The results are reported in counts per minute (cts/min) and include the instrument background. The μR meter exposure rate measurements also include the instrument backgrounds.

Smear samples were counted for both alpha and beta-gamma activity, and the net count rates are converted to dis/min- 100 cm^2 after subtracting the appropriate background.

An integrated background measurement of the ambient radiation field at select interior locations was taken with a pressurized ion chamber.

The instrument survey data and the smear results were reviewed with respect to the NRC's "Guidelines for Decontamination of Facilities and Equipment Prior To Release for Unrestricted Use or Termination of Licenses For By-Product, Source or Special Nuclear Material;" The Surgeon General's Guidelines as included in 10 CFR Part 172 "Grand

Junction Remedial Action Criteria"; and 40 CFR 192 "Health and Environmental Protection Standards for Uranium Mill Tailings" (see Appendix 6).

The primary instrument for determining the interior surface contamination was the PAC-4G-3. This instrument has the greatest sensitivity for identifying "hot spots" in the presence of the general background. "Hot spot" identifications were based exclusively on this instrument (see Table 3). Most of these determinations were based on the beta-gamma measurements. Alpha radiation was seldom observed indicating that the contamination is embedded in the structural material or covered.

Survey Results for 105 East

All interior levels of the 105 East residence were found to be contaminated; this included the first, second, and third floors, the basement, and an attic crawl space. The interior radiation levels, as determined by the instrument survey, are listed on a room-by-room basis in Table 2. Radiation levels at specific "hot spots" are tabulated in Table 3, and the locations of these hot spots are shown in Figures 13 (first floor), 14 (second floor), 15 (third floor and attic crawl space), and 16 (basement). The first floor was extensively contaminated. Based on PRM-7 (μ R meter) measurements, the general background varied between 80 μ R/h and 300 μ R/h. Thirty-five locations were identified as specific hot spots on this level of the structure. Radiation levels ranged to in excess of 200,000 dis/min-100 cm^2 beta-gamma based on PAC-4G-3 measurements and 300,000 cts/min gamma based on PRM-5-3 measurements. No loose contamination was detected on any of the 42 smears taken on this level.

The second floor also exhibited significant levels of contamination. The general background on the second floor, based on PRM-7 (μ R meter) measurements, ranged between 100 μ R/h, and 300 μ R/h. Seventeen locations were identified as specific hot spots on this level. Radiation levels ranged as high as 200,000 dis/min-100 cm^2 beta-gamma based on PAC-4G-3 measurements and 150,000 cts/min gamma

based on PRM-5-3 measurements. No loose contamination was detected on any of the 30 smears taken on this level.

The general background radiation on the third floor, based on PRM-7 (μ R meter) measurements, ranged between 30 μ R/h and 100 μ R/h. Nine locations were identified as hot spots on this floor. Radiation levels ranged as high as 900,000 dis/min-100 cm^2 beta-gamma and 200,000 dis/min-100 cm^2 alpha as determined by PAC-4G-3 measurements and 70,000 cts/min gamma as determined by PRM-5-3 measurements.

Cursory measurements made at access points to an attic crawl space above the third floor indicated the presence of contamination. Levels up to 80 μ R/h, 20,000 dis/min-100 cm^2 beta-gamma, and 10,000 cts/min gamma were observed.

The basement of the 105 East residence had been identified as the center of activity for the radium-processing effort. The general background in this area as determined by PRM-7 (μ R meter) measurements ranged from 100 μ R/h to 320 μ R/h. Seventeen locations in the basement were identified as hot spots. Radiation levels at these locations ranged as high as 200,000 dis/min-100 cm^2 beta-gamma based on PAC-4G-3 measurements and 200,000 cts/min gamma based on PRM-5-3 measurements. No loose contamination was detected on any of the 21 smears taken on this level.

An instrument survey of accessible exterior surfaces of this structure also was conducted. This included the roof of the porches (both front and rear), the chimneys, and exterior walls adjacent to "hot spots" on the first floor. Contamination was identified on the chimney at the rear (north end) of the house (up to 100,000 dis/min-100 cm^2 beta-gamma and 50,000 cts/min gamma), as well as on the adjacent vent stack (up to 10,000 dis/min-100 cm^2 beta-gamma and 50,000 cts/min gamma). These results are listed in Tables 2 and 3, and the location of this chimney is shown in Figure 15.

The garage to the rear (north) of the 105 East residence (see Fig. 3) was extensively contaminated. Specific hot spots were difficult to identify because of the poor condition of the structure. Radiation levels up to 20,000 dis/min-100 cm^2 beta-gamma and 50,000 cts/min gamma were observed. These results are listed in Table 2.

Survey Results for 107 East

The 107 East residence was contaminated, as expected, to a significantly lesser extent than was the adjoining residence at 105 East. The radiation levels in 107 East, as determined by the instrument surveys, are listed in Table 2. Locations of specific hot spots are shown in Figures 17 (first floor), 18 (second floor), 19 (third floor), and 20 (basement). Radiation levels at these locations are tabulated in Table 3.

The first floor had a general background based on PRM-7 (μ R meter) measurements of 15 μ R/h to 40 μ R/h, except for the back porch where the level rose to 70 μ R/h as the common wall with 105 East was approached. Nine hot spots were located on this floor, with radiation levels measuring up to 300,000 dis/min-100 cm^2 beta-gamma and 8,000 dis/min-100 cm^2 alpha based on PAC-4G-3 measurement and 25,000 cts/min gamma based on PRM-5-3 measurements. No loose contamination was identified on any of the 27 smears taken on this level.

The second floor of the 107 East residence had a general background, based on PRM-7 (μ R meter) measurements, ranging from 15 μ R/h to 30 μ R/h. Three hot spots were located on this floor. Radiation levels at these locations measured up to 20,000 dis/min-100 cm^2 beta-gamma and 15,000 cts/min gamma. No loose contamination was identified on any of the 38 smears taken on this level.

The third floor of had a general background of 20 μ R/h to 30 μ R/h, except for the north hall, where the level rose to 50 μ R/h in the vicinity of the common wall with 105 East. Three hot spots were located on this floor; radiation levels measured up to 24,000 dis/min-100 cm^2 beta-gamma and 5,000 dis/min-100 cm^2 alpha with gamma levels up to 10,000 cts/min. No loose contamination was found on any of the 20 smears taken on this level. There was no accessible attic crawl space in this residence.

The basement of the 107 East residence had a general background of 25 μ R/h to 60 μ R/h except for under the rear (north) porch (a storage area), where the level rose to 240 μ R/h. Five hot spots were identified in the basement, with radiation levels measuring up to 100,000 dis/min-100 cm^2 beta-gamma and 40,000 dis/min-100 cm^2 alpha based on

PAC-4G-3 measurements and up to 20,000 cts/min gamma based on PRM-5-3 measurements. Even higher levels were found in the area under the rear porch exterior to the basement. Three of the 35 smears taken in the basement indicated the presence of loose contamination.

An instrument survey of some accessible exterior surfaces of this structure was also conducted. This included the roof of the porches (both front and rear), and the chimneys. No specific "hot spots" were identified. The results are delineated in Table 2.

The garage to the rear (north) of the 107 East residence (see Fig. 3) was also surveyed. No specific contamination was identified in this structure. The radiation levels observed are tabulated in Table 2. Some indeterminate fraction of this radiation emanates from the backyard of the adjoining residence.

AMBIENT RADIATION LEVELS

The ambient external penetrating radiation field was determined on each level of each residence. Measurements were made using a Reuter Stokes (RSS-111) pressurized ionization chamber. The locations at which the measurements were taken are indicated in Figures 13 through 20. The results, as tabulated in Table 4, indicated that the highest level measured was 183 $\mu\text{R}/\text{h}$ on the first floor of the 105 East residence. The levels observed in the 107 East residence were much lower, ranging from 21 $\mu\text{R}/\text{h}$ to 38 $\mu\text{R}/\text{h}$. All measurements were made both differentially and integrally for approximately 24-hour periods. No significant deviations as a function of time were observed. Typical differential radiation levels as a function of time are portrayed in Figure 26. The measurements with the portable μR meter and the pressurized ion chamber are in substantial agreement, with the possible exception of the 105 East basement.

Radiation levels in excess of the 20 $\mu\text{R}/\text{h}$ above-background standard set in 40 CFR 192 for occupied buildings (see Appendix 6) were found throughout the structure.

AIR SAMPLES

Air samples were collected on each level of each residence. The locations at which the air samples were collected are indicated in Figures 13 through 20. The radon (^{222}Rn) and thoron (^{220}Rn) concentrations and the calculated milliWorking Levels (mWL) are presented in Table 5. The detailed calculations used in evaluating the air samples are given in Appendix 3. No long-lived radioactive particulate was found in any of the air samples.

A second air sample was collected at each air sampling location on Millipore membrane filter paper. Alpha spectroscopy was performed on these samples to determine the presence of any actinon (^{219}Rn) activity in the air (see Appendix 3). No actinon was found in any of these samples.

The air samples revealed radon daughter Working Levels ranging from 21 mWL to 309 mWL inside the structure. These levels are well above the 20 mWL limit recommended in 40 CFR 192, "Health and Environmental Protection Standards for Uranium Mill Tailings," as the maximum annual average allowable.

The radon concentration (^{222}Rn pCi/l) and the radon daughter Working Level showed significant fluctuations as a function of time. These results were based on measurements made using an Eberline Radon Gas Monitor (RGM-2) to establish the radon concentrations and an ANL Environmental Working Level Monitor (EWLM-II) to establish the radon daughter Working Levels. In general, these parameters tended to rise, as expected, during periods when the residence was closed and access was restricted. Minimum values were observed when frequent access was permitted and, hence, more rapid exchange between the indoor and outdoor air was sustained. Minimum and maximum values for these parameters typically varied by a factor of two to three. Examples of this effect are shown in Figures 21 through 23.

The data illustrated in Figure 21 represent a situation wherein the RGM-2 and the EWLM-2 instruments were put into operation at 11:00 A.M. on October 29 and the residence was secured. The radon (and concomitant Working Level) increased by about a factor of three during the ensuing three-hour period and then leveled off. At about 16:30, the security was violated and the radon level dropped over about a three-hour period, returning to the unsecured level, where it remained throughout the night. Figure 22 represents an unsecured situation (i.e., an open window) for a

24-hour period. Figure 23 illustrates a situation similar to Figure 21, but on the second floor of the residence where the radon concentration was somewhat lower. The hour-by-hour results of the RGM-2 and the EWLM-2 readings are in substantial agreement considering the uncertainties associated with these measurements. The results of the three methods used for these measurements, when compared at the same time (see Figs. 21 through 23), agree within the errors associated with the individual measurements (see Appendix 3).

EXTERIOR SURVEY

The land surface surrounding the Stratford Avenue structure was surveyed to the lot lines with three survey instruments (PAC-4G-3, PRM-5-3 and PRM-7). The general background based on PRM-7 (μ R meter) measurements varied between 10 μ R/h and 500 μ R/h. Surface surveys indicated the backyard of the 105 East residence was the area most severely contaminated. The radiation levels, as determined by the instrument surveys, are delineated on a section basis in Table 6. The exterior area was divided into 19 sections, as shown in Figure 24. Twenty-four locations were identified as specific hot spots. These spots and the radiation levels are tabulated in Table 7. Radiation levels ranged as high as 100,000 dis/min-100 cm^2 beta-gamma based on PAC-4G-3 measurements and in excess of 500,000 cts/min gamma based on PRM-5-3 measurements. The primary instrument for identifying the exterior contamination was the PRM-5-3. This instrument has the greatest sensitivity for detecting subsurface sources of radiation. Exterior hot spot identifications were based exclusively on this instrument (see Table 7).

Air samples were taken in the backyard of the 105 East residence to establish the concentration of airborne contamination in the exterior environs. The levels were low (i.e., 3 milliWorking Level's-radon daughters) as expected, with no long-lived radioactive particulate nor any actinon detected. These results are included in Table 5. The location of each sample is identified in Figure 24.

EFFLUENT SAMPLES

Sewer water samples and a sewer sludge sample were collected from each of two locations offsite (see Fig. 11). Samples were taken from the effluent of the residence sanitary system into the city sewer and from the confluence of the Stratford Avenue sewer line and the main sewer line along Union Avenue. The results of the analyses of these samples as given in Table 8, indicated the presence of contamination.

The effluent samples were identified according to sewer sludge (SS) and sewer water (SW) and within each sample, according to suspended solids (i.e., filterable material) and dissolved solids (i.e., material remaining after evaporation of clear aqueous).

A significant level of radium decay chain contamination (i.e., 40 pCi/g) was found in the solid material (both sludge and suspended solids) in the residence effluent (see Table 8). This was not unexpected because of the high levels of radium decay chain contamination found in the residence. These results confirm the evaluation that the site sewer system is contaminated.

A somewhat elevated level of uranium (i.e., 18 pCi/g - see Table 8) also was found in the suspended solids from the water sample taken at the main sewer line confluence (see Fig. 11). This sample, however, was extremely small (0.15 g), and the radium decay chain level was below detectable limits. Hence, these results were not deemed significant with respect to contamination originating from the Lansdowne residence. Inorganic fertilizers used to fertilize lawns frequently contain elevated levels of uranium carried over from the phosphate ore used to manufacture the fertilizer. These fertilizers, being washed into the sewer system, frequently result in anomalies of this magnitude. While this contamination is deemed unrelated to the subject property, these results cannot be used to rule out the possibility of radium contamination in the sewers.

SOIL SAMPLES

An initial composited surface soil sample (19-S1) was formed from material collected at five locations at the site (see Fig. 25). This sample was well mixed and subjected to detailed analyses to establish the specific

contaminating radioisotopes present in the soil. The results of these analyses, as shown in Tables 9 and 11, indicated the presence of abnormal concentrations of ^{226}Ra (and daughters), ^{230}Th , and ^{227}Ac . The absence of ^{239}Pu and normal concentrations of uranium was established.

Soil Corings

Environmental soil samples (soil corings) were taken from four locations on the site. The results of the analysis of these corings identified as 19-S2 through 19-S5 are presented in Table 9. The location of each coring is shown on Figure 25. In addition, two background soil corings (19-SB21 and 19-SB22) were taken at an offsite location (see Fig. 11) to determine background levels of radionuclides in soil for the Lansdowne area. The results of the analyses of these samples are also included in Table 9.

The background soil corings indicated that normal levels of radioactivity in the soil for this area are about 1.4 pCi/g for uranium, 1.5 pCi/g for radium and 1.6 pCi/g for thorium. The soil corings taken at the site revealed relatively normal levels for uranium and thorium, but greatly enhanced levels for radium. Radium levels in these corings ranged as high as 700 pCi/g (19-S3) in the parkway in front of the residence and approached 300 pCi/g (19-S5) along the lot line in the rear of the residence. The soil coring taken from the area of the east lot line (19-S2) was only slightly enhanced in radium (4.6 pCi/g), but the soil coring taken from the area of the west lot line (19-S4) had a somewhat greater level of enhancement (11 pCi/g) (see Table 9 and Figure 25).

Samples 19S3B and 19S5B were subjected to additional radiochemical analyses for ^{230}Th and ^{227}Ac (see Table 11). The concentrations of these isotopes in these samples was within the normal range except for slightly elevated levels of ^{230}Th in sample 19S5B.

These results confirm that the radium contamination is widespread throughout the site at least to the 1-ft level and probably extends into land adjacent to the site.

Soil Borings

A subsurface investigation using soil boring techniques was conducted throughout the site. A total of 11 bore holes (identified as 19-S6 through 19-S16) were drilled to depths of between 3 ft and 12 ft. The location of each hole is shown on Figure 25. Split-spoon soil samples were taken in 1 ft increments from each hole. The results of the analyses of these soil samples, as given in Table 10, revealed relatively normal levels for uranium and thorium, but as with the soil corings, elevated levels for radium were noted. While the most severe contamination occurred within the 1 ft level (e.g., 475 pCi/g in sample 19-S11-1), in several cases the contamination was still found at the 3 ft level (up to 114 pCi/g in sample 19-S11-3), and in one case (19-S16), the contamination descended to the 8-ft level (see Table 10 and Fig. 25). The highest level of contamination was found in the front yard (19-S11).

The soil samples taken from the east side of the property (19-S7, 19-S8 and 19-S9) had only slightly elevated levels of contamination. This contamination was restricted to a depth of 1 ft. Samples taken from the front (south end) of the property (19-S10, 19-S11, and 19-S12) had substantially elevated levels of radium contamination. In the west front (19-S11 and 19-S12), contamination extended to the 3-ft level where impervious rock was encountered.

The soil samples taken from the west side of the property (19-S13, 19-S14, and 19-S15) also had elevated levels of contamination extending, in one case, to the 5-ft level. However, the contamination encountered below the 2-ft level was below the criteria established for remedial action (see Appendix 6).

The highest level of soil contamination was found in the rear (north end) of the property. The samples taken from the east rear (19-S6) had only modest contamination (~ 12 pCi/g at the 1 ft level), but the samples taken from west rear (19-S16) had substantial contamination (453 pCi/g in the first foot), decreasing to background at the 9-ft level. Below the 3-ft level, the contamination was lower than established criteria for remedial action (see Appendix 6).

Samples 19-S11-1, 19-S16-1, and 19-S16-6 were subjected to additional radiochemical analyses for ^{230}Th and ^{227}Ac (see Table 11). The concentrations of ^{227}Ac in these samples were within the normal range; however, the concentrations for ^{230}Th were somewhat elevated (e.g. 19-S11-1 had 30 pCi/g of ^{230}Th).

Six of the samples exhibiting contamination were selected for analysis by an independent group as a method of applying a quality assurance (QA) check of the analysis methods. In no case was the discrepancy between the two methods greater than twice the standard error (2σ).

Each bore hole was logged in 2-ft increments descending from the surface. A gamma spectrum (0 to 2.6 MeV), based on the response of a 2 x 2-in NaI(Tl) detector, was taken at each position. The 1.46-MeV gamma ray from ^{40}K and the 0.61 MeV gamma ray from the ^{226}Ra decay chain were the only gamma rays readily resolvable from the continuum. However, gamma spectrometric analysis of background soil samples using a hyperpure germanium detector indicated that the soil in this area contains ^{226}Ra decay chain and ^{232}Th decay chain radioactivities in about equal quantities (i.e., about 2 pCi/g of each, see Table 9).

For the purpose of evaluating the bore hole logging data, the portion of the spectrum containing the 0.61 MeV gamma ray (i.e., 0.56 to 0.67 MeV) was integrated. No attempt was made to correct for background. The results of these integrations are given in Table 12. These data indicate that the contamination was principally ^{226}Ra decay chain and confined to 19-S11 (grade to 2 ft) 19-S12 (grade to 2 ft), 19-S15 (grade to 4 ft), and 19-S16 (grade to 8 ft). It should be noted, however, that the detailed interpretation of the subsurface contamination has been based on the analyses of the split-spoon soil samples (see above).

The bore-hole logging detector sees a radiation field substantially larger than the bore hole. Contamination anomalies beyond the bore hole, and hence not determined by the soil analyses, can be detected in this manner. While these results cannot quantify contamination, they can form a basis for justification of a need for additional subsurface investigation. No such anomalies were observed in any of these bore holes.

ESTIMATED EXTENT OF CONTAMINATION

Any estimate of the total mass and volume of radioactively contaminated material that would be generated if remedial action were undertaken at this site is subject to many uncertainties. For example, one can only surmise as to the actual depth of contamination within structural materials. For the purposes of this report, it has been assumed that contamination on concrete or brick will require removal to a depth of 2 in; contamination on wooden floors and plaster will require removal to 3/4 in, the standard thickness of such materials. Contamination in soil has been assumed to descend to an average depth of 1 ft throughout the site.

Estimates of the total radioactivity of contaminated material are subject to such large uncertainties that no attempt has been made to even guess at this quantity.

Since the scope of this activity did not provide for sampling adjacent property, authorization for such sampling was not solicited at this time.

Within the framework of these uncertainties and limitations, estimates of volume and mass for contaminated material have been made and are presented in Table 13. The total would consist of an estimated 54,000 ft³ of material.

DOSE AND POTENTIAL HAZARD EVALUATION

EXTERNAL EXPOSURE

To assess the potential radiological hazard from external exposure to the radiation field, a conservative (worst-case) situation was assumed. Since residential occupancy is currently not involved, it was assumed that an individual would be exposed 40 hours per week, 50 weeks per year to the maximum interior ambient radiation level observed, which was 183 μ R/h (see Table 4). The annual radiation dose from this source would be (see Appendix 8):

$$183 \mu\text{R/h} \times 40 \text{ h/W} \times 50 \text{ W/Yr} \times 1 \text{ remR} = 0.37 \text{ rem/Yr.}$$

Since this dose is below the NRC limit of 500 mrem per year for members of the general public, no radiological hazard exists at this site in terms of external exposure as long as the facility is not subjected to residential occupancy.

INTERNAL EXPOSURE

To assess the potential for radiological hazard based on potential internal exposure, it was necessary to assume "conservative" but nevertheless plausible scenarios whereby the radioactive contamination was assimilated internally. A hypothetical, yet conceivable, worst-case situation was developed whereby an individual was assumed to be excavating the contaminated soil (dry) to a 1-ft depth for a working day (8 hours). For this case, a resuspension factor of 10^{-6} m^{-1} and a breathing rate of $9.6 \text{ m}^3/\text{working day}$ were used. The assumption was made that the average concentration of contaminants in the soil was equal to the maximum measured value (a conservative assumption). All calculations are based on methods outlined in ORNL/NUREG/TM-190, Vol. 3.⁽³⁾ These calculations approximate the ICRP-30 guidelines for hazard analysis (see Appendix 8).

The maximum concentrations of soil contamination found was 696 pCi $^{226}\text{Ra}/\text{g}$ (sample 19-S3-B). Based on this level of contamination, the following hazard level (50-year dose commitment for one working day under the conditions identified above) was calculated (see Appendix 8):

Adult inhalation of aerosol:
(units: mrem/pCi x pCi/m³ x m³ = mrem)

Radium:	Bone:	(0.092)	(320)	(9.6)	= 283	mrem
	Total Body:	(0.0095)	(320)	(9.6)	= 29	mrem
	Lung:	(0.11)	(320)	(9.6)	= 338	mrem
Natural Uranium:	Bone:	(0.44)	(1.4)	(9.6)	= 5.9	mrem
	Total Body:	(0.083)	(1.4)	(9.6)	= 1.1	mrem
	Lung:	(1.71)	(1.4)	(9.6)	= 23	mrem
Natural Thorium:	Bone:	(0.200)	(0.92)	(9.6)	= 1.8	mrem
	Total Body:	(0.030)	(0.92)	(9.6)	= 0.26	mrem
	Lung:	(0.593)	(0.92)	(9.6)	= 5.2	mrem

The radium insult is based on the maximum level of radium contamination (696 pCi/g) found at location 19-S3 (see Fig. 25). The natural uranium

insult is based on the normal levels of uranium in the soil (3 pCi/g) which were found throughout the site. The natural thorium insult was also based on the normal levels of thorium (2 pCi/g) found throughout the site. These levels of uranium and thorium in the soil are consistent with background levels for this geographical area.

As can be seen from these results, there is potential for a hazard arising from airborne radium contamination.

An attempt to put this risk in perspective has been made based on comparisons made by Cohen and Lee (see Appendix 8). The worst case above (370 mrem/h from external exposure) equates to smoking less than three packs of cigarettes per year on this basis.

CONCLUSIONS

Based on the results of the comprehensive radiological assessment of this facility, the following conclusions can be made:

1. The radon daughter (i.e., Working Level) concentration in the air seems to be above criteria for unrestricted use.
2. The elevated levels of radioactivity, while not posing an immediate hazard, are nevertheless substantially above criteria and seemingly preclude the continuing use of this building as a residence.
3. Much of the soil surrounding the structure is contaminated above guideline levels. The fraction of this contaminated soil that is above criteria has not been explicitly determined. This determination would be made at such time as the contaminated soil was removed.
4. All drains emanating from the structure must be presumed contaminated and disposed of accordingly.
5. The potential for airborne contamination during dismantling is substantial and, hence, precautions must be taken to prevent any airborne

contamination from reaching the general public. Additionally, suitable control governing breathing air for the workers must be instituted.

6. The potential for airborne contamination as a result of fire is of concern. Precautions should be taken to insure against such an eventuality.

REFERENCES

1. U. S. Department of Energy. 1981. "Requirements for Radiation Protection." DOE 5480.1, Chapter XI.
2. U. S. Department of Health, Education and Welfare. 1970. "Radiological Health Handbook." Bureau of Radiological Health, Rockville, MD.
3. U. S. Nuclear Regulatory Commission. 1981. "Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities." Vol. III. ORNL/NUREG/TM-190 V3. Prepared by Oak Ridge National Laboratory.

Figure 1. Map of Philadelphia Area Showing Lansdowne.

Figure 2. Map of Lansdowne Area Showing Location of Stratford Ave. Residence.

ANL-HP DWG. NO. 85-22

Figure 3. Site Map of Lansdowne Property.

Figure 4. Lansdowne Structure - Front View.

Figure 5. Lansdowne Structure - Rear View.

Figure 6. Lansdowne Property - West Side.

Figure 7. Lansdowne Property - East Side.

Figure 8. **First Floor of 105 East-Interior.**

Figure 9. Second Floor of 105 East-Interior.

Figure 10. Basement of 105 East-Interior.

ANL-HP DWG. NO. 85-29

Figure 11.
Area Map Showing Background Coring and Sewer Sample Locations.

Figure 12. Soil Sample Analysis Flow Sheet.

Figure 13. First Floor of 105 East.

Figure 14. Second Floor of 105 East.

ANL-HP DWG. NO. 85-40

Figure 15. Third Floor of 105 East.

Figure 16. Basement of 105 East.

Figure 17. First Floor of 107 East.

Figure 18. Second Floor of 107 East.

Figure 19. Third Floor of 107 East.

Figure 20. Basement of 107 East.

Figure 21. Rn Concentrations and Working Levels vs. Time - 105 East Kitchen.

Figure 22. Rn Concentrations and Working vs. Time. - 105 East Dining Room.

105 E. STRATFORD 2nd FLOOR

Figure 23. Rn Concentrations and Working Levels vs. Time - 105 East Second Floor.

ANL-HP DWG. NO. 85-47

AIR SAMPLE0 30
FEET

Figure 24. Site Map Identifying External Survey Sectors.

Figure 25. Site Map Showing Coring and Boring Locations.

ANL-HP DWG. NO. 85-46

Figure 26. Differential Radiation Level vs. Time (RSS-111).

RADIATION LEVEL (micro R/hr)

Table 1. Contaminated Furniture and Personal Items

Item Number	Description ^a	Contamination ^{b,c} (dis/min-100 cm ²)		Smears	
		Alpha	Beta	Number	Results (dis/min) α β
105 East Residence					
57	Rocking Chair	0	2.5k	76	NCD ^d
63	Table	0	0	98	16 52
117	Chair	0	2.5k	83	NCD
222	Flag	0	0.5k	142	NCD
223	Rug	0	25k	156	NCD
225	Rug	8k	15k	159	NCD
228	Rug	0	20k	162/163	NCD
244	Rug	0	>100k	No Smear	
245	Rug	0	10k	No Smear	
246	Rug	0	50k	No Smear	
Misc.	Hatchet	0	5k	No Smear	
Misc.	Jar	0	2.5k	No Smear	
Misc.	Vase	0	5k	No Smear	
Misc.	3 Ledgers	0.3k	5k	60	NCD
107 East Residence					
Misc.	Book	0.5k	1.2k	342	NCD
013 B2 ^e	Wardrobe Cabinet	0.5k	0.8k	358	NCD
021 B1	Chest of Drawers	0.3k	0.4k	359	NCD
016 B1	Chest of Drawers	15k	45k	360	NCD
014 B1	Chest of Drawers	0.5k	1.3k	361	NCD
012 B1	Book Shelf	1k	3k	362	3 0
Misc.	Bed Slats	0.5k	NCD	364	NCD
018 B1	Bed Frame (Head)	0.2k	0.4k	366	NCD
017 B1	Bed Frame (Foot)	15k	25k	368	NCD
Misc.	Book	4k	10k	370	10 55
Misc.	Book	0.5k	0.5k	371	0 55
Misc.	Book	0.2k	0.5k	372	NCD
Misc.	Book	0.5k	0.8k	373	8 38
Misc.	Book	0.2k	0.4k	374	NCD
052, Or ^e	Chest of Drawers*	0.5k	1k	381	5 21
001 Gr ^e	Chest of Drawers*	0.3k	NCD	388	21 84
008 Gr	Chest of Drawers	0.2k	NCD	389	7 0
Misc.	Ping Pong Slats	0.4k	0.5k	390	87 237
005 Rd ^e	Table Legs	2k	5k	392	NCD
Misc.	Green Glass Bowl	NCD	10k	394	NCD
008 Rd	China Cabinet	3.5k	4.5k	395	NCD
Misc.	Ping Pong Table Top	4k	13k	399	NCD
005 Rd	Table Leaves	13k	18k	401	NCD
008 Or	Desk	0.4k	1k	402	NCD
003 Or	Chair	0.3k	NCD	405	NCD
Misc.	Book	3k	8k	411	NCD
Misc.	Book	0.4k	0.5k	415	NCD
Misc.	Yellow Vase	0.3k	20k	417	NCD

TABLE 1 - (cont'd.)

Item Number	Description ^a	Contamination ^{b,c} (dis/min-100 cm ²)		Smears	
		Alpha	Beta	Number	Result (dis/min) α β
107 East Residence - (cont'd.)					
Misc.	Book	0.3k	1k	421	NCD
Misc.	Tool Box	1.3k	3k	424	NCD
Misc.	Cookie Sheet	15k	25k	477	NCD
Misc.	Tray	0.1k	0.4k	478	NCD
Misc.	Picture	2.5k	10k	482	NCD
059 Or	Sewing Cabinet	0.2k	0.5k	485	NCD
041 Or	Chair	10k	17k	486	NCD
Misc.	Chair	0.2k	0.5k	487	NCD
Misc.	Rocking Chair	0.5k	0.8k	488	NCD
007 Wh ^e	Chair	2k	4k	490	NCD
012 Or	Bread Box	1k	2k	492	NCD
026 Bl	Table	0.3k	0.5k	491	NCD
014 Wh	Chest of Drawers	0.4k	0.5k	493	NCD
030 Bl	Mirror	0.2k	0.5k	494	NCD
Misc.	Drawer	12k	20k	No Smear	
026 Bl	Mirror	1k	2k	496	NCD
				498	NCD

FOOTNOTES FOR TABLE 1

^a Items marked with an asterisk (*) were subsequently decontaminated.

^b The beta mode direct readings and alpha mode direct readings were taken with PAC-4G-3 instruments. The beta mode detects both electromagnetic and particulate radiation. If an area indicated a higher count rate than the area background, a beta-mode reading was obtained. The instrument was then switched to the alpha mode, and a reading of the alpha contamination was obtained. In the alpha mode the instrument only responds to particles with high specific ionization, such as alpha particles. The beta-mode readings are compensated for any alpha contribution by subtracting the alpha-mode reading from the beta-mode reading. The area background is subtracted in both the alpha- and beta-mode readings to obtain the net readings. The letter k is used to denote units of 1000.

^c BKGD = Background. The following are the normal area background readings for each instrument.

PAC-4G-3	150-400 cts/min-100 cm ² Beta	0-5 cts/min-100 cm ² alpha
PRM-5-3	400-2000 cts/min	
PRM-7	3-15 μ R/h	

^d NCD = No Contamination Detected.

^e These abbreviations refer to color codes used on stickers with item numbers (i.e., Bl ~ blue, or ~ orange, rd ~ red, and wh ~ white).

Table 2. Instrument Survey Results - Structures

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
<u>105 East-Interior</u> 1st Floor	13					
Back Room(W)					140-180	West Room, Baseboard to 20k β
Walls		4k-10k	NCD ^d	25k-50k		
Floor		6k-10k	NCD	25k-100k		
Overhead		2k-3k	NCD	15k-30k		
Back Room (E)					140-180	East Room Baseboard to 20k β
Walls		4k-6k	NCD	15k-50k		
Floor		10k-20k	NCD	25k-100k		
Overhead		2k-3k	NCD	15k-30k		
Kitchen					200-300	
Walls		6k-10k	NCD	25k-150k		Baseboard to 30k β
Floor		10k-30k	NCD	35k-200k		
Overhead		4k-6k	NCD	25k-150k		
Bathroom					200-280	
Walls		10k-30k	NCD	35k-150k		Baseboard to 50k β
Floor		20k-30k	NCD	35k-150k		
Overhead		2k-4k	NCD	25k-40k		
Dining Room					240-300	
Walls		4k-8k	NCD	25k-50k		Baseboard to 40k β
Floor		20k-40k	NCD	35k-300k		
Overhead		1k-3k	NCD	25k-50k		
Living Room					180-220	
Walls		4k-8k	NCD	30k-50k		Baseboard to 20k β
Floor		20k-40k	NCD	30k-300k		
Overhead		1k-3k	NCD	30k-50k		
Front Porch					80-120	Enclosed porch
Walls		4k-10k	NCD	15k-50k		

TABLE 2 - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{ba,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Floor		4k-8k	NCD	15k-100k		
Overhead		1k-4k	NCD	15k-30k		
Stairwell (S)					140-180	South Stairwell Ascending
Walls		2k-4k	NCD	25k-50k		
Stairs		6k-10k	NCD	25k-50k		30k β at Wall
Overhead		1k-3k	NCD	25k-50k		
Stairwell (N)					200-240	North Stairwell Ascending
Walls		6k-10k	NCD	25k-40k		Baseboard to 30k β
Stairs		10k-20k	NCD	30k-50k		Landing 50k β
Overhead		4k-8k	NCD	25k-100k		
2nd Floor	14					
South Room					120-150	
Walls		4k-6k	NCD	20k-50k		Baseboard to 20k β
Floor		10k-20k	NCD	30k-50k		Spots to 50k β
Overhead		1k-2k	NCD	20k-25k		
Center Room					150-200	
Walls		4k-6k	NCD	20k-40k		Baseboard to 20k β
Floor		10k-20k	NCD	35k-100k		Spots to 200k β
Overhead		4k-6k	NCD	20k-30k		40k β over Bay Window
North Room					200-300	
Walls		8k-20k	NCD	25k-50k		Baseboard to 40k β
Floor		30k-50k	NCD	50k-150k		Spots to 200k β
Overhead		4k-6k	NCD	20k-40k		
Bathroom					100-150	
Walls		10k-20k	NCD	5k-10k		
Floor		30k-50k	NCD	5k-10k		Spots to 80k β
Overhead		6k-8k	NCD	20k-35k		

TABLE 2. - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Hall					150-250	
Walls		6k-10k	NCD	10k-30k		
Floor		10k-20k	NCD	30k-40k		Spot >500k γ
Overhead		1k-2k	NCD	20k-30k		
3rd Floor	15					
South Room					30-50	
Walls		2k	NCD	15k-20k		
Floor		10k-16k	200k	15k-20k		
Overhead		2k	NCD	5k-10k		
Center Room					60-80	
Walls		2k	NCD	15k-20k		
Floor		8k-12k	80k	25k-30k		Spots 100k β
Overhead		2k	NCD	5k-10k		
North Room					60-100	
Walls		2k	NCD	15k-20k		
Floor		8k-12k	16k	25k-30k		
Overhead		2k	NCD	5k-10k		
Stairwell (N)					50-100	North stairwell descending
Walls		2k	NCD	20k-30k		
Stairs		2k	NCD	50k-70k		
Overhead		2k	NCD	10k-20k		
Attic Crawl						
Space Entrance (S)		20k	NCD	10k	40	South entrance
Attic Crawl						
Space Entrance (N)		7k	NCD	10k	80	North entrance

TABLE 2 - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Basement	16					
South Room					100-180	Furnace room
Walls		4k-8k	NCD	25k-100k		Spots to 50k β
Floor		4k-10k	NCD	25k-100k		Spots to 50k β
Overhead		4k-20k	NCD	50k-150k		Spots to 100k β
Center-East					160-200	Laundry room
Walls		4k-10k	NCD	25k-150k		Spots to 50k β
Floor		4k-10k	NCD	25k-50k		Spots to 50k β
Overhead		10k-20k	NCD	50k-200k		Spots to 50k β
Center-West					120-160	Entrance room
Walls		6k-8k	NCD	35k-100k		
Floor		6k-8k	NCD	40k-150k		
Overhead		6k-10k	NCD	40k-150k		
North Room					160-320	"Hot" room
Walls		6k-8k	NCD	30k-150k		spots to 50k β
Floor		4k-8k	NCD	40k-150k		
Overhead		6k-20k	NCD	50k-200k		
Stairwell (East)						Stairwell ascending
Walls		4k-8k	NCD	25k-50k		Door 15k-25k β
Stairs		10k	NCD	25k-100k		
Overhead		10k	NCD	25k-50k		
Garage	3				60-200	105 East
Walls		2k-8k	NCD	10k-25k		
Floor		10k-20k	NCD	25k-50k		Spots to 200k β
Overhead		2k-6k	NCD	20k-25k		
<u>105 East Exterior</u>						
Back Porch (N)						North porch
Roof		1k-5k	NCD	20k-25k		
Walls (Stucco)		2k-3k	NCD	10k-25k		
Chimney		5k-100k	NCD	50k		
Vent Stack		10k	NCD	50k		

TABLE 2 - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Front Porch (S)						South porch
Roof		1k	NCD	5k-15k		
Walls		1k	NCD	5k		
<u>107 East-Interior</u>						
1st Floor	17					
Back Porch (N)					20-70	North porch
Walls		2k-4k	NCD	4k-20k		
Floor		1k-15k	NCD	10k-25k		
Overhead		1k-3k	NCD	5k-20k		
Kitchen					20-30	
Walls		1k-4k	NCD	4k-10k		
Floor		1k-2k	NCD	8k-10k		
Overhead		1k-2k	NCD	7k-10k		
Laundry Room					30-40	
Walls		1k-4k	NCD	10k		
Floor		1k	NCD	10k-15k		
Overhead		2k-4k	NCD	15k-20k		
Dining Room					15-30	
Walls		1k-2k	NCD	4k-10k		
Floor		1k	8k	5k-15k		
Overhead		1k-2k	NCD	4k-12k		
Living Room					15-25	
Walls		1k-4k	NCD	4k-7k		
Floor		1k-2k	NCD	5k-10k		
Overhead		1k-2k	NCD	5k-8k		
Front Porch (S)					10-20	South porch
Walls		1k-2k	NCD	3k-5k		
Floor		1k-2k	8k	3k-5k		
Overhead		1k-2k	NCD	3k-4k		

TABLE 2 - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Stairwell (S)					15-20	South stairwell ascending
Walls		2k-3k	NCD	8k-10k		
Stairs		2k-3k	NCD	10k-12k		
Overhead		2k-3k	NCD	6k-8k		
Stairwell (N)					20-30	North stairwell ascending
Walls		2k-3k	NCD	10k-15k		
Stairs		2k-3k	NCD	12k-17k		
Overhead		2k-3k	NCD	10k-15k		
2nd Floor	18					
South Room					15-20	
Walls		1k	NCD	6k-8k		
Floor		1k	NCD	8k-10k		
Overhead		1k	NCD	6k		
Center Room					15-20	
Walls		1k	NCD	7k-10k		
Floor		1k	NCD	8k-10k		
Overhead		1k	NCD	6k-7k		
North Room					15-20	
Walls		1k-2k	NCD	9k-11k		
Floor		1k-2k	NCD	10k-13k		
Overhead		1k	NCD	8k-10k		
Bathroom					25	
Walls		1k-3k	NCD	10k-13k		
Floor		1k-3k	NCD	15k		
Overhead		1k-2k	NCD	12k-14k		

TABLE 2 - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Hall					15-20	
Walls		1k	NCD	8k-10k		
Floor		1k-3k	0.8k	10k-15k		
Overhead		2k	NCD	8k-12k		
Stairwell (N)					20-30	North stairwell ascending
Walls		1k	NCD	10k-15k		
Stairs		1k-5k	NCD	10k-15k		
Overhead		1k	NCD	5k-7k		
3rd Floor	19					
South Room					20-30	
Walls		1k	5k	4k-5k		
Floor		1k	NCD	5k-7k		
Overhead		1k	NCD	3k-4k		
North Room					20-30	
Walls		1k-2k	NCD	4k-6k		
Floor		1k-2k	NCD	4k-6k		
Overhead		1k	NCD	4k-5k		
Hall					20-50	
Walls		1k	NCD	4k-6k		
Floor		1k	NCD	8k-10k		
Overhead		1k	NCD	4k-5k		
Basement	20					
South Room					25-35	Unfinished room
Walls		2k-3k	NCD	5k-8k		
Floor		2k-3k	5k	8k-10k		
Overhead		2k-3k	NCD	8k-10k		

TABLE 2. - (cont'd.)

Location	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		PRM-5-3 w/PG-2 (cts/min) ^c	PRM-7 (μR/h) ^c	Comments
		Beta	Alpha			
Center Room					25-35	Finished room
Walls		1k-2k	NCD	4k-8k		
Floor		2k-4k	NCD	6k-8k		
Overhead		1k-2k	NCD	6k-8k		
North Room (N)					35-50	West-furnace room
Walls		4k-5k	NCD	10k-15k		
Floor		6k-8k	15k	10k		
Overhead		2k-3k	NCD	10k-15k		
North Room (E)					30-40	East-entrance room
Walls		1k-15k	NCD	10k-15k		
Floor		10k-20k	NCD	10k		
Overhead		1k-2k	NCD	10k-15k		
Under Porch (N)		10k-40k	NCD	25k-35k	100-240	North-under back porch
Stairwell					40-60	Stairwell-ascending
Walls		2k-10k	NCD	10k-15k		
Stairs		10k-15k	NCD	15k		
Overhead		1k-2k	NCD	15k-20k		
Garage	3				15-30	107 East
Walls		1k	NCD	3k-5k		
Floor		1k-3k	NCD	1k-3k		
Overhead		1k	NCD	2k-3k		
105 East Exterior						
Back Porch (N)						North porch
Roof		1k-2k	NCD	10k-15k		
Walls		2k-3k	NCD	5k-10k		
Chimney		2k-3k	NCD	5k-10k		
Front Porch (S)						South porch
Roof		1k	NCD	3k-4k		
Walls		1k	NCD	3k-4k		

FOOTNOTES FOR TABLE 2

^aIndicates figure showing location.

^bThe beta mode direct readings and alpha mode direct readings were taken with PAC-4G-3 instruments. The beta mode detects both electromagnetic and particulate radiation. If an area indicated a higher count rate than the area background, a beta-mode reading was obtained. The instrument was then switched to the alpha mode, and a reading of the alpha contamination was obtained. In the alpha mode the instrument only responds to particles with high specific ionization, such as alpha particles. The beta-mode readings are compensated for any alpha contribution by subtracting the alpha-mode reading from the beta-mode reading. The area background is subtracted in both the alpha- and beta-mode readings to obtain the net readings. The letter k is used to denote units of 1000.

^cBKGD = Background. The following are the normal area background readings for each instrument.

PAC-4G-3	150-400 cts/min-100 cm ² Beta	0-5 cts/min-100 cm ² alpha
PRM-5-3	400-2000 cts/min	
PRM-7	3-15 µR/h	

^dNCD = No Contamination Detected.

Table 3. Specifically Identified Contamination - Interior

Location	Identification Number	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		Comments
			Beta	Alpha	
<u>105 East</u>					
1st Floor					
Back Room (W)	28	13	40k	NCD ^c	West room
	27	13	100k	NCD	
Back Room (E)	29	13	50k	NCD	East room
Kitchen	30	13	100k	NCD	
	31	13	100k	NCD	
	34	13	100k	NCD	
	61	13	30k	NCD	
Bathroom	32	13	100k	NCD	
Dining Room	35	13	>200k	NCD	
	36	13	>200k	NCD	
	37	13	>200k	NCD	
	38	13	>200k	NCD	
	39	13	>200k	NCD	
	40	13	>200k	NCD	
	41	13	>200k	NCD	
	42	13	>200k	NCD	
	43	13	30k	NCD	
	44	13	>200k	NCD	
	45	13	>200k	NCD	
	46	13	>200k	NCD	
	47	13	>200k	NCD	
	48	13	>200k	NCD	
Living Room	49	13	30k	NCD	
	50	13	30k	NCD	
	51	13	>200k	NCD	
	52	13	>200k	NCD	

Table 3 - (cont'd.)

Location	Identification Number	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		Comments
			Beta	Alpha	
Front Porch	53	13	100k	NCD	
	54	13	100k	NCD	Door
	55	13	20k-40k	NCD	Radiator-South
	56	13	100k	NCD	Three Spots in Area
	57	13	50k	NCD	Radiator
	58	13	50k	NCD	Window Sill
	59	13	50k	NCD	Window Sill
	60	13	40k-200k	NCD	Chimney and Wall
	33	13	50k	NCD	North Stairwell
Stairwell (N)					
2nd Floor					
South Room	10	14	10k	NCD	Door
	11	14	30k	NCD	Door
	12	14	100k	NCD	
	13	14	100k	NCD	
Center Room	14	14	40k	NCD	On Ceiling
	15	14	200k	NCD	
	16	14	100k	NCD	
	17	14	200k	NCD	
North Room	18	14	200k	NCD	
	19	14	200k	NCD	
	20	14	160k	NCD	
	21	14	160k	NCD	
Bathroom	22	14	160k	NCD	Fixtures; Tub 50k,
	24	14	100k	NCD	
	25	14	100k	NCD	
Hall	26	14	50k	NCD	Hand Rail
	23	14	200k	NCD	

Table 3 - (cont'd.)

Location	Identification Number	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		Comments
			Beta	Alpha	
3rd Floor					
South Room	7	15	400k	200k	
	8	15	400k	NCD	
	9	15	2k	NCD	Ceiling
Center Room	5	15	200k	10k	
	6	15	900k	80k	
North Room	1	15	50k	0.7k	
	2	15	60k	16k	
	3	15	70k	0.6k	
	4	15	30k	10k	Sink
Basement					
South Room	62	16	100k	NCD	
	63	16	100k-200k	NCD	Pipes and overhead
	64	16	100k	NCD	Pipes
	65	16	40k	NCD	Chimney and wall
	66	16	50k	NCD	Overhead
	67	16	50k	NCD	Window well
	68	16	50k	NCD	Overhead
Center East	69	16	100k	NCD	Walls
	70	16	40k	NCD	Overhead
	71	16	100k	NCD	Sewer pipe
	72	16	100k	NCD	Overhead
Center West	74	16	50k	NCD	Wall
	75	16	50k	NCD	Overhead
	76	16	50k	NCD	Wall and overhead
North Room	77	16	50k-100k	NCD	Wall and overhead
	78	16	20k	NCD	Wall
Stairwell	73	16	30k-50k	NCD	Door and molding

Table 3. - (cont'd.)

Location	Identification Number	Figure Number ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²)		Comments
			Beta	Alpha	
107 East					
1st Floor					
Kitchen	118	17	20k	NCD	
Dining Room	110	17	40k	8k	
Living Room	114	17	4k	0.2k	Ceiling beam
	115	17	300k	NCD	Floor
	116	17	20k	NCD	Posts
	117	17	30k	NCD	Landing
	Front Porch	111	17	30k	8k
112		17	200k	NCD	Floor
113		17	90k	NCD	Door
2nd Floor					
South Room	105	18	20k	NCD	
Hall	104	18	5k	NCD	Post
	106	18	5k	0.8k	Landing
3rd Floor					
South Room	102	19	24k	5k	Cabinet
	103	19	3k	0.8k	
Stairwell	101	19	4k	0.8k	Shelf over stairs
Basement					
South Room	107	20	60k	5k	Floor
	108	20	100k	40k	Oil tank
	109	20	5k	NCD	Corner
North Room (W)	119	20	50k	15k	Furnace room
Under Porch (N)	120	20	700k	NCD	Under back porch

FOOTNOTES FOR TABLE 3

^aIndicates figure showing location.

^bThe beta mode direct readings and alpha mode direct readings were taken with PAC-4G-3 instruments. The beta mode detects both electromagnetic and particulate radiation. If an area indicated a higher count rate than the area background, a beta-mode reading was obtained. The instrument was then switched to the alpha mode, and a reading of the alpha contamination was obtained. In the alpha mode the instrument only responds to particles with high specific ionization, such as alpha particles. The beta-mode readings are compensated for any alpha contribution by subtracting the alpha-mode reading from the beta-mode reading. The area background is subtracted in both the alpha- and beta-mode readings to obtain the net readings. The letter k is used to denote units of 1000.

^cBKGD = Background. The following are the normal area background readings for each instrument.

PAC-4G-3	150-400 cts/min-100 cm ² beta	0-5 cts/min-100 cm ² alpha
PRM-5-3	400-2000 cts/min	
PRM-7	3-15 μ R/h	

^dNCD = No Contamination Detected.

Table 4. Ambient Penetrating Radiation Measurements

Sample Number	Location	Figure Number ^a	Reuter Stokes RSS-111			PRM-7 (μR/h)
			Time (h)	Activity (μR)	Rate (μR/h)	
1	105 3rd Floor	15	23.3	1490	63.9	50-60
2	105 2nd Floor	14	23.7	2687	113.5	100
3	105 1st Floor	13	22.8	4180	183.1	180
4	105 Basement	16	24	2251	93.8	60
5	107 3rd Floor	19	23.2	486	20.9	20
6	107 Basement	20	29	722	24.9	20-30
7	107 2nd Floor	18	42.7	990	23.2	25
8	107 1st Floor	17	46.8	1777	38.0	42

^aIndicates figure showing location at which measurement was made.

Table 5. Air Sample Results

Sample Number	Location	Figure Number ^a	Radon ²²² Rn (pCi/ℓ)	Radon Daughters (mWL) ^b	Thoron ²²⁰ Rn (fCi/ℓ)	Actinon ²¹⁹ Rn (pCi/ℓ)
1	105 Basement Laundry Room	16	30.9	309	-	-
2	105 1st Floor Living Room	13	5.7	57	10	BDL ^c
3	105 2nd Floor Bedroom	14	3.4	34	4	BDL
4	105 Basement Laundry Room	16	8.3	83	37	BDL
6	105 1st Floor Kitchen	13	5.3	53	13	BDL
8	105 3rd Floor Center Room	15	4.9	49	13	BDL
9	105 2nd Floor Center Room	14	2.1	21	2.4	BDL
10	105 Backyard	24	0.3	3	3.4	BDL
11	105 2nd Floor Center Room	14	5.6	56	8.7	BDL
12	105 1st Floor Dining Room	13	4.2	42	11	BDL
13	105 Basement Center	16	9.5	95	54	BDL

Table 5 - (cont'd.)

Sample Number	Location	Figure Number ^a	Radon ²²² Rn (pCi/l)	Radon Daughters (mWL) ^b	Thoron ²²⁰ Rn (fCi/l)	Actinon ²¹⁹ Rn (pCi/l)
14	107 3rd Floor	19	10.6	106	20	BDL
15	107 Basement	20	3.9	39	23	BDL
16	107 2nd Floor	18	2.8	28	28	BDL
17	107 1st Floor	17	4.8	48	18	BDL

^aIndicates figure showing location at which measurement was made.

^bWorking Level (WL) is defined as any combination of short-lived radon-decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy. The numerical value of the WL is derived from the alpha energy released by the total decay through RaC' of the short-lived radon-daughter products, RaA, RaB, and RaC at radioactive equilibrium with 100 pCi of ²²²Rn per liter of air. A milliWorking Level (mWL) is 10^{-3} WL.

^cBDL = Below Detectable Limits.

Table 6. Instrument Survey Results - Exterior

Location ^a	PAC-4G-3 Direct Readings ^{b,c} (dis/min-100 cm ²) Beta	PRM-5-3 w/PG-2 (cts/min)	PRM-7 (μR/h) ^c
I	2k-8k	10k-150k	40-150
II	1k	15k	30
III	0.8k	5k	30
IV	0.7k	5k	20
V	0.7k	4k-5k	10-20
VI	0.7k	3.5k-5k	10-20
VII	0.7k	2.5k-3k	10
VIII	0.8k	3.5k-5k	15
IX	1k-20k	10k-50k	20-100
X	1k-5k	20k-100k	50-60
XI	2k-20k	10k-100k	60-120
XII	1k	4k-10k	10-15
XIII	1k-10k	5k-10k	20-60
XIV	1k-10k	5k-25k	50-200
XV	1k	5k-15k	50-100
XVI	10k-30k	50k-500k	200-300
XVII	10k-100k	>500k	500
XVIII	10k-60k	>500k	300
XIX	40k	400k	300-500

^aLocations of these sections are identified in Figure 24.

^b

The beta mode direct readings and alpha mode direct readings were taken with PAC-4G-3 instruments. The beta mode detects both electromagnetic and particulate radiation. If an area indicated a higher count rate than the area background, a beta-mode reading was obtained. The instrument was then switched to the alpha mode, and a reading of the alpha contamination was obtained. In the alpha mode the instrument only responds to particles with

Table 6 - Footnotes (cont'd.)

high specific ionization, such as alpha particles. The beta-mode readings are compensated for any alpha contribution by subtracting the alpha-mode reading from the beta-mode reading. The area background is subtracted in both the alpha- and beta-mode readings to obtain the net readings. The letter k is used to denote units of 1000.

^cBKGD = Background. The following are the normal area background readings for each instrument.

PAC-4G-3	150-400 cts/min-100 cm ² beta	0-5 cts/min-100 cm ² alpha
PRM-5-3	400-2000 cts/min	
PRM-7	3-15 μ R/h	

Table 7. Specifically Identified Contaminated-Exterior

Location ^a	Identification Number	PRM-5-3 w/PG-2 (cts/min) ^b	Comments
II	201	15k	
VI	202	30k	
	203	30k	
VIII	204	10k	
	205	7k	
	206	20k	
	207	10k-30k	
	208	6k	Sewer Vent
	209	30k	
IX	210	200k	
	211	500k	
	212	200k	
	213	40k	
	214	20k	
X	-	20k-100k	General Contamination
XI	215	100k	
XII	216	15k	
XIII	217	35k	
	218	40k	
	219	>500k	
	220	40k	
XVI	223	500k	
XVII	221	>500k	
XVIII	222	>500k	
XIX	224	400k	

^aSection Locations are identified in Figure 24.

^bBackground 2k cts/min. The letter k denotes units of 1000.

Table 8 - Gamma Spectral and Uranium Fluorometric Analyses
of Sewer Samples

Sample Number ^a	Gamma Spectra, pCi/g $\pm$ σ or pCi/l $\pm$ σ					
		²³² Th	²²⁶ Ra			
	¹³⁷ Cs	Decay Chain	Decay Chain	Uranium Fluorometric		
				μ g/g $\pm$ 10%	pCi/g $\pm$ 10%	
19-SW-17(SS)	0.13 $\pm$ 0.04	0.66 $\pm$ 0.07	40 $\pm$ 4	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2	
19-SW-17(DS)	<0.02	<0.04	<0.02	0.24 $\pm$ 0.02	0.16 $\pm$ 0.02	
19-SS-18(SS)	0.08 $\pm$ 0.03	0.79 $\pm$ 0.08	36 $\pm$ 4	2.7 $\pm$ 0.3	1.8 $\pm$ 0.2	
19-SS-18(DS)	<0.02	<0.04	<0.02	2.5 $\pm$ 0.3	1.7 $\pm$ 0.2	
19-SW-19(SS)	BDL ^b	BDL	BDL	26.8 $\pm$ 2.7	18.1 $\pm$ 1.8	
19-SW-19(DS)	<0.02	<0.04	<0.02	0.1 $\pm$ 0.01	0.07 $\pm$ 0.01	
19-SS-20(SS)	0.11 $\pm$ 0.03	0.80 $\pm$ 0.03	5.0 $\pm$ 0.5	1.5 $\pm$ 0.2	1.0 $\pm$ 0.1	
19-SS-20(DS)	5 $\pm$ 1	<0.04	<0.02	1.3 $\pm$ 0.1	0.9 $\pm$ 0.1	

^aSW refers to sewer water and SS refers to sewer sludge; (SS) refers to suspended solids (units: pCi/g); and samples 19-SW-17 and 19-SS-18 were taken from the residence effluent, and samples 19-SW-19 and 19-SS-20 were taken from the main sewer line confluence (see text).

^bBDL refers to Below Detectable Limit.

Table 9 - Gamma Spectral and Uranium Fluorometric Analyses of Soil Coring Samples

Sample Number	Gamma Spectra, pCi/g±σ				Uranium Fluorometric μg/g±10% pCi/g±10%	
	137Cs	232Th	226Ra			
			Decay Chain	Decay Chain		
BACKGROUND ENVIRONMENTAL SOIL						
19-SB-21A	0.28±0.02	1.58±0.08	1.52±	0.07	1.9±0.2	1.3±0.2
19-SB-21B	0.23±0.01	1.69±0.09	1.54±	0.06	2.0±0.2	1.4±0.2
19-SB-21C	0.14±0.01	1.90±0.10	1.61±	0.08	2.0±0.2	1.4±0.2
19-SB-21D	0.03±0.01	1.63±0.09	1.53±	0.07	2.0±0.2	1.4±0.2
19-SB-22A	0.64±0.04	1.52±0.09	1.55±	0.08	1.9±0.2	1.3±0.2
19-SB-22B	0.22±0.03	1.55±0.11	1.51±	0.08	1.9±0.2	1.3±0.2
19-SB-22C	0.11±0.02	1.58±0.10	1.47±	0.08	1.9±0.2	1.3±0.2
19-SB-22D	0.07±0.02	1.73±0.13	1.50±	0.08	2.0±0.2	1.4±0.2
ENVIRONMENTAL SOIL						
19-S1 ^a	---	2.0 ±1.0	2800	±300	3.9±0.4	2.7±0.3
19-S-2A	0.60±0.04	1.71±0.11	4.57±	0.21	2.2±0.2	1.5±0.2
19-S-2B	0.58±0.05	2.06±0.15	4.64±	0.22	2.1±0.2	1.4±0.1
19-S-2C	0.25±0.02	1.97±0.12	3.24±	0.15	2.4±0.2	1.6±0.2
19-S-2D	<0.09	2.25±0.15	2.18±	0.11	2.8±0.3	1.9±0.2
19-S-3A	2.03±0.13	1.84±0.30	274.0 ±	12.9	3.0±0.3	2.0±0.2
19-S-3B	<0.64	1.95±0.20	696.3 ±	32.7	3.1±0.3	2.1±0.2
19-S-3C	<0.22	2.01±0.24	174.4 ±	8.2	3.4±0.3	2.3±0.2
19-S-3D	<0.12	2.42±0.21	25.4 ±	1.2	4.3±0.4	2.9±0.3
19-S-4A	1.10±0.06	1.49±0.10	9.85±	0.46	2.4±0.2	1.6±0.2
19-S-4B	0.56±0.05	1.76±0.14	10.88±	0.51	2.4±0.2	1.6±0.2
19-S-4C	0.20±0.02	1.63±0.11	6.57±	0.31	2.4±0.2	1.6±0.2
19-S-4D	0.12±0.03	1.78±0.13	3.64±	0.18	2.3±0.2	1.6±0.2
19-S-5A	1.68±0.11	1.41±0.23	177.2 ±	8.2	2.6±0.3	1.8±0.2
19-S-5B	0.56±0.08	1.45±0.29	283.1 ±	13.0	3.2±0.3	2.2±0.2
19-S-5C	<0.46	2.30±0.56	136.7 ±	6.3	3.0±0.3	2.0±0.2
19-S-5D	<0.16	2.10±0.22	59.0 ±	2.7	2.9±0.3	2.0±0.2

^aThis sample also contained ^{230}Th (1310 $\pm$ 100 pCi/g) and ^{227}Ac (32 $\pm$ 3 pCi/g). ^{239}Pu and ^{238}Pu were determined to be <0.03 pCi/g and <0.02 pCi/g, respectively.

Table 10 - Gamma Spectral and Uranium Fluorometric Analyses of Soil Boring Samples

Sample Number	Gamma Spectra, pCi/g $\pm\sigma$			Uranium Fluorometric $\mu\text{g/g}\pm 10\%$ pCi/g $\pm 10\%$	
	^{137}Cs	^{232}Th Decay Chain	^{226}Ra Decay Chain		
19-S6-1	0.34 $\pm$ 0.03	1.91 $\pm$ 0.12	11.61 $\pm$ 0.54	3.1 $\pm$ 0.3	2.1 $\pm$ 0.2
19-S6-2	0.08 $\pm$ 0.02	1.74 $\pm$ 0.11	5.22 $\pm$ 0.24	3.2 $\pm$ 0.3	2.2 $\pm$ 0.2
19-S6-3	0.15 $\pm$ 0.02	1.94 $\pm$ 0.11	5.44 $\pm$ 0.25	4.2 $\pm$ 0.4	2.9 $\pm$ 0.3
19-S6-4	0.06 $\pm$ 0.02	2.12 $\pm$ 0.12	3.23 $\pm$ 0.15	4.3 $\pm$ 0.4	2.9 $\pm$ 0.3
19-S6-5	<0.05	1.99 $\pm$ 0.11	2.96 $\pm$ 0.14	4.5 $\pm$ 0.4	3.1 $\pm$ 0.3
19-S6-6	-	-	-	3.4 $\pm$ 0.3	2.3 $\pm$ 0.2
19-S6-7	<0.04	1.91 $\pm$ 0.11	1.72 $\pm$ 0.08	4.2 $\pm$ 0.4	2.9 $\pm$ 0.3
19-S6-8	<0.02	1.82 $\pm$ 0.09	1.52 $\pm$ 0.07	3.4 $\pm$ 0.3	2.3 $\pm$ 0.2
19-S7-1	<0.05	1.67 $\pm$ 0.11	6.11 $\pm$ 0.29	2.3 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S7-2	0.41 $\pm$ 0.02	1.53 $\pm$ 0.09	3.37 $\pm$ 0.16	2.3 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S7-3	0.38 $\pm$ 0.04	1.64 $\pm$ 0.12	2.89 $\pm$ 0.15	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S7-4	0.06 $\pm$ 0.02	2.64 $\pm$ 0.15	2.77 $\pm$ 0.14	4.6 $\pm$ 0.5	3.1 $\pm$ 0.3
19-S7-5	<0.08	2.80 $\pm$ 0.17	2.63 $\pm$ 0.13	4.3 $\pm$ 0.4	2.9 $\pm$ 0.3
19-S7-6	0.06 $\pm$ 0.02	1.90 $\pm$ 0.11	1.70 $\pm$ 0.10	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S7-7	<0.08	2.54 $\pm$ 0.16	1.87 $\pm$ 0.10	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2
19-S7-8 (8 in)	<0.05	2.09 $\pm$ 0.12	1.35 $\pm$ 0.07	2.2 $\pm$ 0.2	1.5 $\pm$ 0.2
19-S8-1	0.34 $\pm$ 0.03	2.07 $\pm$ 0.12	4.30 $\pm$ 0.20	3.4 $\pm$ 0.3	2.3 $\pm$ 0.2
19-S8-2	0.14 $\pm$ 0.03	2.10 $\pm$ 0.14	2.46 $\pm$ 0.13	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S8-3	0.13 $\pm$ 0.03	1.67 $\pm$ 0.13	2.14 $\pm$ 0.11	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S8-4	<0.06	2.16 $\pm$ 0.13	1.54 $\pm$ 0.08	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S8-5	<0.09	2.44 $\pm$ 0.16	2.03 $\pm$ 0.11	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2
19-S8-6	<0.06	2.14 $\pm$ 0.13	2.02 $\pm$ 0.10	5.2 $\pm$ 0.5	3.6 $\pm$ 0.4
19-S8-7	<0.11	2.36 $\pm$ 0.15	2.17 $\pm$ 0.11	5.9 $\pm$ 0.6	4.0 $\pm$ 0.4
19-S8-8	<0.05	2.67 $\pm$ 0.15	2.39 $\pm$ 0.12	4.8 $\pm$ 0.5	3.3 $\pm$ 0.3
19-S9-1	0.24 $\pm$ 0.04	1.92 $\pm$ 0.13	2.48 $\pm$ 0.13	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S9-2	0.14 $\pm$ 0.02	1.69 $\pm$ 0.10	1.91 $\pm$ 0.10	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S9-3	<0.09	1.78 $\pm$ 0.12	1.62 $\pm$ 0.09	2.5 $\pm$ 0.3	1.7 $\pm$ 0.2
19-S9-4	0.10 $\pm$ 0.03	1.75 $\pm$ 0.14	1.59 $\pm$ 0.09	2.9 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S9-5	<0.07	1.85 $\pm$ 0.11	1.67 $\pm$ 0.08	3.0 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S9-6	<0.05	1.86 $\pm$ 0.11	1.45 $\pm$ 0.07	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S9-7	<0.09	2.32 $\pm$ 0.15	1.85 $\pm$ 0.09	3.6 $\pm$ 0.4	2.5 $\pm$ 0.2
19-S10-1	0.75 $\pm$ 0.08	2.85 $\pm$ 0.26	11.88 $\pm$ 0.52	2.5 $\pm$ 0.3	1.7 $\pm$ 0.2
19-S10-2	0.13 $\pm$ 0.03	2.28 $\pm$ 0.15	2.32 $\pm$ 0.13	3.4 $\pm$ 0.3	2.3 $\pm$ 0.2
19-S10-3	0.05 $\pm$ 0.02	2.48 $\pm$ 0.15	2.88 $\pm$ 0.15	4.7 $\pm$ 0.5	3.2 $\pm$ 0.3
19-S10-4	<0.22	2.59 $\pm$ 0.18	3.28 $\pm$ 0.16	7.4 $\pm$ 0.7	5.1 $\pm$ 0.5

Table 10 - (cont'd.)

Sample Number	Gamma Spectra, pCi/g $\pm$ σ			Uranium Fluorometric	
	^{137}Cs	^{232}Th Decay Chain	^{226}Ra Decay Chain	$\mu\text{g/g}\pm 10\%$	pCi/g $\pm 10\%$
19-S11-1	<0.96	1.93 $\pm$ 0.19	475.0 $\pm$ 22.3	3.1 $\pm$ 0.3	2.1 $\pm$ 0.2
19-S11-2	0.32 $\pm$ 0.09	1.55 $\pm$ 0.28	134.6 $\pm$ 6.3	3.1 $\pm$ 0.3	2.1 $\pm$ 0.2
19-S11-3 (3 in)	<0.39	2.01 $\pm$ 0.21	114.3 $\pm$ 5.4	5.3 $\pm$ 0.5	3.6 $\pm$ 0.4
19-S12-1	0.27 $\pm$ 0.04	1.39 $\pm$ 0.19	13.0 $\pm$ 0.7	2.2 $\pm$ 0.2	1.5 $\pm$ 0.2
19-S12-2	0.22 $\pm$ 0.06	2.12 $\pm$ 0.30	70.1 $\pm$ 3.5	2.5 $\pm$ 0.3	1.7 $\pm$ 0.2
19-S12-3 (6 in)	<0.29	2.10 $\pm$ 0.15	76.0 $\pm$ 3.9	3.8 $\pm$ 0.4	2.6 $\pm$ 0.3
19-S13-1	0.59 $\pm$ 0.05	1.51 $\pm$ 0.13	5.12 $\pm$ 0.25	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S13-2	0.43 $\pm$ 0.03	1.61 $\pm$ 0.10	4.16 $\pm$ 0.20	3.2 $\pm$ 0.3	2.2 $\pm$ 0.2
19-S13-3	0.13 $\pm$ 0.02	1.50 $\pm$ 0.12	2.29 $\pm$ 0.12	3.3 $\pm$ 0.3	2.3 $\pm$ 0.2
19-S13-4	0.07 $\pm$ 0.01	1.32 $\pm$ 0.09	1.89 $\pm$ 0.09	2.9 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S13-5	<0.07	1.73 $\pm$ 0.12	1.60 $\pm$ 0.09	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S13-6	<0.06	1.63 $\pm$ 0.10	1.67 $\pm$ 0.08	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S13-7	<0.08	1.20 $\pm$ 0.11	1.26 $\pm$ 0.07	2.2 $\pm$ 0.2	1.5 $\pm$ 0.2
19-S13-8	<0.05	1.45 $\pm$ 0.09	1.17 $\pm$ 0.06	1.9 $\pm$ 0.2	1.3 $\pm$ 0.2
19-S13-9	<0.09	1.59 $\pm$ 0.12	1.39 $\pm$ 0.08	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S13-10	<0.05	1.57 $\pm$ 0.11	1.68 $\pm$ 0.08	4.0 $\pm$ 0.4	2.7 $\pm$ 0.3
19-S14-1	0.24 $\pm$ 0.02	1.56 $\pm$ 0.11	8.16 $\pm$ 0.34	2.3 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S14-2	0.12 $\pm$ 0.03	1.66 $\pm$ 0.13	3.65 $\pm$ 0.18	3.1 $\pm$ 0.3	2.1 $\pm$ 0.2
19-S14-3	<0.13	1.71 $\pm$ 0.10	3.87 $\pm$ 0.17	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2
19-S14-4	<0.18	1.95 $\pm$ 0.16	1.78 $\pm$ 0.09	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S14-5	<0.11	1.78 $\pm$ 0.10	1.97 $\pm$ 0.10	3.0 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S14-6	<0.15	1.49 $\pm$ 0.13	1.53 $\pm$ 0.09	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2
19-S14-7	<0.12	0.82 $\pm$ 0.06	1.51 $\pm$ 0.08	4.3 $\pm$ 0.4	2.9 $\pm$ 0.3
19-S14-8	<0.14	0.86 $\pm$ 0.09	1.34 $\pm$ 0.07	3.5 $\pm$ 0.4	2.4 $\pm$ 0.2
19-S14-9	<0.16	1.11 $\pm$ 0.12	1.46 $\pm$ 0.09	4.1 $\pm$ 0.4	2.8 $\pm$ 0.3
19-S14-10	<0.10	1.29 $\pm$ 0.09	1.79 $\pm$ 0.09	5.8 $\pm$ 0.6	4.0 $\pm$ 0.4
19-S15-1	<0.28	1.97 $\pm$ 0.23	47.41 $\pm$ 2.23	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S15-2	0.17 $\pm$ 0.04	1.59 $\pm$ 0.19	18.08 $\pm$ 0.87	2.2 $\pm$ 0.2	1.5 $\pm$ 0.2
19-S15-3	<0.16	1.82 $\pm$ 0.13	7.68 $\pm$ 0.38	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S15-4	<0.07	1.93 $\pm$ 0.16	3.38 $\pm$ 0.16	3.0 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S15-5	<0.10	1.84 $\pm$ 0.12	4.73 $\pm$ 0.20	3.0 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S15-6	<0.15	2.02 $\pm$ 0.22	2.89 $\pm$ 0.15	2.7 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S15-7(10 in)	<0.16	2.40 $\pm$ 0.15	2.80 $\pm$ 0.14	3.4 $\pm$ 0.3	2.3 $\pm$ 0.2

Table 10 - (cont'd.)

Sample Number	Gamma Spectra, pCi/g $\pm\sigma$			Uranium Fluorometric	
	^{137}Cs	^{232}Th Decay Chain	^{228}Ra Decay Chain	$\mu\text{g/g}\pm 10\%$	pCi/g $\pm 10\%$
19-S16-1	<0.36	2.15 $\pm$ 0.19	453.0 $\pm$ 21.3	2.6 $\pm$ 0.3	1.8 $\pm$ 0.2
19-S16-2	0.11 $\pm$ 0.04	1.68 $\pm$ 0.17	65.8 $\pm$ 3.1	2.4 $\pm$ 0.2	1.6 $\pm$ 0.2
19-S16-3	<0.13	2.28 $\pm$ 0.21	29.2 $\pm$ 1.4	3.0 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S16-4	<0.14	2.14 $\pm$ 0.20	12.8 $\pm$ 0.6	3.2 $\pm$ 0.3	2.2 $\pm$ 0.2
19-S16-5	<0.06	1.65 $\pm$ 0.12	10.5 $\pm$ 0.5	2.9 $\pm$ 0.3	2.0 $\pm$ 0.2
19-S16-6	<0.10	2.00 $\pm$ 0.14	10.8 $\pm$ 0.5	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S16-7	<0.09	1.88 $\pm$ 0.16	5.23 $\pm$ 0.26	2.8 $\pm$ 0.3	1.9 $\pm$ 0.2
19-S16-8	<0.06	1.75 $\pm$ 0.11	5.10 $\pm$ 0.24	4.5 $\pm$ 0.5	3.1 $\pm$ 0.3
19-S16-9	<0.06	1.50 $\pm$ 0.12	2.68 $\pm$ 0.14	7.6 $\pm$ 0.8	5.2 $\pm$ 0.5
19-S16-10	<0.04	1.87 $\pm$ 0.11	2.01 $\pm$ 0.10	5.4 $\pm$ 0.5	3.7 $\pm$ 0.4
19-S16-11	<0.06	1.47 $\pm$ 0.11	2.53 $\pm$ 0.14	6.4 $\pm$ 0.6	4.4 $\pm$ 0.4
19-S16-12	<0.05	1.40 $\pm$ 0.07	2.47 $\pm$ 0.12	4.6 $\pm$ 0.5	3.1 $\pm$ 0.3

Table 11
Radiochemical Analyses for Thorium and Actinium
(pCi/g $\pm \sigma$)

Sample Number	^{227}Ac	^{230}Th	^{232}Th	^{228}Th
19-S1	32. ± 3	1310 ± 100	2.6 ± 0.3	1.8 ± 0.3
19-S-3B	0.19 ± 0.05	1.3 ± 0.1	1.4 ± 0.1	1.3 ± 0.1
19-S-5B	0.08 ± 0.04	4.2 ± 0.2	1.2 ± 0.1	1.4 ± 0.1
19-S11-1	0.24 ± 0.06	30 ± 2	1.7 ± 0.1	1.9 ± 0.1
19-S16-1	0.11 ± 0.05	5.3 ± 0.3	1.4 ± 0.1	1.5 ± 0.1
19-S16-6	0.16 ± 0.05	1.6 ± 0.1	1.6 ± 0.1	1.6 ± 0.1

Table 11
Soil Borings - Logging Data

Bore Hole	Gamma-Spectra Peak Integral ^a	Comments
19-S6-Grade	5451	
2 ft	4969	
4 ft	5208	
6 ft	5465	
8 ft	4813	
19-S7-Grade	2570	
2 ft	3358	
4 ft	4736	
6 ft	3163	
8 ft	4243	
19-S8-Grade	3034	
2 ft	3871	
4 ft	4833	
6 ft	5634	
8 ft	6002	
19-S9-Grade	2001	
2 ft	3310	
4 ft	3761	
6 ft	4970	
7 ft	5481	
19-S10-Grade	4043	
2 ft	4382	
2.7 ft	4870	
19-S11-Grade	71029	Contamination ^b
2 ft	40365	Contamination
Bottom	46231	Contamination
19-S12 Grade	7740	Contamination
Bottom	7236	Contamination
19-S13-Grade	2782	
2 ft	3549	
4 ft	3310	
6 ft	3155	
8 ft	3326	
10 ft	3595	

Table 11 - (cont'd.)

Bore Hole	Gamma Spectra Peak Integral ^a	Comments
19-S14-Grade	4048	
2 ft	3894	
4 ft	3610	
6 ft	2955	
8 ft	3038	
19-S15-Grade	14139	Contamination
2 ft	4445	
4 ft	8318	Contamination
6 ft	5440	
19-S16-Grade	39593	Contamination
2 ft	17508	Contamination
4 ft	6632	Contamination
6 ft	4903	
8 ft	6666	Contamination
10 ft	4003	
12 ft	3694	

^aIntegral of the 0.61 MeV peak (0.56-0.67 MeV).

^bIndicates the unambiguous presence of ²²⁶Ra decay chain contamination.

Table 13

Estimated Volume and Mass of Contaminated Material
That Could Be Generated by Remedial Action

Type Material	Density (g/cm ³)	Estimated Volume		Estimated Mass	
		m ³	ft ³	kg	lbs (avoir)
Soil	1.5	680	24,000	1.0x10 ⁶	2.2x10 ⁶
Rubble	0.8	850	30,000	0.7x10 ⁶	1.5x10 ⁶
Total		1,530	54,000	1.7x10 ⁶	3.7x10 ⁶

APPENDICES

Appendices 1 through 5 and 7 contain detailed descriptions of the array of instruments and computational and analytical procedures typically employed by ANL's Radiological Survey Group in its comprehensive radiological assessments. Although the specific instruments and techniques used in a given survey depend on the conditions encountered and the information sought, descriptions of the entire array have been included here for completeness. The exact instruments and methods used in the survey reported in this document are specified in appropriate discussions in the text.

Appendix 6 contains excerpts from numerous regulations, standards, and guidelines relative to radiological conditions and exposure to radiation. Not all these necessarily apply at each site surveyed. Again, however, all have been included for completeness. The pertinent regulations, standards, and guidelines for this survey are cited in the text.

Appendix 8 contains a generic discussion of the nature and sources of radiation, its potential danger to humans, and methods utilized to evaluate radiation exposures.

APPENDIX 1

INSTRUMENTATION

I. PORTABLE RADIATION SURVEY METERS

A. Gas-Flow Proportional Survey Meters

The Eberline PAC-4G-3 was the primary instrument used for surveying. This instrument is a gas-flow proportional counter which utilizes a propane gas-proportional detector, 51 cm² (AC-21), 100 cm², or 325 cm² (AC-22) in area, with a thin double-aluminized Mylar window (~ 0.85 mg/cm²).

Since this instrument has multiple high-voltage settings, it can be used to distinguish between alpha and beta-gamma contamination. This instrument was initially used in the beta mode. In that mode, the detector responds to alpha and beta particles and x- and gamma-rays. When areas indicated a higher count rate than the average instrument background, the beta-mode reading was recorded, and the instrument was then switched to the alpha mode to determine any alpha contribution. In the alpha mode, the instrument responds only to particles with high-specific ionization. The alpha voltage is set to 1600 V, and the input discriminator is set to 1.5 mV. The instrument is then calibrated in the alpha mode with four flat-plate, infinitely-thin NBS-traceable ²³⁹Pu standards, and in the beta mode with a flat-plate, infinitely-thin NBS-traceable ⁹⁰Sr-⁹⁰Y standard. The PAC-4G-3 instruments are calibrated to an apparent 50% detection efficiency.

B. Beta-Gamma End Window Survey Meter

When an area of contamination was found with a PAC instrument, a reading was taken with an Eberline Beta-gamma Geiger-Mueller Counter, Model E-530, with a HP-190 probe. This probe has a thin mica end window and is, therefore, sensitive to alpha and beta particles and x- and gamma-rays. A thin piece of aluminum is added to the mica, making the window density approximately 7 mg/cm². At this density, the instrument is not sensitive to the majority of alpha emissions. A maximum reading is obtained with the probe placed in contact with the area of contamination. In this position, the response (in mR/h) to gamma radiation is generally conservative relative to a determination of mrad/h at 1 cm. This instrument is calibrated in mR/h with a ²²⁶Ra standard.

C. Low-Energy Gamma Scintillation Survey Meter

An Eberline Model PRM-5-3 with a PG-2 gamma scintillation detector was used to determine low-energy x and gamma radiation. The PG-2 detector consists of a thin NaI(Tl) scintillation crystal 5 cm (2 in.) in diameter by 2 mm thick. This instrument is calibrated on three separate high voltages for three energy regions using ²³⁹Pu (17 keV), ²⁴¹Am (59.5 keV), and ²³⁵U (185.7 keV) sources. This instrument can be operated in either a differential (to discriminate between different energy regions) or integral mode.

APPENDIX 1 (cont'd.)

D. High-Energy Micro "R" Scintillation Survey Meter

An Eberline Micro "R" meter model PRM-7 was used to detect high-energy gamma radiation. This instrument contains an internally mounted NaI(Tl) scintillation crystal 2.5 cm (1 in.) in diameter by 2.5 cm (1 in.) thick and can be used to measure fields of low-level radiation between 10 μ R/h and 5000 μ R/h. This instrument is used to survey ambient background radiation. It is held 1 m (3 ft.) from the surface during the survey. This instrument is also calibrated with a standard ^{226}Ra source and checked daily with a ^{137}Cs - ^{137m}Ba source.

E. Integrating Radiation Meter

In addition to the PRM-7, a pressurized ion chamber (Reuter Stokes Model RSS-111) was used at selected locations to determine the ambient radiation field. The RSS-111 has three output modes: (1) instantaneous exposure rate, (2) strip chart differential readout, and (3) integrated exposure. The chamber is mounted on a tripod, 3 ft (~ 1 m) above the surface and has a uniform energy response from about 0.2 MeV to about 4 MeV. A 3-h period of operation is usually sufficient to obtain significant data.

II. SMEAR-COUNTING INSTRUMENTATION

A. Large Area Counter

An ANL-designed gas-flow proportional detector connected to an Eberline Mini Scaler Model MS-2 was used to count multiple smears simultaneously. This detector has a double-aluminized Mylar window (400 cm^2) and uses P-10 (90% argon and 10% methane) as the counting gas. The metal sample holder for this detector has been machined to hold ten smear papers. This particular system consists of two Mini Scalers and two detectors. One is used to count in the alpha mode; the other is used in the beta mode. Up to ten samples can be counted simultaneously.

B. Proportional Counters

Any smear taken from a contaminated area was counted individually in a Nuclear Measurements Corporation gas-flow proportional counter (PC-5 or PC-3A). These instruments have been modified to contain a double-aluminized Mylar spun top window. This top is placed over non-conducting media (e.g. paper smears) to negate the dielectric effect on the counter. This counter also uses P-10 counting gas. Smears are counted in both the alpha and beta modes.

C. Calibration Procedures

The PC counters are calibrated by adjusting the input discriminator with the high voltage set at 700 V until it begins to count an alpha source.

APPENDIX 1 (cont'd.)

The plateaus are run to establish the operating voltages for alpha and beta-gamma. The MS-2 input discriminator is set to 2 mV and again plateaus are run to establish the operating voltages.

D. Liquid Scintillation Counter

In areas where low-energy beta emitting nuclides (e.g., ^3H and ^{14}C) are known to have been used, the smear survey is performed using expanded polystyrene. The polystyrene is dissolved in a liquid scintillation cocktail. The vial of liquid is counted in a Nuclear Enterprises, Inc., Liquid Scintillation Counter LSC-2 designed to measure picocurie quantities of these nuclides. Dual channels with associated single-channel analyzers provide capability for counting beta spectra at two energy regions simultaneously.

III. AIR-SAMPLING DEVICE

A. ANL Radon Progeny Pump (Filter Queen)

Air samples were collected using a commercially available (ANL-modified Filter Queen) vacuum cleaner identified as the "Princess Model." Air was drawn through a filter medium at a flow rate of 40 m³/h. The filters consist of 200-cm² sheets of Hollingsworth-Vose (HV-70) or LB5211-9 mil filter paper. The collection efficiency at these flow rates for 0.3- μm particles is about 99.9%.

B. Actinon Pump

A separate air sample can be taken with a positive displacement pump drawing about 20 liters/min through a Millipore membrane (0.5 to 0.8 μm) filter paper for about one hour. An alpha spectrum can be measured from a section of this filter paper. The ratio of actinon (^{219}Rn) daughters (6.62 MeV α , AcC) to radon (^{222}Rn) daughters (7.69 MeV α , RaC') can be determined from this spectrum.

C. Tritium

A cold trap was set up with dry ice and methanol. An air sample was taken with a positive displacement pump drawing about 20 l/min through the cold trap for two to three hours. The water vapor from the air condenses on the sides of the cold trap. At the end of sampling, a 1 ml aliquot of the condensed water vapor and 10 ml of scintillation cocktail are mixed in a 20 ml counting vial.

The windows on the Liquid Scintillation Counter (LSC-2) are set to count the beta particles from ^{14}C and ^3H . The samples in the vials are counted for four minutes after they have settled and cleared.

The relative humidity reading is measured with a sling psychrometer. The wet and dry bulb readings are recorded.

APPENDIX 1
(cont'd.)

IV. GAMMA SPECTRAL INSTRUMENTATION

A. Contamination Identification

A Nuclear Data Multichannel Analyzer Model ND-100, utilizing a 7.6-cm (3-in.) diameter by 7.6-cm (3-in.) thick NaI(Tl) lead shielded scintillation crystal is commonly used for determining a gamma spectrum. The crystal and lead shielding are located inside the radiological survey vehicle. This instrument is calibrated with NBS-traceable gamma sources. This system can be used to identify contaminant radionuclides by analyzing the gamma-rays emitted by samples from contaminated areas.

Hyperpure Germanium detectors (ORTEC - 17% efficiency right-circular cylinders) can be used when more sophisticated gamma-ray analyses are required. These detectors are coupled to Nuclear Data Multichannel Analyzers (Models ND-60, ND-66 or ND-100).

B. Borehole Logging

The gamma-ray spectrum of a borehole is logged using the Bicron 5.1 cm (2 in) by 5.1 cm (2 in) NaI crystal and either the ND-66 or the ND-100. This crystal is specially designed to withstand the temperature changes that can be encountered in boreholes. Permanent records of the spectrum are produced by the teletype printer and paper tape punch or the Centronix Printer and Magnetic Tape Drive.

C. Portable Analyzer

A Nuclear Data portable multichannel analyzer, ND-6, utilizing a 5 cm diameter by 5 cm thick (2 in by 2 in) NaI(Tl) scintillation crystal is commonly used for determining the gamma-ray spectrum of items or areas that cannot be taken to the mobile laboratory. This instrument is battery operated and has both internal storage capabilities and a tape cassette. This instrument is also calibrated with NBS-traceable gamma-ray sources and is used to identify contaminant radionuclides from their emitted gamma-rays.

APPENDIX 2

CONVERSION FACTORS

I. INSTRUMENTATION

The factors used to convert the instrument readings to units of disintegrations per minute per 100 cm² (dis/min-100 cm²) and the derivation of those factors are listed below.

A. Conversion Factors

	<u>PAC-4G-3</u> <u>(51 cm²)</u>		<u>PAC-4G-3</u> <u>(100 cm²)</u>		<u>Floor</u> <u>Monitor</u> <u>(FM-4G)</u>	
	<u>Alpha</u>	<u>Beta</u>	<u>Alpha</u>	<u>Beta</u>	<u>Alpha</u>	<u>Beta</u>
To 100 cm ²	1.96	1.96	1.00	1.00	0.31	0.31
dis/min per cts/min for ⁹⁰ Sr- ⁹⁰ Y	-	2	-	2	-	2
dis/min per cts/min for ²³⁹ Pu	2	-	2	-	2	-
dis/min per cts/min for normal U	3.5	2.7	2.7	2.4	3.0	2.5
dis/min per cts/min for ²²⁶ Ra plus daughters	1.7	1.8	1.7	1.8	1.7	1.8

E. Derivation of Conversion Factors. Floor Monitor

Window Area: ~ 325 cm²

Conversion to 100 cm² = 0.31 times Floor Monitor readings

. PAC-4G-3

Window Area: ~ 51 cm²

Conversion to 100 cm² = 1.96 times PAC reading

Window Area: ~ 100 cm²

Conversion to 100 cm² = 1.00 times PAC reading.

. 2π Internal Gas-Flow Counter, PC counter

Geometry: Solid Steel Spun Top - 0.50

APPENDIX 2 (cont'd.)

Geometry: Mylar Spun Top - 0.43

Mylar spun top counting {double-aluminized Mylar window ($\sim 0.85 \text{ mg/cm}^2$)} utilizes the well of the PC counter and is a method developed and used by the Argonne National Laboratory Health Physics Section for negating the dielectric effect in counting samples on nonconducting media.

The PAC-4G-3 and PC counters were calibrated as described in Appendix 1. With a flat-plate, infinitely thin ^{226}Ra plus short-lived daughters standard used as a source of alpha emissions, the plate was counted in a 2π Internal Gas-Flow Counter (PC counter) with the source leveled to an apparent 2π geometry. The alpha counts per minute (cts/min) reading was found to be 1.86×10^4 cts/min, or $1.86 \times 10^4 \div 0.51^* = 3.65 \times 10^4$ disintegrations per minute (dis/min) alpha. Since the source was infinitely-thin, the alpha component was used as the total alpha dis/min of the source.

The same ^{226}Ra plus daughters source, when counted with the PAC instrument in the alpha mode, was found to be 2.18×10^4 cts/min at contact. The conversion factor for cts/min to dis/min for the PAC instrument is $3.65 \times 10^4 \div 2.18 \times 10^4 = 1.7$ dis/min per cts/min alpha.

The same source was covered with two layers of conducting paper, each 6.31 mg/cm^2 , to absorb the alpha emissions. With the PC counter in the beta mode and the paper in good contact with the chamber, the count was found to be 1.17×10^4 cts/min or $1.17 \times 10^4 \div 0.50 = 2.35 \times 10^4$ dis/min beta. With the PAC-4G-3 in the beta mode and in contact with the covered source in the center of the probe, the count was found to be 1.36×10^4 cts/min. This indicates a conversion factor of $2.35 \times 10^4 \div 1.36 \times 10^4 = 1.7$ dis/min per cts/min beta-gamma. All three detectors (51 cm^2 , 100 cm^2 , and 325 cm^2) gave readings similar to those reported above for the alpha and beta-gamma modes.

Utilizing a 1.25 in. x 1.25 in. x 0.005 in. ($3.2 \text{ cm} \times 3.2 \text{ cm} \times 0.013 \text{ cm}$) normal uranium foil as a source of uranium alpha emissions, the foil was counted in a PC counter with the source leveled to an apparent 2π geometry. The same normal uranium source, covered with two layers of conducting paper in good contact with the chamber, each 6.31 mg/cm^2 to negate the alpha emissions, was counted for composite beta and gamma emissions in the PC counter. The source was leveled to an apparent 2π geometry; however, no provision was made for backscatter.

The normal uranium source was also counted with the PAC instruments using all three detector areas in the alpha mode and covered with two layers of conducting paper in the beta mode. The conversion factors were calculated as for ^{226}Ra .

*The value of 0.51 includes the following factors: geometry (g) = 0.50; backscatter factor (bg) = 1.02; sample absorption factor (sa) = 1.0; window air factor (waf) = 1.0. The product of $g \times bg \times sa \times waf$ is 0.51.

APPENDIX 2
(cont'd.)

II. SMEAR COUNT

The conversion factors for cts/min-100 cm² to dis/min-100 cm² for smear counts are given below:

A. Conversion Equation (Alpha)

$$\frac{\text{cts/min} - (\text{Bkgd})}{g \times bf \times sa \times waf} = \text{dis/min } \alpha$$

A geometry (g) of 0.43 is standard for all flat-plate counting using the Mylar spun top.

A backscatter factor (bf) of 1.0 is used when determining alpha activity on a filter media.

The self-absorption factor (sa) is assumed to be 1, unless otherwise determined.

If the energies of the isotope are known, the appropriate window air factor (waf) is used; if the energies of the isotopes are not known, the (waf) of ²³⁹Pu (0.713) is used.

The (waf) for alpha from ²²⁶Ra plus daughters is 0.55.

B. Conversion Equation (Beta)

$$\frac{\text{cts/min} - \{\beta \text{ Bkgd (cts/min)} + \alpha \text{ cts/min}\}}{g \times bf \times sa \times waf} = \text{dis/min } \beta$$

A geometry (g) of 0.43 is standard for all flat-plate counting using the Mylar spun top.

A backscatter factor (bf) of 1.1 is used when determining beta activity on a filter media.

A self-absorption factor (sa) is assumed to be 1, unless otherwise determined.

If the energies of the isotopes are known, the appropriate window air factor (waf) is used; if the energies of the isotopes are unknown, the (waf) of ⁹⁰Sr-⁹⁰Y (0.85) is used.

The (waf) for betas from ²²⁶Ra plus daughters is 0.85.

APPENDIX 2
(cont'd.)

III. TRITIUM SMEAR COUNT

The conversion equation for cts/min-100 cm² to dis/min-100 cm² for popcorn smear counts is given below:

$$C_e = \frac{A_e - B}{Y}$$

where: C_e = dis/min removable contamination
 A_e = measured counts/min of removable contamination
 B = measured background of clean popcorn dissolved in the scintillation cocktail
 Y = combined yield of the counter and scintillation cocktail as given in more detail in Appendix 3, Section VA.

For the Nuclear Enterprises, Inc., Liquid Scintillation Counter (LSC-2), the high voltage is set to 900 Volts. The A channel threshold is set at 360 and the window is set at 999 for ¹⁴C. The B gain is set at times ten (x10). The B channel threshold is set at 150 and the window is set at 825 for ³H.

APPENDIX 3

AIRBORNE RADIONUCLIDE CONCENTRATION CALCULATIONS

Calculations for determining radon concentrations in air samples collected with an Argonne National Laboratory-designed air sampler using HV-70 or LB-5211 filter media are summarized in Sections I through IV of this appendix; the basic assumptions and calculations used to derive the air concentrations also are included. Calculations for determining tritium concentrations in air samples collected by condensing water vapor from the air are summarized in Section V of this appendix.

I. RADON CONCENTRATIONS

The following postulates are assumed in deriving the radon (^{222}Rn) concentrations based on the RaC' alpha count results.

- A. RaA, RaB, RaC, and RaC' are in equilibrium.
- B. RaA is present only in the first count and not the 100-minute decay count.
- C. One-half of the radon progeny is not collected on the filter media, (i.e., unattached fraction).
- D. The geometry factor (g) is 0.43 for both the alpha and beta activity.
- E. The backscatter factor (bf) for the alpha activity is 1.0.
- F. The sample absorption factor (sa) for RaC' is 0.77.
- G. The window air factor (waf) for RaC' is 0.8.
- H. RaB and RaC, being beta emitters, are not counted in the alpha mode.
- I. The half-life of the radon progeny is approximately 36 minutes, based on the combined RaB and RaC half-lives.
- J. Thoron and long-lived alpha emitters are accounted for using the 360-minute decay count and the seven-day count, respectively.
- K. For all practical purposes, RaC' decays at the rate of the composite of RaB and RaC, which is about 36 minutes.

The following postulates are assumed in deriving the thoron (^{220}Rn) concentrations.

- L. ThA, ThB, ThC and ThC' are in equilibrium.
- M. ThA and RaC' have decayed by the 360-minute decay count.

APPENDIX 3
(cont'd.)

- N. The geometry factor (g), backscatter factor (bf), sample absorption factor (sa) and window air factor (waf) all are the same for thoron as for radon.
- O. ThB and 64% of ThC, being beta emitters, are not counted in the alpha mode.
- P. The half-life of the thoron progeny is 10.64 hours (638.4 minutes) based on the ThB half-life.
- Q. For all practical purposes, 36% of the ThC (alpha branch) and the ThC' decay at the same rate as ThB which is 638.4 minutes.
- R. The counter does not differentiate between the ThC alphas and the ThC' alphas.

The following postulates are assumed in deriving the actinon (^{219}Rn) concentrations:

- S. AcA, AcB and AcC are in equilibrium.
- T. AcA has decayed by the 100-minute decay count.
- U. The geometry (g), backscatter (bf), sample absorption (sa) and window air factor (waf) factors all are the same for actinon as for radon.
- V. AcB, being a beta emitter, is not counted in the alpha mode.
- W. The half-life of the actinon progeny is 36.1 minutes based on the AcB half-life.
- X. For all practical purposes, the AcC decays at the same rate as AcB, which is 36.1 minutes.
- Y. 84% of the AcC decays by 6.62 MeV α emissions and 16% decays by 6.28 MeV α emissions.

The following postulate is assumed in deriving the long-lived concentration:

- Z. The long-lived activity, as determined from the seven-day count, is assumed to be constant during the entire counting period. This assumption is valid for isotopes with half-lives longer than a few years.

APPENDIX 3 (cont'd.)

II. EQUATIONS USED TO DERIVE AIR CONCENTRATIONS

$$A_o = \frac{A}{e^{-\lambda t}}$$

where: A_o = activity (dis/min) present at the end of the sampling period (usually 40 minutes)

A = activity (dis/min) at some time, t , after end of the sampling period

t = time interval (minutes) from end of sampling period to counting interval (usually ≈ 100 minutes)

$$\lambda = \frac{0.693}{t_{1/2}}$$

$t_{1/2}$ = half-life of isotope (minutes).

Concentration is determined by the equation:

$$C = \frac{A_o \lambda}{f} \times \frac{1}{1 - e^{-\lambda t_s}}$$

where: C = concentration (dis/min-m³)

A_o = activity on filter media at end of sampling period (dis/min)

f = sampling rate (m³/min = m³/h $\times$ 1 h/60 minutes)

t_s = length of sampling time (minutes)

$$\lambda = \frac{0.693}{t_{1/2}}$$

$t_{1/2}$ = half-life of isotope or controlling parent (minutes).

III. ACTINON CORRECTION

Since the actinon (²¹⁹Rn) progeny (AcB & AcC) decays at the AcB half-life of 36 minutes, it cannot be distinguished from the radon (²²²Rn) progeny using standard air sampling with HV-70 or LB-5211 filter media and standard alpha-counting techniques. A positive displacement pump is used to collect a sample on Millipore membrane (0.5 to 0.8 μ m) filter media. The

APPENDIX 3

(cont'd.)

sample rate is approximately 20 liters/minute for a sampling time of at least 90 minutes. The center portion of the sample is removed and counted in an alpha spectrometer which exhibits the 6.62 MeV AcC alpha emissions and the 7.69 MeV RaC' alpha emissions. If these two peaks are observed in the spectrum, then the following calculations are performed:

$$B_j = \sum_{i=1}^n b_{ij}$$

where: B_j = summation of the counts in n channels under peak j

b_{ij} = the number of counts in channel i of peak j

j = 1 for the 6.62 MeV peak of actinon; 2 for the 7.69 MeV peak of radon

n = total number of channels in the summation.

The fractions of the activity with a 36-minute half-life due to actinon and radon are then:

$$\text{Actinon} = \frac{B_1/0.84}{B_1/0.84 + B_2}$$

$$\text{Radon} = \frac{B_2}{B_1/0.84 + B_2}$$

where 1 refers to actinon progeny and 2 refers to radon progeny.

IV. EXAMPLE CALCULATION

Data have been created to correspond to values likely to occur if all possible types of contamination are present in the air of a room where a sample is collected. The applications of the equations for determining all types of activity and their concentrations are given below:

Data	$f = 40 \text{ m}^3/60 \text{ min}$	$t = 40 \text{ min}$
at $t = 100 \text{ min}$		$A^s = 2000 \text{ dis/min}$
at $t = 360 \text{ min}$		$A = 140 \text{ dis/min}$
at $t = 7 \text{ days}$		$A = 5 \text{ dis/min}$

For long-lived activity:

$$A_o = A = 5 \text{ dis/min}$$

$$C(L) = A_o / fxt_s = \frac{5}{40/60 \times 40} = 0.19 \text{ dis/min-m}^3.$$

APPENDIX 3
(cont'd.)

For thoron:

$$A_o = \frac{140-5}{\exp - \frac{0.693 \times 360}{638.4}} = 199.6 \text{ dis/min}$$

$$C(\text{Tn}) = \frac{199.6 \times \frac{0.693}{638.4}}{40/60} \times \frac{1}{1 - \exp - \frac{0.693 \times 40}{638.4}} = 7.6 \text{ dis/min-m}^3$$

For radon (^{222}Rn) and actinon (^{219}Rn), activity due to thoron at $t = 100 \text{ min}$:

$$A = \frac{135}{\exp - \frac{0.693 \times 260}{638.4}} = 179 \text{ dis/min.}$$

Activity due to the isotopes with a 36-minute half-life:

$$A = 2000 - 179 - 5 = 1816 \text{ dis/min}$$

$$A_o = \frac{1816}{\exp - \frac{0.693 \times 100}{36}} = 12,454 \text{ dis/min}$$

$$C(36) = \frac{12,454 \times \frac{0.693}{36}}{40/60} \times \frac{1}{1 - \exp - \frac{0.693 \times 40}{36}} = 669.7 \text{ dis/min-m}^3.$$

When an actinon peak is seen at 6.62 MeV, the counts under the two peaks are summed. For example, if 10 channels are summed, the following counts are found:

For 6.62 MeV peak: 44 in 10 channels, where the 6.62 alpha emissions are 84% of the total.

For 7.69 MeV peak: 601 counts in 10 channels, where the 7.69 MeV alpha emissions are 100% of the total.

APPENDIX 3
(cont'd.)

$$B_1 = 44$$

$$B_1/0.84 = 52 \text{ counts}$$

$$B_2 = 601 \text{ counts}$$

$$\text{Actinon} = 52/653 = 0.08$$

$$\text{Radon} = 601/653 = 0.92$$

$$C(\text{Rn}) = C(36) \times \text{Radon}\% = 669.7 \times 0.92 = 616.1 \text{ dis/min-m}^3$$

$$C = C(36) \times \text{Actinon}\% = 669.7 \times 0.08 = 53.6 \text{ dis/min-m}^3.$$

Since we assume that on the average half of the progeny is not adhered to the filter paper, the above concentrations are then doubled to determine actual concentrations in the air. We assume that there is no unattached fraction for the long-lived activity.

$$C \text{ actual} = C \text{ measured} \times \text{progeny correction factor}$$

$$C(\text{L}) = 0.19 \text{ dis/min-m}^3$$

$$C(\text{Tn}) = 7.6 \text{ dis/min-m}^3 \times 2 = 15.2 \text{ dis/min-m}^3$$

$$C(\text{An}) = 53.6 \text{ dis/min-m}^3 \times 2 = 107.2 \text{ dis/min-m}^3$$

$$C(\text{Rn}) = 616 \text{ dis/min-m}^3 \times 2 = 1232 \text{ dis/min-m}^3.$$

These would then be the resulting concentrations in dis/min-m^3 . To convert to pCi/l , divide the concentrations by 2.2×10^3 :

$$C(\text{L}) = \frac{0.19 \text{ dis/min-m}^3}{2,220 \text{ dis/min-m}^3/\text{pCi/l}} = 8.6 \times 10^{-5} \text{ pCi/l}$$

$$C(\text{Tn}) = \frac{15.2 \text{ dis/min-m}^3}{2,220 \text{ dis/min-m}^3/\text{pCi/l}} = 0.0068 \text{ pCi/l}$$

$$C(\text{An}) = \frac{107.2 \text{ dis/min-m}^3}{2,220 \text{ dis/min-m}^3/\text{pCi/l}} = 0.048 \text{ pCi/l}$$

$$C(\text{Rn}) = \frac{1232 \text{ dis/min-m}^3}{2,220 \text{ dis/min-m}^3/\text{pCi/l}} = 0.55 \text{ pCi/l}.$$

APPENDIX 3 (cont'd.)

V. RADON MONITORING INSTRUMENTS

Continuous monitoring of the radon concentration (and concomitant Working Level) is accomplished by using a commercially available Eberline Radon Gas Monitor Model 2 (RMG-2) and/or an Environmental Working Level Monitor Model 2 (EWLM-2) designed and built at Argonne National Laboratory (ANL). Details of these instruments can be found in their respective operating manuals. The manual for the former instrument is available from the Eberline Division of the Thermo Electron Corporation, P.O. Box 2108, Santa Fe, New Mexico 87501. The manual for the latter instrument is available from the authors of this report at Argonne National Laboratory. A brief summary describing each instrument is given below.

RADON GAS MONITOR (RGM-2):

The Model RGM-2 Radon Gas Monitor is a complete, semi-portable system for continuous measurement of radon gas. The instrument incorporates a 1 liter scintillation cell detector for radon gas detection and a microcomputer for data analysis. A pump is included for continuous gas flow, and an alphanumeric printer is used to record the data for unattended operation. The electronics section contains a variable high voltage supply and a charge-sensitive input amplifier. The power supply source is designed to operate from normal power line sources or from a dc power source, and it incorporates an internal battery as backup for power source disturbances. All the electronic circuits are solidstate with integrated circuits used extensively to enhance reliability.

The microcomputer is programmed to provide data output, in picocuries per liter (pCi/l), by computing the data from gross detector counts divided by the detector calibration factor and subtracting the detector background counts. Normal data output is printed hourly and a 24-hour average is printed at the end of a 24-hour period. A test routine; status conditions of alarm, power and airflow; and day/time-of-day functions are included. Operator control is provided by a 16-key keyboard.

The instrument is housed in an insulated steel cabinet for environmental protection. Detachable legs and handles are provided for ease of transportation.

ENVIRONMENTAL WORKING LEVEL MONITOR (EWLM-2)

The Environmental Working Level Monitor (EWLM) is an instrument used to automatically monitor airborne Rn-daughter concentrations and the Working Level (WL). It is an ac powered, microprocessor based instrument with an external inverter provided for dc operation if desired. The microprocessor's control power unit (CPU) controls the actuation of the detector assembly and processes its output signals to yield the measurements in the proper units. The detectors are fully automated and require no manual operations once the instrument is programmed. They detect and separate the alpha emitters of RaA and RaC' as well as detecting the beta emitters of RaB and RaC. The resultant pulses from these detected radioisotopes are

APPENDIX 3 (cont'd.)

transmitted to the CPU. The programmed microprocessor performs the mathematical manipulations necessary to output accurate Rn-daughter concentrations and the WL. A special subroutine within the system program enables the EWLM to run a calibration procedure on command which yields calibration data. This data can then be processed in a separate program on most computers capable of BASIC programming. This calibration program results in the derivation of coefficients and beta efficiencies which provides the calibrated coefficients and beta efficiencies required by the main system program to assure proper calibration of the individual EWLM's.

Each of these instruments require calibration procedures to insure that output numbers are commensurate with the radon levels and Working Levels being ascertained.

The Radon Gas Monitor (RGM-2) was calibrated with a Radon bubbler constructed from an NBS standard radium source. The efficiency determined in this fashion was consistent with the efficiency value supplied by the manufacturer. This instrument (RGM-2) determines picoCuries per liter of radon. Assuming equilibrium between the radon parent and the short-lived daughters these values are readily converted to Working Levels.

The Environmental Working Level Monitor (EWLM-2) was calibrated by determining the efficiency of each detector using standard sources. The instrument then determines the Working Level from these efficiencies and the radioactivity in the radon daughter products collected on the filter paper. Since only one-half of the radon progeny are collected on the filter paper (see Section Ic of this Appendix) the values determined with this instrument are increased by a factor of two to account for the "unattached fraction" of radon daughters present in the air but not collected on the filter paper.

VI. TRITIUM CONCENTRATIONS

It is assumed that all the tritium in the air is part of a water molecule and that all the water vapor is collected in the cold trap.

A. Yield

A secondary tritium standard is made by taking a primary standard of known concentration and diluting it with distilled water to make a secondary standard of approximately 5×10^4 dis/min. The activity of the secondary standard is calculated from the dilution ratio and by using the decay equation:

$$I = I_0 e^{-\lambda t}$$

APPENDIX 3 (cont'd.)

where: I_0 = dis/min of the primary standard at the date indicated for this standard.

$$\lambda = \frac{0.693}{t_{1/2}}$$

$t_{1/2}$ = half-life of ^3H or 12.28 years.

t = time interval from the primary standard date to the time of mixing the secondary standard.

I = dis/min of the secondary standard at the time it was mixed with distilled water.

The scintillation standard is mixed at the time of use by taking a 1 ml aliquot of the secondary standard and dissolving it in 10 ml of the scintillation cocktail. The activity of this scintillation standard is calculated using the decay equation above. Now, however,

I_0 = dis/min of the secondary standard at the time of mixing.

t = time interval from mixing the secondary standard to mixing the scintillation standard.

I = dis/min of the scintillation standard at the time it was mixed with the cocktail.

The combined yield of the counter and the scintillation cocktail are determined using the following equation.

$$Y = \frac{A_s - B}{I}$$

where: Y = yield

A_s = measured counts of a tritium standard

B = measured background

I = dis/min of the standard in the scintillation cocktail at the time of calibration as calculated from the decay equation given above.

B. Humidity

The grams of water per cubic meter of dry air (ϵ) are determined from the composite humidity chart (see Fig. 3A).

APPENDIX 3 (cont'd.)

C. Tritium

The activity of 1 ml of the condensate is then:

$$C_e = \frac{A_e - B}{Y}$$

where: C_e = dis/min-ml of the water vapor

A_e = measured counts of the water vapor sample

B = measured background of distilled water dissolved in the scintillation cocktail.

The concentration of tritium in the air is then:

$$C_a = \frac{C_e \times \epsilon}{\rho \times 2.22 \text{ dis/min-pCi}}$$

where: C_a = $\mu\text{Ci/m}^3$

ϵ = humidity ($\text{gmH}_2\text{O/m}^3$ dry air)

ρ = water density (1 gm/ml)

D. Example

The secondary standard was mixed April 5, 1984, in the liquid scintillation cocktail. The activity of the scintillation standard was calculated and the information recorded on the scintillation vial as indicated:

Data on April 5, 1984: $I_o = 4.14 \times 10^4$ dis/min of the tritium scintillation standard at the time it was prepared.

Data on May 1, 1984: $A_s = 8854.75$ cts/min from the tritium standard

$B = 29.25$ cts/min background

Wet bulb = 56°F, Dry Bulb = 68°F

$A_e = 78$ cts/min from the water vapor sample

Source strength at the time the sample was collected:

APPENDIX 3
(cont'd.)

$$I = 4.14 \times 10^4 \times \exp - \frac{0.693 \times 0.0712}{12.28} = 4.12 \times 10^4$$

Combined counter and scintillation cocktail yield:

$$Y = \frac{8854.75 - 29.25}{4.12 \times 10^4} = 0.214$$

Humidity: $\epsilon = 8.25 \text{ g/m}^3$

Concentration in a 1 ml aliquot of the condensate:

$$C_e = \frac{78 - 29.25}{0.214} = 228 \text{ dis/min-ml.}$$

Concentration in the air: $C_a = \frac{228 \times 8.25}{1 \times 2.22} = 847 \text{ pCi/m}^3$

$$847 \text{ pCi/m}^3 \times 10^{-3} \text{ m}^3/\ell = 0.85 \text{ pCi}/\ell.$$

Reference

1. Weast, R.C. (Editor-in-Chief). 1959. Handbook of Chemistry and Physics, 59th Edition (1978-1979) D-232, E-45, F11.

Figure 3A Absolute Humidity Chart.

APPENDIX 4

SAMPLE PREPARATION AND ANALYSIS, GENERIC PROTOCOL

I. SOIL-SAMPLE PREPARATION

Soil samples are acquired as previously described. These samples are bagged and identified at the collection site and returned to ANL. If there is an indication of radioactive contamination, the sample is sealed in a Nalgene jar. At ANL, the soil samples are logged into the soil-sample book, and each sample is weighed (on a tared balance scale) and the weight is marked on the container. This weight is recorded in the soil book as a "wet weight."

After all samples are marked, weighed, and recorded, they are dried. Each sample is placed in a pyrex beaker marked with the sample identification number. If more than one beaker is necessary, additional numbers (e.g., 1-3, 2-3, 3-3) are used. The original containers are saved for repackaging the dried samples. The beaker is set in an 80°C oven until the soil is dry (approximately 48 hours). The sample is returned to the original container and reweighed using a tared balance scale. This weight is also marked on the container and in the soil-sample book, where it is referred to as a "dry weight."

After all the samples are returned to their original containers, the milling process is started. Each dried sample is transferred to a 2.3-gallon ceramic mill jar containing mill balls (1½" x 1½" Burundum cylinders). The mill jar number is marked on the original container. The jars are sealed and the samples are milled for two hours or until sufficient material is produced to obtain 100 g and 5 g samples for analyses. The samples are milled six at a time. A second set of six jars is prepared while the milling of the first set is proceeding. After each sample is milled, the mill balls are removed with tongs and placed in a tray. A large plastic bag is inverted over the mill jar. Both are inverted and shaken until all the soil is transferred to the bag. If the soil plates the inside of the mill jar, a small paint brush is used to loosen the soil before the jar is inverted. A separate brush is used for each jar to prevent cross-contamination of the soil samples.

After milling, each sample is sieved through a number 30 standard testing sieve (600 μ mesh) and transferred to a 12" x 12" ziplock bag. Rocks and dross are bagged separately from the sieved material. The bags are marked with the sample number, the sieve number and R(rocks) or S(soil). The balance is tared and the weights of the soil (or rocks) are measured and recorded in the soil-sample book. A 100-g sample of the sieved material is transferred to a 4-oz. Nalgene bottle. These samples are analyzed by suitable analytical techniques, including, as a minimum, gamma spectroscopy (GeLi). A 5-g sample of the sieved material is transferred to a 1-oz Nalgene bottle. One gram of this sample is used for the determination of uranium by laser fluorometry; 100 grams of this are needed for radiochemical analysis for Pu, Am, and Th if these analyses are required. The bottles containing these weighed samples are marked with sample number and date, and

APPENDIX 4
(cont'd.)

this information is recorded in the soil-sample book. The rocks (and dross) and remaining soil are placed in storage.

The sieves, mill jars, and Burundum milling balls used in this work are classified in two sets. One set is used for background samples exclusively. The other set is used for all samples from suspect areas. Soil samples with elevated levels of radioactivity based on instrument measurements are milled in one-gallon Nalgene bottles using Burundum balls from the set used for suspect samples. After use, these balls are either decontaminated (see below) or disposed of as radioactive waste. The Nalgene bottles are always disposed of as radioactive waste. The sieves used for these samples are also from the set used for suspect samples and are decontaminated after use.

II. EQUIPMENT DECONTAMINATION

The care of the milling apparatus is as important as the actual sample preparation. Proper care prevents cross-contamination of successive samples. The beakers used to dry the samples are washed thoroughly by placing a small amount of Haemo-Sol in each beaker and filling with warm water. The beaker is then scrubbed thoroughly on the inside and scoured on the outside with scouring powder. The beakers are rinsed three times with tap water and three times with demineralized water, and finally dried thoroughly before reuse.

The milling apparatus (tongs, brushes, milling jars, lids and milling balls) are rinsed. The tongs and brushes are washed thoroughly with Haemo-Sol. Eight Burundum balls are returned to each milling jar along with about one pint of clean road gravel, one spoon of Haemo-Sol, one spoon of scouring powder with bleach, and one quart of water. The lid is tightened on the jar and the jar is placed on the rolling mill and rolled for approximately two hours or until the balls and the inside of the jar appear to be physically clean. After this time, the mill jar is removed from the rolling mill and its contents are dumped into a screen or basket. The lid and balls are then rinsed thoroughly three times with tap water followed by three times with demineralized water. The inside of the jar is rinsed until it is absolutely clean. The milling apparatus is air dried with warm air. Room air is drawn through the mill jars with a hose which is attached to a fume hood or specially constructed drying box.

The sieves are rinsed, washed in Haemo-Sol, thoroughly rinsed (three times with tap water, followed by three rinses with demineralized water) and then air dried as above before reuse.

III. WATER AND SLUDGE

Water samples are collected in 0.1-liter, 0.5-liter, and/or 1-liter quantities as deemed appropriate. These samples are forwarded directly to a certified radiochemistry laboratory for preparation and analysis. The customary analysis procedure consists of filtration to obtain the suspended solids followed by evaporation to obtain the dissolved solids. Both sus-

APPENDIX 4 (cont'd.)

pended and dissolved solids are analyzed by appropriate radiochemical analytical techniques.

Sludge samples are collected in 0.1-liter bottles and are processed as outlined above for water samples.

IV. VEGETATION, TRASH AND RUBBLE

Samples of potentially contaminated vegetation, trash (e.g. piping, ducts, conduit, etc.), and rubble are collected, bagged, and labeled at the site and returned to ANL for analysis.

Vegetation samples are initially weighed and transferred to Marinelli beakers for gamma spectrometric analysis. Then they are ashed, reweighed, and analyzed by appropriate analytical techniques.

Trash and rubble samples are forwarded to a certified radiochemistry laboratory for analysis.

V. TRITIUM FROM SOLID MATERIALS

Samples of solid materials (e.g., concrete) suspected of containing tritium are collected, broken into small pieces, and submitted to a certified radiochemistry laboratory for analysis. The standard analytical procedure consists of transferring a 20-40 g sample to a ceramic boat followed by heating in a tube furnace at 425°C for a period of two hours (~ 40 min to reach temperature and ~ 80 min heating at temperature). Helium is used as a flow gas through the tube during heating, and the tritium is collected in two traps on the downstream side of the furnace. The first trap is immersed in an ordinary ice bath (0°C); the second trap is immersed in a CO₂-Freon bath (-57°C). The collected tritiated water from both traps is combined, made up to a known volume, and an aliquot taken for liquid scintillation counting of the tritium.

VI. ANALYSIS PROCEDURES

A 100-g fraction from each soil sample is analyzed by high resolution gamma-ray spectroscopy using a germanium crystal detector coupled to a multichannel analyzer. This analysis allows for a quantitative determination of the ²²⁶Ra decay chain (via the 609 keV γ-ray of ²¹⁴Pb) and the ²³²Th decay chain (via the 911 keV γ-ray of ²²⁸Ac), as well as any other gamma emitting radionuclide (e.g. ¹³⁷Cs) present in the soil.

The total uranium (elemental) present in the soil is determined by an acid leach of the soil sample followed by laser fluorometry of the leached sample.

Thorium analysis consists of an acid leach of the soil (using a ²³⁴Th spike for yield determination) followed by plating a thin source of the

APPENDIX 4
(cont'd.)

radiochemically separated thorium and determining the thorium isotopes (^{228}Th and ^{232}Th) by alpha spectroscopy.

The results of the above measurements allow for quantitative determination of the relative amounts of normal uranium, natural uranium, tailings (i.e., ^{226}Ra decay chain), thorium (^{232}Th), mesothorium (^{228}Ra decay chain), radiothorium (^{228}Th decay chain), plutonium (^{238}Pu , $^{239,240}\text{Pu}$), and americium (^{241}Am) present in the contaminated material.

A mass spectrometric analysis of the uranium fraction is conducted when it is known or it is surmised that depleted or enriched uranium might be present.

APPENDIX 5

CALCULATION OF URANIUM SPECIFIC ACTIVITY

The specific activity for normal uranium was obtained by summing the measured specific activities for the individual isotopes weighted according to their normal abundances. Best values for these specific activities were taken from A. H. Jaffey et al., Phys. Rev.C 4 1889 (1971). The half-life for each isotope was taken from David C. Kocher, "Radioactive Decay Tables - A Handbook of Decay Data for Application to Radiation Dosimetry and Radiological Assessments" (1981). The percent abundances were taken from N. E. Holden, BNL-NCS-50605 (1977). Atomic weights were taken from the Handbook of Chemistry and Physics, 52nd Edition (1971). The specific activity of ^{234}U was calculated from the half-life.

Isotope	Specific Activity (dis/min- μg)	Half-life (years)	Abundance (atom %)	Atomic Weight (grams)	Abundance (wt %)
^{234}U	1.387×10^4	2.446×10^5	0.0054	234.0409	0.0053
^{235}U	4.798	7.038×10^8	0.720	235.0439	0.7110
^{238}U	0.746	4.4683×10^9	99.2746	238.0508	99.2837
			100.0000		100.0000

where $(\text{wt } \%)_i =$

$$\frac{(\text{atom } \%)_i (\text{atomic weight})_i}{\sum_j (\text{atom } \%)_j (\text{atomic weight})_j} = \frac{(\text{atom } \%)_i (\text{atomic weight})_i}{238.0289}$$

Specific activity for normal uranium:

$$\begin{array}{rcl} 0.746 \times 0.99284 \times 2 & = & 1.481 \text{ dis/min-}\mu\text{g from } ^{234}\text{U} \text{ \& } ^{238}\text{U} \\ 4.798 \times 0.00711 & = & 0.034 \text{ dis/min-}\mu\text{g from } ^{235}\text{U} \\ & & \hline & & 1.515 \text{ dis/min-}\mu\text{g for normal U} \end{array}$$

or $(1.515 \text{ dis/min-}\mu\text{g}) / (2.22 \text{ dis/min-pCi}) = 0.683 \text{ pCi}/\mu\text{g}$

where ^{234}U is assumed to be in secular equilibrium with the ^{238}U parent.

Note that 2.25% of the total activity is due to ^{235}U and 48.87% each is due to ^{234}U and ^{238}U .

Calculation of the specific activity of other than normal mixtures of uranium isotopes are performed in a similar manner. For example, uranium having the isotopic composition (atom %) 238(0.99268), 236(0.000007), 235(0.007233), 234(0.000064) and 233(0.000012) as determined by mass spectrometry would have the composition (weight %) of 238(.99278), 236(0.000007), 235(0.007142), 234(0.000063), and 233 (0.000012) and the following specific activity:

APPENDIX 5
(cont'd.)

0.99278	x 0.746	= 0.7406 dis/min- μ g	from ^{238}U
0.000007	x 1.436×10^2	= 0.0010 dis/min- μ g	from ^{236}U *
0.007142	x 4.798	= 0.0343 dis/min- μ g	from ^{235}U
0.000063	x 1.387×10^4	= 0.8738 dis/min- μ g	from ^{234}U
0.000012	x 2.140×10^4	= 0.2568 dis/min- μ g	from ^{233}U **
		<u>1.9065</u>	dis/min- μ g U total

corresponding to:

$$(1.9065 \text{ dis/min-}\mu\text{g}) / (2.22 \text{ dis/min-pCi}) = 0.859 \text{ pCi}/\mu\text{g U}$$

*The half-life for ^{236}U (2.342×10^7 yr) and the corresponding specific activity (1.436×10^2 dis/min- μ g) were taken from K. F. Flynn et. al., J. Inorg. Nucl. Chem. 34 1121 (1972).

**The half-life for ^{233}U (1.5911×10^5 yr) and the corresponding specific activity (2.140×10^4 dis/min- μ g) were taken from A. H. Jaffey, K. F. Flynn et. al., Phys. Rev. C 9 1991 (1974).

APPENDIX 6

PERTINENT RADIOLOGICAL REGULATIONS,
STANDARDS, AND GUIDELINES

- I. U.S. NUCLEAR REGULATORY COMMISSION
DIVISION OF FUEL CYCLE AND MATERIAL SAFETY
WASHINGTON, D.C.
July 1982

GUIDELINES FOR DECONTAMINATION OF FACILITIES AND
EQUIPMENT PRIOR TO RELEASE FOR UNRESTRICTED
USE OR TERMINATION OF LICENSES FOR BY-PRODUCT
SOURCE, OR SPECIAL NUCLEAR MATERIAL

(These have been retyped for
purposes of this report)

The instructions in this guide, in conjunction with Table 1, specify the radioactivity and radiation exposure rate limits which should be used in accomplishing the decontamination and survey of surfaces or premises and equipment prior to abandonment or release for unrestricted use. The limits in Table 1 do not apply to premises, equipment, or scrap containing induced radioactivity for which the radiological considerations pertinent to their use may be different. The release of such facilities or items from regulatory control will be considered on a case-by-case basis.

1. The licensee shall make a reasonable effort to eliminate residual contamination.
2. Radioactivity on equipment or surfaces shall not be covered by paint, plating, or other covering material unless contamination levels, as determined by a survey and documented, are below the limits specified in Table 1 prior to applying the covering. A reasonable effort must be made to minimize the contamination prior to use of any covering.
3. The radioactivity on the interior surfaces of pipes, drain lines, or duct work shall be determined by making measurements at all traps, and other appropriate access points, provided that contamination at these locations is likely to be representative of contamination on the interior of the pipes, drain lines, or duct work. Surfaces of premises, equipment, or scrap which are likely to be contaminated but are of such size, construction, or location as to make the surface inaccessible for purposes of measurement shall be presumed to be contaminated in excess of the limits.
4. Upon request, the Commission may authorize a licensee to relinquish possession or control of premises, equipment, or scrap having surfaces contaminated with materials in excess of the limits specified. This may include, but would not be limited to, special circumstances such as razing of buildings, transfer of premises to another organization continuing work with radioactive materials, or conversion of facilities to a long-term storage or standby status. Such request must:

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(cont'd.)

- a. Provide detailed, specific information describing the premises, equipment or scrap, radioactive contaminants, and the nature, extent, and degree of residual surface contamination.
 - b. Provide a detailed health and safety analysis which reflects that the residual amounts of materials on surface areas, together with other considerations such as prospective use of the premises, equipment or scrap, are unlikely to result in an unreasonable risk to the health and safety of the public.
5. Prior to release of premises for unrestricted use, the licensee shall make a comprehensive radiation survey which establishes that contamination is within the limits specified in Table 1. A copy of the survey report shall be filed with the Division of Fuel Cycle and Material Safety, USNRC, Washington, D.C. 20555, and also the Director of the Regional Office of the Office of Inspection and Enforcement, USNRC, having jurisdiction. The report should be filed at least 30 days prior to the planned date of abandonment. The survey report shall:
- a. Identify the premises.
 - b. Show that reasonable effort has been made to eliminate residual contamination.
 - c. Describe the scope of the survey and general procedures followed.
 - d. State the findings of the survey in units specified in the instruction.

Following review of the report, the NRC will consider visiting the facilities to confirm the survey.

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(cont'd.)

TABLE 1

ACCEPTABLE SURFACE CONTAMINATION LIMITS

NUCLIDES ^a	AVERAGE ^{bcf}	MAXIMUM ^{bdf}	REMOVABLE ^{bef}
U-nat, ²³⁵ U, ²³⁸ U and associated decay products	5000 dis/min-100 cm ² α	15,000 dis/min-100 cm ² α	1000 dis/min-100 cm ² α
Transuranics, ²²⁶ Ra, ²²⁸ Ra, ²³⁰ Th, ²²⁸ Th, ²³¹ Pa, ²²⁷ Ac, ¹²⁵ I, ¹²⁹ I	100 dis/min-100 cm ²	300 dis/min-100 cm ²	20 dis/min-100 cm ²
Th-nat, ²³² Th ⁹⁰ Sr, ²²³ Ra, ²²⁴ Ra, ²³² U, ¹²⁶ I, ¹³¹ I, ¹³³ I	1000 dis/min-100 cm ²	3,000 dis/min-100 cm ²	200 dis/min-100 cm ²
Beta-gamma emitters (nu- clides with decay modes other than alpha emission or spontaneous fission) except ⁹⁰ Sr and others noted above.	5000 dis/min-100 cm ² βγ	15,000 dis/min-100 cm ² βγ	1000 dis/min-100 cm ² βγ

APPENDIX 6
(cont'd.)

TABLE 1

ACCEPTABLE SURFACE CONTAMINATION LEVELS

- ^aWhere surface contamination by both alpha and beta-gamma emitting nuclides exists, the limits established for alpha and beta-gamma emitting nuclides should apply independently.
- ^bAs used in this table, dis/min (disintegrations per minute) means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.
- ^cMeasurements of average contaminant should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.
- ^dThe maximum contamination level applies to an area of not more than 100 cm².
- ^eThe amount of removable radioactive material per 100 cm² of surface area should be determined by wiping that area with dry filter or soft absorbent paper, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire surface should be wiped.
- ^fThe average and maximum radiation levels associated with surface contamination resulting from beta-gamma emitters should not exceed 0.2 mrad/h at 1 cm and 1.0 mrad/h at 1 cm, respectively, measured through not more than 7 milligrams per square centimeter of total absorber.

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(cont'd.)

II.

SURGEON GENERAL'S GUIDELINES
as included in 10 CFR Part 712
Grand Junction Remedial Action Criteria

712.1 Purpose

(a) determination by DOE of the need for, priority of and selection of appropriate remedial action to limit the exposure of individuals in the area of Grand Junction, Colorado, to radiation emanating from uranium mill tailings which have been used as construction-related material.

(b) The regulations in this part are issued pursuant to Pub. L. 92-314 (86 Stat. 222) of June 16, 1972.

712.2 Scope

The regulations in this part apply to all structures in the area of Grand Junction, Colorado, under or adjacent to which uranium mill tailings have been used as a construction-related material between January 1, 1951, and June 16, 1972, inclusive.

712.3 Definitions

As used in this part:

(a) "Administrator" means the Administrator of Energy Research and Development or his duly authorized representative.

(b) "Area of Grand Junction, Colorado," means Mesa County, Colorado.

(c) "Background" means radiation arising from cosmic rays and radioactive material other than uranium mill tailings.

(d) "DOE" means the U.S. Department of Energy or any duly authorized representative thereof.

(e) "Construction-related material" means any material used in the construction of a structure.

(f) "External gamma radiation level" means the average gamma radiation exposure rate for the habitable area of a structure as measured near floor level.

APPENDIX 6

(cont'd.)

(g) "Indoor radon daughter concentration level" means that concentration of radon daughters determined by: (1) averaging the results of six air samples each of at least 100 hours duration, and taken at a minimum of 4-week intervals throughout the year in a habitable area of a structure, or (2) utilizing some other procedure approved by the Commission.

(h) "Milliroentgen" (mR) means a unit equal to one-thousandth (1/1000) of a roentgen which roentgen is defined as an exposure dose of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign.

(i) "Radiation" means the electromagnetic energy (gamma) and the particulate radiation (alpha and beta) which emanate from the radioactive decay of radium and its daughter products.

(j) "Radon daughters" means the consecutive decay products of radon-222. Generally, these include Radium A (polonium-218), Radium B (lead-214), Radium C (bismuth-214), and Radium C' (polonium-214).

(k) "Remedial action" means any action taken with a reasonable expectation of reducing the radiation exposure resulting from uranium mill tailings which have been used as construction-related material in and around structures in the area of Grand Junction, Colorado.

(l) "Surgeon General's Guidelines" means radiation guidelines related to uranium mill tailings prepared and released by the Office of the U.S. Surgeon General, Department of Health, Education and Welfare on July 27, 1970.

(m) "Uranium mill tailings" means tailings from a uranium milling operation involved in the Federal uranium procurement program.

(n) "Working Level" (WL) means any combination of short-lived radon daughter products in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of potential alpha energy.

712.4 Interpretations

Except as specifically authorized by the Administrator in writing, no interpretation of the meaning of the regulations in this part by an officer or employee of DOE other than a written interpretation by the General Counsel will be recognized to be binding upon DOE.

712.5 Communications

Except where otherwise specified in this part, all communications concerning the regulations in this part should be addressed to the Director,

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(cont'd.)

Division of Safety, Standards, and Compliance, U.S. Department of Energy, Washington, D.C. 20545.

712.6 General radiation exposure level criteria for remedial action.

The basis for undertaking remedial action shall be the applicable guidelines published by the Surgeon General of the United States. These guidelines recommended the following graded action levels for remedial action in terms of external gamma radiation level (EGR) and indoor radon daughter concentration level (RDC) above background found within dwellings constructed on or with uranium mill tailings.

EGR	RDC	Recommendation
Greater than 0.1 mR/h	Greater than 0.05 WL	Remedial action indicated.
From 0.05 to 0.1 mR/h	From 0.01 to 0.05 WL	Remedial action may be suggested.
Less than 0.05 mR/h	Less than 0.01 WL	No remedial action indicated

712.7 Criteria for determination of possible need for remedial action

Once it is determined that a possible need for remedial action exists, the record owner of a structure shall be notified of that structure's eligibility for an engineering assessment to confirm the need for remedial action and to ascertain the most appropriate remedial measure, if any. A determination of possible need will be made if as a result of the presence of uranium mill tailings under or adjacent to the structure, one of the following criteria is met:

(a) Where DOE approved data on indoor radon daughter concentration levels are available

(1) For dwellings and schoolrooms: An indoor radon daughter concentration level of 0.01 WL or greater above background.

(2) For other structures: An indoor radon daughter concentration level of 0.03 WL or greater above background.

(b) Where DOE approved data on indoor radon daughter concentration levels are not available:

(1) For dwellings and schoolrooms:

APPENDIX 6 (cont'd.)

(i) An external gamma radiation level of 0.05 mR/h or greater above background.

(ii) An indoor radon daughter concentration level of 0.01 WL or greater above background (presumed).

(A) It may be presumed that if the external gamma radiation level is equal to or exceed 0.02 mR/h above background, the indoor radon daughter concentration level equals or exceeds 0.01 WL above background.

(B) It should be presumed that if the external gamma radiation level is less than 0.001 mR/h above background, the indoor radon daughter concentration level is less than 0.01 WL above background, and no possible need for remedial actions exists.

(C) If the external gamma radiation level is equal to or greater than 0.001 mR/h above background but is less than 0.02 mR/h above background, measurements will be required to ascertain the indoor radon daughter concentration level.

(2) For other structures:

(i) An external gamma radiation level of 0.15 mR/h above background averaged on a room-by-room basis.

(ii) No presumptions shall be made on the external gamma radiation level/indoor radon daughter concentration level relationship. Decisions will be made in individual cases based upon the results of actual measurements.

712.8 Determination of possible need for remedial action where criteria have not been met.

The possible need for remedial action may be determined where the criteria in 712.7 have not been met if various other factors are present. Such factors include, but are not necessarily limited to, size of the affected area, distribution of radiation levels in the affected area, amount of tailings, age of individuals occupying affected area, occupancy time, and use of the affected area.

712.9 Factors to be considered in determination of order of priority for remedial action.

In determining the order or priority for execution of remedial action, consideration shall be given, but not necessarily limited to, the following factors:

(a) Classification of structure. Dwellings and schools shall be considered first.

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(cont'd.)

(b) Availability of data. Those structures for which data on indoor radon daughter concentration levels and/or external gamma radiation levels are available when the program starts and which meet the criteria in 712.7 will be considered first.

(c) Order of application. Insofar as feasible remedial action will be taken in the order in which the application is received.

(d) Magnitude of radiation level. In general, those structures with the highest radiation levels will be given primary consideration.

(e) Geographical location of structures. A group of structures located in the same immediate geographical vicinity may be given priority consideration particularly where they involved similar remedial efforts.

(f) Availability of structures. An attempt will be made to schedule remedial action during those periods when remedial action can be taken with minimum interference.

(g) Climatic conditions. Climatic conditions or other reasonable considerations may affect the scheduling of certain remedial measures.

712.10 Selection of appropriate remedial action.

(a) Tailings will be removed from those structures where the appropriately averaged external gamma radiation level is equal to or greater than 0.05 mR/h above background in the case of dwellings and schools and 0.15 mR/h above background in the case of other structures.

(b) Where the criterion in paragraph (a) of this section is not met, other remedial action techniques, including but not limited to sealants, ventilation, and shielding may be considered in addition to that of tailings removal. DOE shall select the remedial action technique or combination of techniques, which it determines to be the most appropriate under the circumstances.

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(cont'd.)

III.

40 CFR Part 192
HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS
FOR
URANIUM MILL TAILINGS

(Excerpts have been retyped for purposes of this report)

SUBPART B--Standards for Cleanup of Open Lands and Buildings Contaminated with Residual Radioactive Materials from Inactive Uranium Processing Sites

192.10 Applicability

This subpart applies to land and buildings which are part of any processing site designated by the Secretary of Energy under Pub. L. 95-604, Section 102. Section 101 of Pub. L. 95-604, states that "processing site" means--

(a) any site, including the mill, containing residual radioactive materials at which all or substantially all of the uranium was produced for sale to any Federal agency prior to January 1, 1971, under a contract with any Federal agency, except in the case of a site at or near Slick Rock, Colorado, unless--

(1) such site was owned or controlled as of January 1, 1978, or is thereafter owned or controlled, by a Federal agency, or

(2) a license [issued by the (Nuclear Regulatory) Commission or its predecessor agency under the Atomic Energy Act of 1954 or by a State as permitted under Section 274 of such Act] for the production at such site of any uranium or thorium product derived from ores is in effect on January 1, 1978, or is issued or renewed after such date; and

(b) Any other real property or improvement thereon which--

(1) is in the vicinity of such site, and

(2) is determined by the Secretary, in consultation with the Commission, to be contaminated with residual radioactive materials derived from such site.

192.11 Definitions

(a) Unless otherwise indicated in this subpart, all terms shall have the same meaning as defined in Title I of the Act or in Subpart A.

(b) Land means any surface or subsurface land that is not part of a disposal site and is not covered by an occupiable building.

(c) Working Level (WL) means combination of short-lived radon decay products in one liter of air that will result in the ultimate emission of alpha particles with a total energy of 130 billion electron Volts.

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(cont'd.)

(d) Soil means all unconsolidated materials normally found on or near the surface of the earth including, but not limited to silts, clays, sands, gravel, and small rocks.

192.12 Standards

Remedial actions shall be conducted so as to provide reasonable assurance that, as a result of residual radioactive materials from any designated processing site:

(a) the concentration of radium-226 in land averaged over any area of 100 square meters shall not exceed the background level by more than--

(1) 5 pCi/g, averaged over the first 15 cm of soil below the surface, and

(2) 15 pCi/g, averaged 15 cm thick layers of soil more than 15 cm below the surface.

(b) in any occupied or habitable building---

(1) the objective of remedial action shall be, and reasonable effort shall be made to achieve, an annual average (or equivalent) radon decay product concentration (including background) not to exceed 0.02 WL. In any case, the radon decay product concentration (including background) shall not exceed 0.03 WL, and

(2) the level of gamma radiation shall not exceed the background level by more than 20 microroentgens per hour.

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(cont'd.)

- IV. DOE 5480.1 Chg. 6, Chapter XI
(Excerpts have been retyped for purposes of this report.)

REQUIREMENTS FOR RADIATION PROTECTION

(Excerpts have been retyped for purposes of this report. Table XI-1 has been modified to reflect the fundamental definition of the Curie as a unit of radioactivity. The designation of uranium is changed to reflect the original usage of the terms normal and natural.)

1. PURPOSE This chapter establishes radiation protection standards and requirements for Department of Energy and Department of Energy contractor operations based upon the recommendations of the Environmental Protection Agency and the National Council on Radiation Protection and Measurement.
2. DEFINITIONS
 - a. Controlled Area. Any area to which access is controlled in order to protect individuals from exposure to radiation and radioactive materials.
 - b. Dose Commitment. The dose equivalent (rem) received by specific organs during a period of one calendar year, that was the result of uptakes of radionuclides by a person occupationally exposed.
4. REQUIREMENTS.
 - a. Occupationally Related Exposure of Individuals in Controlled Areas. Radiation exposures shall be limited to levels reasonably achievable within the standards prescribed below.

(1) Radiation Protection Standards for External and Internal Exposures

<u>Type of Exposure</u>	<u>Exposure Period</u>	<u>Dose Equivalent (Dose or Dose Commitment¹ rem)</u>
Whole body, head and trunk, gonads, lens of the eye ² , red bone marrow, active blood-forming organs.	Year	5 ³
	Calendar Quarter	3

APPENDIX 6
(cont'd.)

Unlimited areas of the skin (except hands and forearms). Other organs, tissues, and organ systems (except bone).	Year	15
	Calendar Quarter	5
Bone	Year	30
	Calendar Quarter	10
Forearms ⁴	Year	30
	Calendar Quarter	10
Hands ⁴ and Feet	Year	75
	Calendar Quarter	25

¹To meet the above dose commitment standards, operations must be conducted in such a manner that it would be unlikely that an individual would assimilate in a critical organ, by inhalation, ingestion, or absorption, a quantity of radionuclide or mixture of radionuclides that would commit the individual to an organ dose that exceeds the limits specified in the above table.

²A beta exposure below a maximum energy of 700 keV will not penetrate the lens of the eye; therefore, the applicable limit for these energies would be that for the skin (15 rem/year).

³In special cases, with the approval of EP-30, a worker may exceed 5 rem/year, provided his or her average exposure per year since age 18 will not exceed 5 rem per year. This does not apply to emergency situations.

⁴All reasonable effort shall be made to keep exposures of forearms and hands to the general limit for the skin.

(2) Procedural Requirements

(a) Restrictions

- 1 An individual under age 18 shall neither be employed in, nor allowed to enter, controlled areas in such a manner that he or she will receive doses of radiation in amounts exceeding one-tenth the standards in paragraph 4a(1) above.

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(cont'd.)

- 2 Dose to students under age 18 exposed to radiation during educational activities shall not exceed 0.1 rem/year. This exposure shall be considered a part of the 0.5 rem/year limit for workers under age 18 and not supplemental to it.

- (b) Combining Internal and External Dose. Current year whole body internal dose commitment from radionuclides for which the whole body is the critical organ must be combined with the external whole body dose. Where both the external penetrating dose and internal dose to critical organ are known, they shall be combined for that organ.

- b. Exposure of Individuals and Population Groups in Uncontrolled Areas. Exposures to members of the public shall be as low as reasonably achievable levels within the standards prescribed below.

- (1) Radiation Protection Standards for External and Internal Exposure.

Type of Exposure	Annual Dose Equivalent or Dose Commitment ¹	
	Based on Dose to Individuals at Points of Maximum Probable Exposure	Based on Average Dose to a Suitable Sample of the Exposed Population ²
Whole body, gonads, or bone marrow	0.5 rem (or 500 mrem)	0.17 rem (or 170 mrem)
Other organs (or 1500 mrem)	1.5 rem (or 500 mrem)	0.5 rem

¹In keeping with Department of Energy policy on lowest practicable exposures, exposures to the public shall be limited to as small a fraction of the respective annual dose limits as is reasonably achievable.

²See Paragraph 5.4, Federal Radiation Council Report No. 1, for discussion on concept of suitable sample of exposed population.

APPENDIX 6
(cont'd.)

- (2) Monitoring Requirements. To assure that doses to the public are maintained as low as reasonably achievable consistent with dose standards set forth in paragraph 4b(1) above, effluents to the environment, and other parameters shall be monitored and documented in accordance with DOE 5484.1.
- (3) Concentration Guides.
- (a) Concentration Guides in Attachment XI-1, Table II, were derived for the most part from the dose standards for individuals in paragraph 4b(1) above (assume 168 hours of exposure per week). These guides shall be reduced by a factor of three when applied to a suitable sample of the population. Where transient exposures can be calculated, the concentration guides other than those in Attachment XI-1, Table II, may be used to evaluate compliance with the dose commitment standard.
 - (b) There may be situations where it is not feasible or desirable to evaluate the exposure of individuals and samples of exposed populations to effluents to assure compliance with standards in paragraph 4b(1) above. In those cases, effluent releases to uncontrolled areas shall be such that average concentrations of radioactivity at the point of release are within the concentration guides and are as low as reasonably achievable. The point of release shall be considered to be the point at which the effluents pass beyond the site boundary. Radioactivity concentrations may be averaged over periods up to 1 year.
- (4) Further Limitations on Effluent Discharges. In any situation in which the effluents discharged by one or more activities of the Department, Department contractors, or others cause exposure to approach the standards specified in subparagraph b(1) above, appropriate effluent discharge limits may be set for these operations. In such cases, the manager of the field organization may take the necessary corrective action if all activities concerned are within his or her area of responsibility. Otherwise, each case will be referred to EP-30 for appropriate action including, where appropriate, coordination with actions taken by the Nuclear Regulatory Commission under the Code of Federal Regulations, Title 10, Part 20.106(e).
- (5) Discharge to Sanitary Sewage Systems.
- (a) Effluents may be discharged to public sanitary sewage systems provided:

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(cont'd.)

1 The quantity of radioactivity released in any one month, if diluted by the average monthly quantity of water released by the installation, will not result in an average concentration exceeding the concentration guide in Attachment XI-1, Table I, Column 2.

2 The radiation protection standards in paragraph (1), above, are not exceeded.

(b) Concentrations or quantities of radioactive materials greater than those specified in paragraphs 4(b) and (5)(a) 1 and 2, above, may be released to chemical or sanitary sewage systems owned by the Federal Government provided the standards in paragraph 4b(1) above are not exceeded in uncontrolled areas.

Attachment XI-1

CONCENTRATIONS IN AIR AND WATER ABOVE NATURAL BACKGROUND

Element (atomic number)	Isotope soluble (S) insoluble (I)			Table I Controlled Area		Table II Uncontrolled Area	
				Column 1 Air (pCi/l)	Column 2 Water (pCi/l)	Column 1 Air (pCi/l)	Column 2 Water (pCi/l)
Hydrogen (1)	H	3	S	5000	1×10^8	200	3×10^6
			I	5000	1×10^8	200	3×10^6
Cobalt (27)	Co	60	S	300	1×10^6	10	5×10^4
			I	9	1×10^6	0.3	3×10^4
Silver (47)	Ag	110m	S	200	9×10^5	7	3×10^4
			I	10	9×10^5	0.3	3×10^4
Cesium (55)	Cs	137	S	60	4×10^5	2	2×10^4
			I	10	1×10^6	0.5	4×10^4
Europium (63)	Eu	152	S	10	2×10^6	0.4	8×10^4
			I	20	2×10^6	0.6	8×10^4
Lead (82)	Pb	212	S	20	6×10^5	0.6	2×10^4
			I	20	5×10^5	0.7	2×10^4
Radon (86)	Rn	220	S	300		10	
		222	I	100		3	
Radium (88)	Ra	226	S	0.05	400	0.003	30
			I	0.05	9×10^5	0.002	3×10^4

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(cont'd.)

Thorium (90) ¹ natural	S	0.06	2×10^4	0.002	2000
	I	0.06	6×10^5	0.002	2×10^4
Uranium (92) ² normal	S	0.14	4×10^4	0.006	1200
	I	0.12	1×10^6	0.004	4×10^4

¹The Curie is the activity of that quantity of radioactive material in which the number of disintegrations per second is 3.7×10^{10} . In DOE Order 5480.1, Chapter XI, the Curie was redefined to 3.7×10^{10} dis/sec from Th-232 plus 3.7×10^{10} dis/sec from Th-228. In order to make the above table consistent with the real definition of Curie, the concentrations for natural thorium were multiplied by a factor of 2.

²In this report, the terms natural uranium and normal uranium are used as they were commonly used in the early days of MED work. Natural uranium is uranium as found in nature in equilibrium with all its daughter products. Normal uranium is uranium that has been processed to separate it from its long-lived daughter products (i.e., the daughter products Th-230 through Pb-206).

In Doe Order 5480.1 Chapter XI the Curie is redefined as 3.7×10^{10} dis/sec from U-238 plus 3.7×10^{10} dis/sec from U-234 plus 1.7×10^9 dis/sec from U-235. This is also called natural uranium in these regulations. In order to make the above table consistent with the real definition of Curie, the concentrations for uranium were multiplied by a factor of 2.046. Also, the uranium is called normal uranium as the term is used elsewhere in this report and since the regulation implies that the uranium has been separated from its long-lived daughter products. This is consistent with the earliest use of these terms.

APPENDIX 7

ESTIMATED EXTENT OF CONTAMINATION

I. SOIL

Estimates of the extent of the contamination at the assessed site are based on the total volume, mass, and quantity of radioactive material in the contaminated area. The volume is the product of the surface area and the depth of the contamination. The mass is the product of the volume and the density of the material. A density of 1.5 g/cm^3 is used for soil. The concentration (pCi/g) of the specific radioisotope is determined by radiochemical analysis of the soil. The total quantity of radioactive material is the product of the concentration of the specific radioisotope and the total mass of material.

Often there is more than one contaminant in the soil (or contaminated material) and the contaminants are not uniformly distributed throughout the material. In these cases, it is necessary to estimate the fraction of the material containing each contaminant in order to assess the total quantity of the radioactive material. This estimate of the fraction of the material containing each contaminant is based on the radiochemical analysis of randomly selected samples.

Estimates of the extent of contamination are usually determined for averaged (Option 1) and maximum or worst-case (Option 2) conditions. Sample calculations for the extent of contamination in a typical FUSRAP site are as follows:

$$\begin{aligned} \text{Volume (average)} &= 34,800 \text{ ft}^2 \text{ (area)} \times 3.6 \text{ ft (avg. depth)} = 125,000 \text{ ft}^3 \\ &= 3,550 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{Volume (maximum)} &= 34,800 \text{ ft}^2 \text{ (area)} \times 9 \text{ ft (max. depth)} = 314,000 \text{ ft}^3 \\ &= 8,880 \text{ m}^3 \end{aligned}$$

$$\text{Mass (average)} = 3,550 \text{ m}^3 \times 1,500 \text{ kg/m}^3 = 5.33 \times 10^6 \text{ kg}$$

$$\text{Mass (maximum)} = 8,880 \text{ m}^3 \times 1,500 \text{ kg/m}^3 = 1.33 \times 10^7 \text{ kg}$$

Estimated Total Activity for ^{226}Ra (chain)

$$\begin{aligned} \text{Average: } &5.33 \times 10^6 \text{ kg} \times 14 \times 10^{-12} \text{ Ci/g} \times 10^3 \text{ g/kg} \times .05 \text{ (fraction)*} \\ &= 0.004 \text{ Ci} \end{aligned}$$

$$\begin{aligned} \text{Maximum: } &1.33 \times 10^7 \text{ kg} \times 16 \times 10^{-12} \text{ Ci/g} \times 10^3 \text{ g/kg} \times .05 \text{ (fraction)*} \\ &= 0.011 \text{ Ci.} \end{aligned}$$

*This represents the estimated fraction of the total mass contaminated with the ^{226}Ra chain.

APPENDIX 7 (cont'd.)

II. STRUCTURES

Any estimate of the total mass and volume of radioactively contaminated structural material that would be generated if remedial action were undertaken at a site is subject to many uncertainties. For the purposes of this report, it has been assumed that contamination on concrete, brick, or asphalt will require removal to a depth of 5 cm (2 in.); and contamination on wooden floors and steel will require removal to 2 cm (3/4 in.). These assumptions are believed to be conservative. The densities of the materials are taken to be 2.35 g/cm³ for concrete, 2.2 g/cm³ for brick, 0.5 g/cm³ for wood, 7.8 g/cm³ for steel, and 1.2 g/cm³ for asphalt. Estimates of the surface area contaminated are made during the survey.

It is assumed that the contamination can only be removed by removing the supporting material. The contaminated areas are summed according to host material (e.g., concrete, steel, or wood). The total surface activity was calculated from the activity (dis/min-100 cm²) as measured by the survey meter times the estimated surface area. The activity was then converted to μ Ci. No corrections were made for the depth of the contamination, therefore, the values are underestimated.

A sample calculation follows for two areas of concrete; an 8-ft² area with 7000 dis/min-100 cm² beta-gamma activity and a 2-ft² area with 77,000 dis/min-100 cm² beta-gamma activity.

$$\text{Surface area} = 10 \text{ ft}^2 = 0.93 \text{ m}^2$$

$$\text{Volume} = 0.93 \text{ m}^2 \times 0.05 \text{ m} = 4.6 \times 10^{-2} \text{ m}^3 = 1.6 \text{ ft}^3.$$

$$\text{Mass} = 4.6 \times 10^{-2} \text{ m}^3 \times 2350 \text{ kg/m}^3 = 108 \text{ kg}$$

$$\begin{aligned} \text{Activity} &= (7 \text{ k dis/min-100 cm}^2 \times 8 \text{ ft}^2 \\ &\quad + 77 \text{ k dis/min-100 cm}^2 \times 2 \text{ ft}^2) \times 929 \text{ cm}^2/\text{ft}^2 \\ &= 1.95 \times 10^6 \text{ dis/min} \\ &= 1.95 \times 10^6 / 2.22 \times 10^6 \text{ } \mu\text{Ci} = 0.88 \text{ } \mu\text{Ci} \end{aligned}$$

APPENDIX 8

EVALUATION OF RADIATION EXPOSURES

I. INTRODUCTION

A. Types of Radiation

Radiation is the emission or transmission of energy in the form of waves or particles. Examples are acoustic waves (i.e., sound), electromagnetic waves (such as radio, light, x- and gamma-rays), and particulate radiations (such as alpha particles, beta particles, neutrons, protons, and other elementary particles).

The class of radiation of importance to this report is known as ionizing radiation. Ionizing radiations are those, either electromagnetic or particulate, with sufficient energy to ionize matter, i.e., to remove or displace electrons from atoms and molecules. The most common types of ionizing radiation are x- and gamma-rays, alpha particles, beta particles, and neutrons.

X- and gamma-rays are electromagnetic waves of pure energy, having no charge and no mass or existence at rest. Gamma-rays and x-rays are identical except that x-rays originate in the atom and gamma-rays originate in the nucleus of an atom. X- and gamma-rays are highly penetrating and can pass through relatively thick materials before interacting. Upon interaction, some or all of the energy is transferred to electrons which, in turn, produce additional ionizations while coming to rest.

Alpha particles are positively charged particulates composed of two neutrons and two protons, identical to the nucleus of a helium atom. Due to its comparatively large mass and double charge, an alpha particle interacts readily with matter and penetrates only a very short distance before coming to rest, causing intense ionization along its path.

Beta particles are negatively charged free electrons moving at high speeds. Due to its comparatively small mass and single charge, a beta particle's penetration through matter is intermediate between that of the alpha particle and the gamma-ray, causing fewer ionizations per unit path length than an alpha particle.

B. Sources of Radiation

Ionizing radiations arise from terrestrial radioactive materials (both naturally occurring and man-made), extra-terrestrial (cosmic) sources, and radiation-producing machines. The sources of ionizing radiation important to this report are radioactive materials and cosmic sources.

Most atoms of the elements in our environment remain structurally stable. With time, an atom of potassium, for instance, may change its association with other atoms in chemical reactions and become part of other compounds, but it will always remain a potassium atom. Radioactive atoms,

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(cont'd.)

on the other hand, are not stable and will spontaneously emit radiation in order to achieve a more stable state. Because of this spontaneous transformation, the ratio of protons and neutrons in the nucleus of an atom is altered toward a more stable condition. Radiation may be emitted from the nucleus as alpha particles, beta particles, neutrons, or gamma-rays, depending uniquely upon each particular radionuclide. Radionuclides decay at characteristic rates dependent upon the degree of stability and characterized by a period of time called the half-life. In one half-life, the number of radioactive atoms and, therefore, the amount of radiation emitted, decrease by one half.

The exposure of man to terrestrial radiation is due to naturally occurring radionuclides and also to "man-made" or technologically enhanced radioactive materials. Several dozen radionuclides occur naturally, some having half-lives of at least the same order of magnitude as the estimated age of the earth. The majority of these naturally occurring radionuclides are isotopes of the heavy elements and belong to three distinct radioactive series headed by uranium-238, uranium-235, and thorium-232. Each of these decays to stable isotopes of lead (Pb) through a sequence of radionuclides of widely varying half-lives. Other naturally occurring radionuclides, which decay directly to a stable nuclide, are potassium-40 and rubidium-87. It should be noted that even though the isotopic abundance of potassium-40 is less than 0.012%, potassium is so widespread that potassium-40 contributes about one-third of the radiation dose received by man from natural background radiation. A major portion of the exposure (dose) of man from external terrestrial radiation is due to the radionuclides in the soil, primarily potassium-40 and the radioactive decay-chain products of thorium-232 and uranium-238. The naturally occurring radionuclides deposited internally in man through uptake by inhalation/ ingestion of air, food, and drinking water containing the natural radioactive material also contribute significantly to his total dose. Many other radionuclides are referred to as "man made" in the sense that they can be produced in large quantities by such means as operating nuclear reactors or accelerators, or conducting nuclear weapons tests.

The term "cosmic radiation" refers both to the primary energetic particles of extra-terrestrial origin that are incident on the earth's atmosphere and to the secondary particles that are generated by the interaction of these primary particles with the atmosphere and subsequently reach ground level. Primary cosmic radiation consists of "galactic" particles externally incident on the solar system, and "solar" particles emitted by the sun. This radiation is composed primarily of energetic protons and alpha particles. The first generation of secondary particles (secondary cosmic radiation), produced by nuclear interactions of the primary particles with the atmosphere, consists predominantly of neutrons, protons, and pions. Pion decay, in turn, results in the production of electrons, photons, and muons. At the lower elevations, the highly penetrating muons and their associated decay and collision electrons are the dominant components of the cosmic-ray flux density. These particles, together with photons from the gamma-emitting, naturally occurring radionuclides in the local environment,

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form the external penetrating component of the background environmental radiation field which provides a significant portion of the whole-body radiation dose to man.

In addition to the direct cosmic radiation, cosmic sources include cosmic-ray-produced radioactivity, i.e., cosmogenic radionuclides. The major production of cosmogenic radionuclides is through interaction of the cosmic rays with the atmospheric gases through a variety of spallation or neutron-capture reactions. The four cosmogenic radionuclides that contribute a measurable radiation dose to man are carbon-14, sodium-22, beryllium-7, and hydrogen-3 (tritium), all produced in the atmosphere.

II. BACKGROUND RADIATION DOSES

Background radiation doses are comprised of an external component of radiation impinging on man from outside the body and an internal component due to radioactive materials taken into the body by inhalation or ingestion.

Radiation dose may be expressed in units of rads or rems, depending upon whether the reference is to the energy deposited or to the biological effect. A rad is the amount of radiation that deposits a certain amount of energy in each gram of material. It applies to all radiations and to all materials which absorb that radiation.

Since different types of radiation produce ionizations at different rates as they pass through tissue, differences in damage to tissues (and hence the biological effectiveness of different radiations) has been noticed. A rem is defined as the amount of energy absorbed (in rads) from a given type of radiation multiplied by the factor appropriate for the particular type of radiation in order to approximate the biological damage that it causes relative to a rad of x or gamma radiation. The concept behind the unit "rem" permits evaluation of potential effects from radiation exposure without regard to the type of radiation or its source. One rem received from cosmic radiation results in the same biological effects as one rem from medical x-rays or one rem from the radiations emitted by naturally occurring or man-made radioactive materials.

The external penetrating radiation dose to man derives from both terrestrial radioactivity and cosmic radiation. The terrestrial component is due primarily to the gamma dose from potassium-40 and the radioactive decay products of thorium-232 and uranium-238 in soil, as well as from the beta-gamma dose from radon daughters in the atmosphere. Radon is a gaseous member of the uranium-238 chain. The population-weighted external dose to an individual's whole body from terrestrial sources in the United States has been estimated as 15 mrem per year for the Atlantic and Gulf Coastal Plain, 57 mrem per year for an indeterminate area along the Rocky Mountains, and 29 mrem per year for the majority of the rest of the United States. The overall population-weighted external dose for the U.S. population as a whole has been estimated to be 26 mrem per year.

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(cont'd.)

The cosmic radiation dose, due to the charged particles and neutrons from secondary cosmic rays, is typically about 30% to 50% of the total from all external environmental radiation. The cosmic-ray dose to the population is estimated to be 26 mrem per year for those living at sea level, and increases with increasing altitude. Considering the altitude distribution of the U.S. population, the population-weighted external cosmic-ray dose is 28 mrem per year. The population-weighted total external dose from terrestrial plus cosmic sources is thus 54 mrem per year for the U.S. population as a whole.

The internal radiation doses derive from terrestrial and cosmogenic radionuclides deposited within the body through uptake by inhalation/ingestion of air, food, and drinking water. Once deposited in the body, many radioactive materials can be incorporated into tissues because the chemical properties of the radioisotopes are identical or similar to the properties of stable isotopes in the tissues. Potassium-40, for instance, is incorporated into tissues in the same manner as stable potassium atoms because the chemical properties are identical; radioactive radium and strontium can be incorporated into tissues in the same manner as calcium because their chemical properties are similar. Once deposited in tissue, these radionuclides emit radiation that results in the internal dose to individual organs and/or the whole body as long as the radioactive material is in the body.

The internal dose to the lung is due primarily to the inhalation of polonium-218 and -214 (radon daughters), lead-212 and bismuth-212 (thoron daughters) and polonium-210 (one of the longer-lived radon decay products). The dose to the lung is about 100 mrem per year from inhaled natural radioactivity. The internal dose from subsequent incorporation of inhaled or ingested radioactivity is due to a beta-gamma dose from incorporation of potassium-40, rubidium-87, and cosmogenic nuclides, and an alpha dose from incorporation of primarily polonium-210, radium-226 and -228, and uranium-238 and -234. The dose to man from internally incorporated radionuclides is about 28 mrem per year to the gonads, about 25 mrem per year to the bone marrow, lung, and other soft tissues, and about 117 mrem per year to the bone (osteocytes). The bone dose arises primarily from the alpha-emitting members of the naturally occurring series, with polonium-210 being the largest contributor. The gonadal and soft tissue doses arise primarily from the beta and gamma emissions from potassium-40. The total internal dose from inhaled plus incorporated radioactivity is about 28 mrem per year to the gonads (or whole-body dose), about 125 mrem per year to the lung, about 25 mrem per year to the bone marrow, and about 117 mrem per year to the bone (osteocytes).

The total natural background radiation dose is the sum of the external and internal components. The population-weighted dose for the U.S. population as a whole is about 82 mrem per year to the gonads or whole body, about 179 mrem per year to the lung, about 79 mrem per year to the bone marrow, and about 171 mrem per year to the bone (osteocytes).

APPENDIX 8 (cont'd.)

Besides the natural background radiation, background radiation doses include contributions from man-made or technologically enhanced sources of radiation. By far, the most significant source are x-ray and radiopharmaceutical medical examinations. These contribute a population-averaged dose estimated to be 70 mrem per year for the U.S. population as a whole. Fallout from nuclear weapons testing through 1970 has contributed 50-year dose commitments estimated as 80 mrem external, and 30, 20, and 45 mrem internal to the gonads, lung, and bone marrow, respectively. Contributions from the use of fossil fuels (natural gas and coal) and nuclear reactors; mining, milling, and tailings piles; television sets, smoke detectors, and watch dials could be responsible for an additional 5 mrem per year, averaged over the U.S. population as a whole. In addition, the use of radiation or radioactivity for scientific, industrial, or medical purposes may cause workers in the industry and, to a lesser extent, members of the general public, to receive some radiation exposure above natural background.

III. EVALUATION OF RADIATION DOSE AND POTENTIAL HAZARD

Radiation, regardless of its sources, is considered to be a hazard because of its potential for producing adverse effects on human life. Very large amounts of radiation received over a brief period, i.e., hundreds of rem delivered within a few hours, can produce severe injury or death within days or weeks. Distributed over longer intervals, however, these same doses would not cause early illness or fatality. At doses and rates too low to produce these immediate symptoms, chronic or repeated exposure to radiation can bring about biological damage which does not appear until years or decades later. These low-level effects are stochastic in nature; their probability rather than their severity increases with dose. Primary among these latent or delayed effects are somatic effects, where insults such as cancers occur directly to the individual exposed, and genetic defects, where, through damage to the reproductive cells of the exposed individual, disability and disease ranging from subtle to severe are transmitted to an exposed individual's offspring.

Clinical or observed evidence of a relationship between radiation and human cancers arise from several sources. The most important data come from the victims of Hiroshima and Nagasaki, patients exposed during medical therapy, radium dial painters, and uranium miners. Data exist only for relatively large doses; there have been no direct measurements of increased incidence of cancer for low-level radiation exposures. Evaluation of the available data has lead to estimates of the risk of radiation-induced cancer; estimated risks for the lower doses have been derived by linear extrapolation from the higher doses. All radiation exposures then, no matter how small, are assumed to be capable of increasing an individual's risk of contracting cancer.

Data on genetic defects resulting from radiation exposure of humans is not available to the extent necessary to allow an estimate of the risk of radiation-induced effects. Data from animals, along with general knowledge of genetics, have been used to derive an estimate of the risks of genetic effects.

APPENDIX 8
(cont'd.)

Estimates of health effects from radiation doses are usually based on risk factors as provided in reports issued by the International Commission on Radiological Protection (ICRP), National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR), or United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Multiplying the estimated dose by the appropriate risk factor provides an estimate of the risk or probability of induction of health effects to an individual or his descendants as a result of that exposure. The evaluation of these risk factors is presently subject to large uncertainties and, therefore, potential continual revision. The risk factors recommended by the ICRP for cancer mortality and hereditary ill health to the first and second generations are 10^{-4} per rem of whole-body dose and 4×10^{-5} per rem of gonadal dose, respectively. As an example, a whole-body dose of 1 rem would be estimated to add a risk of cancer mortality to the exposed individual of 10^{-4} , i.e., 1 chance in 10,000. However, a precise numerical value cannot be assigned with any certainty to a particular individual's increase in risk attributable to radiation exposure. The reasons for this are numerous and include the following: (1) uncertainties over the influence of the individual's age, state of health, personal habits, family medical history, and previous or concurrent exposure to other cancer-causing agents, (2) the variability in the latent period (time between exposure and physical evidence of disease), and (3) the uncertainty in the risk factor itself.

To be meaningful, an attempt should be made to view such risk estimates in the appropriate context. One useful comparison is with risks encountered in normal life. Another comparison, potentially more useful, is with an estimation of the risks attributable to natural background radiation. Radiation from natural external and internal radioactivity results in the same types of interactions with body tissues as that from "man-made" radioactivity. Hence, the risks from a specified dose are the same regardless of the source. Rather than going through an intermediate step involving risk factors, doses can also be compared directly to natural background radiation doses.

Besides estimation of risks and comparisons to natural background, doses may be compared to standards and regulations. The appropriate standards, the Department of Energy's "Requirements for Radiation Protection," give limits for external and internal exposures for the whole body and specified organs which are expressed as the permissible dose or dose commitment annually in addition to natural background and medical exposures. There are, in general, two sets of limits, one applicable to occupationally exposed persons and the second applicable to individuals and population groups of the general public. The limits for individuals of the public are one-tenth of those permitted for occupationally exposed individuals. The set of limits important to this report are those applicable to individuals and population groups of the public. The limits for individuals of the public are 500 mrem per year to the whole body, gonads, or bone marrow and 1500 mrem per year to other organs. The limits for population groups of the public are 170 mrem to the whole body, gonads, or bone marrow and 500 mrem

APPENDIX 8 (cont'd.)

per year to other organs, averaged over the group. In either case, exposures are to be limited to the lowest levels reasonably achievable within the given limits.

IV. DOSE DETERMINATION CALCULATION

A. External Exposure

External penetrating radiation dose rates are measured on contact with an end-window beta-gamma Geiger-Mueller (GM) detector (7 mg/cm² window), and at 1 meter with a NaI crystal detector (1 in diameter by 1 in thick) manufactured by Eberline Corporation (PRM-7 μ R Meter). For the purpose of these calculations, the following conservative assumptions are made. First, it is assumed that the half-life of the contaminant is long and, therefore, the dose rate is constant with respect to time. Second, it is assumed that a person is stationary at the location of maximum dose for 40 hours per week for 50 weeks per year. For such a situation, the annual dose (A) for a 0.3 mR/h radiation field (about ten times normal background) would be:

$$A = 40 \text{ h/week} \times 50 \text{ weeks/yr} \times 0.3 \text{ mR/h} = 600 \text{ mR/yr}$$

For the purposes of this example it is assumed that one milliRoentgen of penetrating radiation is equivalent to one millirem of dose. Hence, the maximum dose for this case would be 600 mrem. This value is then compared with the allowable limit of 500 mrem per year for a person non-occupationally exposed.⁽¹⁾

B. Internal Exposure from Soil

The internal radiological hazard from inhalation/ingestion of contamination in soil is assessed by postulating hypothetical "worst case" scenarios. To this end two cases are considered. The first case is based on the situation whereby a child would eat 100 g per year of the contaminated soil. The second case assumes a home gardener would rototill the contaminated soil (dry) to a 1-ft depth for a working day (eight hours) once a year. For this latter case, a resuspension factor of 10^{-6} m^{-1} , a breathing rate of 9.6 m³/working day and a soil density of 1.5 g/cm³, are used. This means 4.39 g (1 ft x 0.305 m/ft x 1.5 g/cm³ x $10^6 \text{ cm}^3/\text{m}^3 \times 10^{-6} \text{ m}^{-1} \times 9.6 \text{ m}^3$) of soil are inhaled each year. In both cases it is assumed that the average concentration of contaminants in the soil is equal to the maximum measured value (a conservative assumption). All calculations are based on methods outlined in ORNL/NUREG/ TM-190, Vol. 3.⁽²⁾ These calculations approximate the ICRP-30 guidelines for hazard analysis.

The adult inhalation and ingestion dose commitment factors for the bone, lung and total body from ²³⁸U, ²³⁵U, ²³⁴U and ²³²Th (and all their significant daughters), as determined in Reference 2, are given in Table 1. For calculation purposes, normal uranium is assumed to be composed of 2.26% ²³⁵U, and 97.74% ²³⁴U and ²³⁸U (in equilibrium) by activity.

APPENDIX 8 (cont'd.)

An example calculation is given below that is based on the above scenarios assuming a soil contamination level of 5 pCi/g of radium-226 EPA limit. This gives the following dose levels (50-year dose commitment):

Ingestion (consumption of 100 g/yr of soil):

Bone:	6.5×10^{-2} mrem/pCi x 5 pCi/g x 100 g = 32.5 mrem
Total Body:	5.5×10^{-3} mrem/pCi x 5 pCi/g x 100 g = 2.75 mrem.

Inhalation (rototilling and breathing ensuing aerosol):

Lung:	1.1×10^{-1} mrem/pCi x 5 pCi/g x 4.39 g = 2.4 mrem
Bone:	9.2×10^{-2} mrem/pCi x 5 pCi/g x 4.39 g = 2.0 mrem
Total Body:	9.5×10^{-3} mrem/pCi x 5 pCi/g x 4.39 g = 0.2 mrem.

There is no regulation setting an allowable limit for radionuclides with both a long radiological half-life and a long biological half-life such as radium.

C. Internal Exposure from Building Materials

The internal radiological hazard from inhalation of contamination on a brick wall is assessed by postulating a hypothetical "worst-case" scenario. To this end, a case is considered whereby a person is using a portable concrete saw in the dry mode of operation to cut a brick wall for an electrical outlet. A typical saw blade used in cutting masonry would have a 30.5-cm (12-in) diameter, a 0.32-cm (1/8-in) thickness, and a 11.1-cm (4 3/8-in) cutting depth. The wobble of the blade would probably increase the width of the cut to a kerf of 0.4 cm. If the cut were 10 cm by 10 cm (4 in by 4 in), the perimeter would then be 41 cm (16 in). The overlap of the cuts upon the brick wall would extend the total span of the cuts to 89 cm (35 in). The area of the brick wall that the blade would consume is then 36 cm². It is assumed that 50% of the brick becomes airborne and respirable. The room has a total volume of 60 m³, and the dust created becomes dispersed throughout the entire room. One person is involved and the job requires one hour. The person inhales 1.2 m³ of air per hour. This means 0.36 cm² (36 cm² x 0.5 x 1.2 m³/h x 1 h/60 m³) of the brick surface would be inhaled. This calculation is also based on methods outlined in ORNL/NUREG/TM190, Vol. 3,² which approximates the ICRP 30 guidelines for hazard analysis.

An example calculation is given below that is based on the above scenario assuming a surface contamination of 3.6×10^5 dis/min-100 cm² normal uranium or 1.62 x 10³ pCi/cm². This gives the following dose levels (50-year dose commitment):

Inhalation (cutting brick):

APPENDIX 8
(cont'd.)

Lung: 7.5×10^{-3} mrem/pCi $\times$ 1620 pCi/cm² $\times$ 0.36 cm² = 4.4 mrem.
 Bone: 1.5×10^{-2} mrem/pCi $\times$ 1620 pCi/cm² $\times$ 0.36 cm² = 8.7 mrem.
 Total Body: 5.1×10^{-1} mrem/pCi $\times$ 1620 pCi/cm² $\times$ 0.36 cm² = 300 mrem.

D. Comparative Risks

An attempt has been made by Cohen and Lee (Health Physics 36, 707, 1979) to compare the risk associated with radiation with risks associated with common individual actions. The following table exemplifies this comparison.

Risks in Individual Actions

<u>Individual Action</u>	<u>Minutes Life Expectancy Lost</u>
smoking a cigarette	10
calorie-rich dessert	50
non-diet soft drink	15
diet soft drink	0.15
crossing a street	0.4
extra driving	0.4/mile
non-fastening seat belt	0.1/mile
1 mrem of radiation	1.5
coast-to-coast drive	1,000
coast-to-coast flight	100
skipping annual PAP test	6,000
moving to unfavorable state	800,000
buying a small car	7,000
choose Vietnam army duty	600,000

As can be seen from this table, the highest risk identified above (300 mrem total body) would be equivalent to smoking $2\frac{1}{2}$ packs of cigarettes per year.

APPENDIX 8
(cont'd.)

TABLE 1

FIFTY-YEAR DOSE COMMITMENT FACTORS (inhalation/ingestion)^a
(mrem/pCi assimilated)

Nuclide ^b	Inhalation			Ingestion	
	Bone	Lung	Total Body	Bone	Total Body
²³⁸ U	7.1×10^{-3}	4.8×10^{-1}	1.5×10^{-2}	2.8×10^{-4}	2.1×10^{-5}
²³⁴ U	7.9×10^{-3}	5.4×10^{-1}	1.6×10^{-2}	3.1×10^{-4}	2.4×10^{-5}
²³⁰ Th	3.1×10^{-1}	5.3×10^{-1}	3.8×10^{-2}	1.2×10^{-3}	9.2×10^{-5}
²²⁶ Ra	4.9×10^{-2}	5.6×10^{-2}	4.7×10^{-3}	4.3×10^{-2}	3.4×10^{-3}
²¹⁰ Po	8.1×10^{-4}	4.6×10^{-2}	1.3×10^{-3}	5.2×10^{-4}	4.1×10^{-4}
²¹⁰ Pb	4.2×10^{-2}	6.2×10^{-3}	3.5×10^{-3}	2.1×10^{-2}	1.7×10^{-3}
Total Chain	4.2×10^{-1}	1.7	7.9×10^{-2}	6.6×10^{-2}	5.6×10^{-3}
²²⁶ Ra Chain	9.2×10^{-2}	1.1×10^{-1}	9.5×10^{-3}	6.5×10^{-2}	5.5×10^{-3}
²³⁸ U+ ²³⁴ U	1.5×10^{-2}	1.0	3.1×10^{-2}	5.9×10^{-4}	4.5×10^{-5}
²³⁵ U	7.2×10^{-3}	4.8×10^{-1}	1.5×10^{-2}	2.8×10^{-4}	2.2×10^{-5}
²³¹ Pa	9.6×10^{-1}	5.9×10^{-1}	1.4×10^{-1}	1.8×10^{-2}	2.1×10^{-3}
²²⁷ Ac	5.4×10^{-1}	1.0	1.0×10^{-1}	1.2×10^{-2}	1.3×10^{-3}
²²³ Ra	9.6×10^{-4}	4.6×10^{-2}	8.6×10^{-4}	1.2×10^{-3}	2.3×10^{-4}
²²⁷ Th	4.8×10^{-4}	6.9×10^{-2}	1.1×10^{-3}	2.7×10^{-5}	5.1×10^{-6}
Total Chain	1.5	2.2	2.6×10^{-1}	3.2×10^{-2}	3.7×10^{-3}
²³² Th	3.3×10^{-1}	4.5×10^{-1}	3.8×10^{-2}	1.3×10^{-3}	9.6×10^{-5}
²²⁸ Th	4.4×10^{-2}	7.2×10^{-1}	1.9×10^{-2}	4.5×10^{-4}	3.8×10^{-5}
²²⁸ Ra	2.9×10^{-2}	4.8×10^{-3}	2.5×10^{-3}	2.1×10^{-2}	1.7×10^{-3}
²²⁴ Ra	3.0×10^{-4}	8.8×10^{-3}	1.8×10^{-4}	4.0×10^{-4}	7.5×10^{-5}
²¹² Pb	2.6×10^{-5}	1.8×10^{-3}	2.9×10^{-5}	1.8×10^{-5}	2.6×10^{-6}
Total Chain	4.0×10^{-1}	1.2	6.0×10^{-2}	2.3×10^{-2}	1.9×10^{-3}

^aData taken from Reference 2.

^bNuclides in the chain that contribute negligibly (e.g., $<10^{-6}$ mrem) have not been included.

APPENDIX 8
(cont'd.)

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