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Background as a Residual Radioactivity Criterion for Decommissioning

Appendix A to the Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities

Draft Report

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ABSTRACT

This report was originally published as an appendix to the draft U.S. Nuclear Regulatory Commission (NRC) document entitled, "Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities." Because of the great interest in this report by members of the public, citizen and environmental organizations, academicians, licensees, and regulators, the NRC staff is publishing this report separately, so that it can be readily available to a diverse audience. This report was created to assist both the NRC staff and interested members of the public in evaluating background radiation (background) as a decommissioning criterion, by serving as a primer on background and providing information on the existing applications of background in regulatory criteria and standards. This report also discusses some of the methods available to measure and distinguish between the very low radiation levels associated with background and man-made sources of radiation.

Two approaches are considered for applying background as a decommissioning criterion; these are the use of background dose rates and background radionuclide concentrations. This report concludes that the temporal and spatial variability of background produces a wide range of doses to United States residents, which prevents the application of background dose rates as a decommissioning criterion. Instead, this report recommends that local background radionuclide concentrations serve as a benchmark for decommissioning criteria, while taking into account the concept of reducing residual radioactivity to a level as low as is reasonably achievable.

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FOREWORD

The NRC is amending its regulations to establish residual radioactivity criteria for decommissioning of licensed nuclear facilities. As part of this initiative, the NRC solicited comments on proposed residual radioactivity criteria, and received numerous comments regarding a "return-to-background" criterion. Such a criterion would require demonstration that all radioactivity attributable to licensed activities had been removed, and that background radiation levels had been restored.

In order for the NRC staff to assess the costs and impacts associated with a return-to-background criterion, it was necessary to obtain extensive information about the levels and variability of background at locations in the United States where licensed nuclear facilities will be decommissioned. This report represents a compilation of this and other information on background, such as estimated health effects associated with background, methods of measuring radiation levels associated with a return-to-background decommissioning criterion, and approaches for applying background as a decommissioning criterion.

Another objective in creating this report was to provide information on background to interested members of the public. Although it was originally published as an appendix to the draft NRC document entitled, "Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities," this report was written in a manner that does not require a specialized scientific education. With that goal in mind, this report has also been published as a stand-alone document so that it can be readily available to a diverse audience.

This report contains information on background that may be considered by the NRC staff for rulemaking on radiological criteria for decommissioning. The results, approaches and/or methods described in this draft NUREG are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein.

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1 INTRODUCTION

1.1 Need for This Report

From January through May 1993, the U.S. Nuclear Regulatory Commission (NRC) conducted a series of workshops throughout the United States to solicit comments on the enhanced participatory rulemaking to establish radiological criteria for the decommissioning of NRC-licensed facilities. The NRC received more than 100 written comments favoring a "return-to-background" decommissioning criterion. Such a criterion would require nuclear facilities to be remediated to background radiation levels (radiation levels that occur naturally in the environment) before they could be released for unrestricted use; the majority of those favoring this criterion were from citizen and environmental organizations, and some were from other organizations. Comments were also received that opposed NRC consideration of a return-to-background decommissioning criterion. On the basis of the comments received from these workshops and the accompanying Federal Register notice (57 FR 58727), the NRC considered a return-to-background decommissioning alternative.

On June 18, 1993, the NRC published in the Federal Register (58 FR 33570) a preliminary list of six regulatory alternatives for establishing radiological criteria for decommissioning. This list included the return-to-background alternative. As discussed in the Federal Register notice, the return-to-background alternative would require removal of all radioactivity attributable to licensed activities and, for a site to be released for unrestricted use, demonstration that background radiation levels had been achieved and that all radioactivity attributable to licensed activities had been removed.

In July 1993, the NRC held four public scoping meetings throughout the United States to obtain comments on the preparation of the draft NRC document entitled, "Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities" (GEIS), which accompanies the proposed rulemaking. A number of comments received from this series of meetings also favored a return-to-background decommissioning alternative. The overall public interest at the GEIS scoping meetings for a return-to-background decommissioning criterion confirmed that the staff should evaluate in the GEIS the establishment of a decommissioning criterion based on radiation levels that occur naturally in the environment.

To properly assess in the GEIS the costs and impacts associated with this rulemaking alternative, it was necessary to obtain extensive information on the causes and estimated health effects associated with background. For background to be used as a decommissioning criterion, it was also necessary to consider methods of measuring the very low radiation levels associated with a return-to-background decommissioning criterion, and to establish the relationship between the scientific definition of background and its application as a regulatory entity.

This report was created to assist the NRC staff and interested members of the public in evaluating background as a decommissioning criterion by providing basic information on the physical properties of this source of radiation, its measurement, the way it is applied in existing regulatory criteria and standards, and the way it may be applied as a future decommissioning criterion.

1.2 Structure of This Report

This report is divided into seven sections, each building on information contained in the previous section(s). The first section is an introduction, and Section 2 is a primer on background that discusses its various physical properties and components, the way it varies over time and space, and the magnitudes of radiological doses from each of its components.

Section 3 contains a discussion of the measurement of background, and some limiting technical and cost considerations in its measurement.

To provide the reader with some regulatory perspective, Section 4 is a brief summary of how background is incorporated into existing standards and criteria developed by the NRC and the U.S. Environmental Protection Agency (EPA) for nuclear facility operations and decommissioning.

Based on information contained in the preceding sections, Section 5 contains a discussion of several options for applying background as a regulatory entity for this rulemaking.

Section 6 summarizes key information from previous sections and contains recommendations for implementing the return-to-background alternative as a residual radiological criterion for decommissioning.

The last section of this report, Section 7, provides a bibliography of related reference literature from a variety of entities.

2 OVERVIEW OF BACKGROUND RADIATION

2.1 Introduction

A number of the elements, present on Earth since its formation, have unstable forms that transmute to other elements in a process called radioactive decay. In this process, energy is released in the form of radiation. This energy can take the form of subatomic-size particles such as alpha and beta particles, or it can be in the form of electromagnetic energy such as x-ray and gamma rays, which are sometimes referred to as "photons." These forms of radiation fall in a category called ionizing radiation, meaning they can create electrical charge when they interact with matter.

Another source of ionizing radiation in our environment originates in outer space, producing particles in the atmosphere that penetrate to ground level. This radiation is energetic enough to also create new radioactive elements by interacting with otherwise stable elements present on Earth. Everything on the planet, including every living thing, is bathed in a sea of radiation from these various sources. This is commonly referred to as "natural background," "background radiation," or more simply, "background."

For perspective, a handful of typical garden soil contains several billion billion unstable atoms that over time will ultimately decay to a stable form. Each second, scores of these atoms undergo this decay process and emit radiation. In a typical environment, thousands of gamma rays impinge on the body each second. The air that people breathe contains naturally occurring radioactivity, and even a person's body contains natural radioactive elements that tend to concentrate in certain tissues, according to their respective chemistry.

In addition to natural sources of radiation, people are exposed to man-made sources of ionizing radiation. Perhaps the most commonly known is x-rays, which are used in dental and medical examinations. Despite this and other sources of ionizing radiation that have been produced during the technological developments of the 20th century, background remains the principal source of exposure for most people. In this and the following sections of this report, the various sources of background, their degree of variability, and the manner in which they are measured and distinguished from man-made sources of radiation will be examined in some detail.

2.1.1 Units of Measurement

To understand background and the significance of its various components, it is necessary to deal with various units of measurement. The degree of radioactivity of a material is a measure of the rate at which its atoms are undergoing decay. For a chemically pure radioactive substance, the decay rate can be calculated from the amount of material and the half-life of that particular radionuclide. The current internationally recognized unit is called the "becquerel" (abbreviated as Bq), which is one disintegration of an atom per second.

Older style units such as the "curie" (abbreviated as Ci) are sometimes still used. Frequently, the concentration of radioactivity in a medium such as soil, water, or air is given, in which case the unit may take such forms as Bq per gram, per liter, or per cubic meter. Frequently, the prefixes milli (one-thousandth), abbreviated as "m," and micro (one-millionth), abbreviated as "μ," are used with radiation units.

2.1.1.1 Units of Measurement for External Radiation

Apart from the measurement of the rate at which a substance is undergoing decay, there is the measurement of the effect of the emitted radiation at some distance from the radioactive material. This can be in terms of the amount of electric charge that is created in air ("roentgen" in the old system, abbreviated as "R," or coulombs per kilogram in the new system, abbreviated as C/kg) or the energy that is transferred to surrounding matter ("rads" in the old system, or "grays" in the new system, abbreviated as "Gy").

2.1.1.2 Units of Measurement for Internal Radiation

When the energy released from a radioactive material is absorbed by body tissues, the energy is transmitted to cells and surrounding fluids and noncellular structures. This absorbed energy has the potential to cause damage at a microscopic level, the effects of which could be immediate (cell death) or delayed (cancer). To provide a common footing in the measurement of different types of radiation and their effects on different parts of the human body, be it from sources external or internal to a person, scientists have introduced a quantity known as the effective dose equivalent, which has lately become known simply as the effective dose. In the current internationally accepted system, the unit is the "sievert" (abbreviated as Sv). The old system of units used "rem," which is equal to one hundredth of a sievert.

2.2 Sources of Radiation

Background is comprised of four major sources (or components) of ionizing radiation. The first source discussed in this report is terrestrial radiation, which produces the largest dose to people living in the Unites States. The remaining components of background, which are cosmic, cosmogenic, and man-made radiation sources, are relatively minor contributors to the dose from background compared to terrestrial radiation. Each of these sources is discussed in the next four sections of this report to give the reader a basic understanding of their origins, physical properties, and relative contributions to the total background dose rate.

2.2.1 Terrestrial Radiation

The naturally occurring forms of radioactive elements that were incorporated into Earth during its formation and that are still present are referred to as "terrestrial radionuclides." Virtually all materials found in nature have some degree of natural radioactivity. Rocks, soil, water, air, plants, and animal life all have varying concentrations of terrestrial radionuclides. The most significant of these are uranium-238 and thorium-232, which both decay in a long chain (or series) of various radionuclides, and potassium-40 and rubidium-87, which have much simpler decay schemes. These principal radionuclides and their decay products, which are commonly referred to as "progeny," are listed in Table 2.1 along with their corresponding half-life, which is the average amount of time it takes for half of the atoms of that radionuclide to undergo decay. The listing is given in order to indicate the immediate parent and decay product for each radionuclide. This table also gives the major types of radiation given off in the decay of each radionuclide. Among these, alpha radiation is the least penetrating, beta radiation and x-rays are somewhat more penetrating, and gamma radiation is the most penetrating.

Table 2.1. Principal Natural Radionuclide Decay Series

Nuclide	Half-Life	Major Radiations
Uranium-238	4.47 billion years	alpha, x-rays
Thorium-234	24.1 days	beta, gamma, x-rays
Protactinium-234m	1.17 minutes	beta, gamma
Uranium-234	245,000 years	alpha, x-rays
Thorium-230	77,000 years	alpha, x-rays
Radium-226	1600 years	alpha, gamma
Radon-222	3.83 days	alpha
Polonium-218	3.05 minutes	alpha
Lead-214	26.8 minutes	beta, gamma, x-rays
Bismuth-214	19.7 minutes	beta, gamma
Polonium-214	164 microseconds	alpha
Lead-210	22.3 years	beta, gamma, x-rays
Bismuth-210	5.01 days	beta
Polonium-210	138 days	alpha
Lead-206	stable	
Thorium-232	14.1 billion years	alpha, x-rays
Radium-228	5.75 years	beta
Actinium-228	6.13 hours	beta, gamma, x-rays
Thorium-228	1.91 years	alpha, gamma, x-rays
Radium-224	3.66 days	alpha, gamma
Radon-220	55.6 seconds	alpha
Polonium-216	0.15 seconds	alpha
Lead-212	10.64 hours	beta, gamma, x-rays
Bismuth-212	60.6 minutes	alpha, beta, gamma, x-rays
Polonium-212	0.305 microseconds	alpha
Thallium-208	3.07 minutes	beta, gamma
Lead-208	stable	
Potassium-40	1.28 billion years	beta, gamma
Argon-40	stable	
Calcium-40	stable	
Rubidium-87	47 billion years	beta
Strontium-87	stable	

Two of the more commonly known radioactive elements in Table 2.1 are radium, which was discovered by Marie Curie and used extensively for luminous watch dials and medical treatments years ago, and radon, a gaseous decay product of radium for which many people now have their homes tested. Another long-lived nuclide not listed here that has a series decay scheme is uranium-235. This radionuclide occurs in nature at a concentration of less than 1 percent of the more abundant uranium-238 and is therefore much less significant in terms of its contribution to background. A number of other less abundant radionuclides can be found in nature; however, they exist in such low concentrations that their contributions to background are negligible.

As an example of the range of concentrations for naturally occurring radionuclides that can be found on Earth, Table 2.2 gives information that has been collected by researchers around the world for the uranium-238 and thorium-232 series and potassium-40. Although the ranges given in this table are typical for soil, even larger variation is possible in certain mineral-rich areas. The concentrations of uranium and thorium in ore-grade deposits of these elements would of course be orders of magnitude higher than the values in these tables.

Table 2.2. Typical Ranges in Average Concentration of Background Radionuclides (Bq per kg)

Material	Uranium-238	Thorium-232	Potassium-40	Reference
Bauxite ore	250	200	n/a	UNSCEAR, 1988
Coal, U.S.	18 (1–540)	21 (2–320)	52 (1–710)	Beck et al, 1980
Copper ore	30–80	23–110	n/a	UNSCEAR, 1988
Crustal rock, U.S.	36	44	850	NCRP, 1987b
Oil shale	56 (37–74)	24 (19–37)	481 (185–962)	Gogolak, 1982
Phosphate fertilizer, U.S.	9200	n/a	n/a	UNSCEAR, 1988
Soil, worldwide	25 (10–50)	25 (7–50)	370 (100–700)	UNSCEAR, 1988
Soil, U.S.	37 (4–141)	36 (4–126)	n/a	Myrick, 1983

Since many people spend most of their time indoors, radiation exposure from background is very much affected by the concentrations of the naturally-occurring radionuclides in building materials. Table 2.3 gives the radionuclide content for some building materials used in the United States. Wood, a principal component in a light frame structure (e.g., a typical home) would generally have negligible natural radionuclide concentrations as compared with stone and masonry materials. As an example of data collected from around the world, Table 2.4 gives radionuclide concentrations for common brick.

Table 2.3 Natural Radionuclide Content of Some Building Materials for the United States (Bq per kg)

Material	Uranium-238 (Radium-226)	Thorium-232	Potassium-40	Reference
Adobe Brick	31	27	583	Ingersoll, 1981
Brick	4–178	1–144	7–1184	Eichholz et al, 1980
Concrete	19–89	15–118	262–1147	"
Concrete Block	41–777	37–81	285–1147	"
Gypsum	13	2	61	Ingersoll, 1981
Red Brick	45	42	522	"
Rock, Storage	57	53	921	"

Table 2.4. Natural Radionuclide Contents of Bricks
(Bq per kg)

Country (type)	Uranium-238 (Radium-226)	Thorium-232	Potassium-40	Reference
Canada (various)	4–120	8–160	200–800	Zikovsky, 1992
Finland (red)	78	62	962	NEA, 1979
Germany (traditional)	59	67	673	"
India	48	26	3	Ramachandran, 1989
Italy (various)	28–81	40–148	365–1060	Bruzzi, 1992
Norway	104	62	1058	NEA, 1979
Sweden	96	127	962	"
United Kingdom (clay)	52	44	703	"

2.2.2 Cosmic Radiation

Cosmic radiation, commonly known as cosmic rays, consists of highly energetic particles, mostly the nuclei of the elements hydrogen and helium. Supernova explosions and other phenomena that occur throughout the universe are believed to be the source and driving force of cosmic rays. When they enter Earth's upper atmosphere, they undergo interactions that lead to the production of charged particles, gamma rays, and neutrons (uncharged particles that are principai constituents of the nuclei of atoms).

Decay and additional interactions ultimately lead to a makeup of "secondary" radiation near the surface of Earth that consists mainly of directly ionizing muons and electrons with a smaller proportion of neutrons that indirectly ionize matter. Although interactions with the atmosphere cause the secondary production of cosmic rays, the air surrounding Earth nonetheless serves as an important shield to living things. Without this shield, the more energetic primary cosmic ray particles would reach Earth's surface.

Another source of radiation from space is charged particles that are associated with flares on the sun. On rare occasions, a solar flare is strong enough to produce a significant radiation dose in the lower reaches of Earth's atmosphere.

2.2.3 Cosmogenic Radiation

Cosmic radiation, which itself leads to a direct radiation dose to people, is also responsible for the production of radioactive elements called "cosmogenic" radionuclides. These radionuclides arise from the collision of the highly energetic cosmic ray particles with stable elements in the atmosphere and in the ground. Many different cosmogenic radionucludes are produce, although the most important is carbon-14. Other less significant cosmogenic radionuclides include hydrogen-3 (also known as tritium), beryllium-7, and sodium-22. Concentrations of these cosmogenically produced nuclides in the air and ocean water are given in Table 2.5. Another source of cosmogenic radionuclides is extraterrestrial matter that intercepts and is captured by Earth's orbit. This contribution is very small,

however, and can be ignored. The entire cosmogenic contribution to background is very small compared with that of the terrestrial and cosmic components.

Table 2.5. Concentrations of Principal Cosmogenically Produced Radionuclides[1]

Nuclide	Troposphere (Bq/kg air)	Oceans (Bq/kg water)
Beryllium-7	0.01	n/a
Carbon-14	n/a	5×10^{-3}
Hydrogen-3	1.2×10^{-3}	n/a
Sodium-22	1×10^{-6}	n/a

[1] From NCRP (1987b).

2.2.4 Man-Made Sources

Human activities have resulted in the production of various sources of radiation. Nuclear reactors and weapons have produced large quantities of radionuclides through the fissioning of uranium and other heavy elements and the activation of various elements. Particle accelerators used in scientific research have produced smaller quantities. Although most of these radionuclides are short lived and quickly decay to stable forms, a few have half lives of several to thousands of years. In this category are cesium-137, strontium-90, the gas krypton-85, and various isotopes of plutonium that have been deposited throughout the globe as the result of nuclear weapons tests conducted in the atmosphere. Concentrations of cesium in surface soil might typically be about a few Bq per kg; however, values as high as 740 Bq per kg have been found from weapons test fallout (Miller and Helfer, 1985).

The global inventory of the naturally produced cosmogenic radionuclides carbon–14 and hydrogen-3 have also been increased through human activities in the nuclear field. Although not "natural," these sources of radiation have very much become part of the background to which humans are exposed. It is sometimes necessary to separately measure these globally distributed radionuclides and to distinguish them from locally produced sources.

2.3 Variability of Background

This section of the report is intended to give the reader a better understanding of the causes and magnitude of background variability. Although background is ubiquitous, each of its components and the corresponding dose they deliver to the United States resident is by no means constant. Background variability can result from natural means, whether terrestrial or extraterrestrial, and human activities. The following sections discuss the causes of variation and the temporal and spatial variability of background for each of its major components.

2.3.1 Causes of Variation

For terrestrial radiation, changes to the land and the makeup of the radionuclide content of soil can result from geophysical phenomena such as mountain formation, earthquakes, volcanoes, glaciers, and changes in ocean levels and river courses and flood plains. On shorter time scales, the outdoor

radiation field is affected by climate and weather through the action of precipitation and wind. Human activities such as soil excavation, building construction, mining, nuclear power production, and fossil fuel combustion can alter the radiation field. To a large extent, humans affect their exposure to inhaled radioactivity from radon with the degree and type of ventilation they use inside homes, schools, and workplaces. Humans also alter the dietary intake of radioactivity through regional, countrywide, and even worldwide food distribution.

The intensity of cosmic radiation depends upon the degree of shielding provided by the atmosphere. It thus depends upon altitude and barometric pressure. Shielding provided by the structures that people inhabit, particularly large apartment and office buildings, reduces cosmic ray exposure. Earth's magnetic field also deflects the incoming cosmic ray particles, and the temperature of the atmosphere has some effect as well. The sun goes through cycles (with a period of about 11 years) that modulate cosmic radiation through interactions with solar wind and magnetic disturbances. The frequency and intensity of solar flares is also tied to the solar cycles.

The production rate of cosmogenic radionuclides depends upon the intensity of the cosmic radiation. Thus, the same phenomena observed with cosmic ray variations can be expected for the rate at which cosmogenic radionuclides are created. Because some of these radionuclides are long-lived, however, the overall amount present on Earth does not change over the short term. Rather, local variations result after atmospheric mixing occurs, and these radionuclides are deposited to Earth's surface according to seasonal precipitation patterns around the globe.

The variability of man-made sources of radiation and radioactivity relates directly to the population distribution and level of technology found in different areas around the world. In some cases, locally produced radioactive materials are dispersed throughout the Earth's atmosphere, land areas, and water bodies. The level of deposition in an area, as in the case of cosmogenic radionuclides, depends upon wind and precipitation patterns.

The temporal and spatial variability of each of the major components of background is discussed separately in the following sections.

2.3.2 Temporal Variability

2.3.2.1 Terrestrial Radionuclides

The changes in background radioactivity concentrations and radiation levels that are associated with various physical phenomena occur on time scales ranging from short duration (hours to days) to medium duration (months and years) to long duration (centuries or more). While only general effects can be predicted for long term changes based on our understanding of geological processes and the history of Earth, a good deal of knowledge has been gathered in recent years on short and medium duration effects by actually measuring the level of radiation at environmental monitoring stations.

2.3.2.1.1 External Terrestrial Radionuclides. The radiation coming from background sources external to the body has been observed to change over time periods ranging from minutes to months. Data collected at the Chester Regional Baseline Station, a rural field site in western New Jersey, is used here to demonstrate the degree of variability (EML, 1978, 1979, 1980, 1981, 1982, 1984, 1985, 1988, 1991).

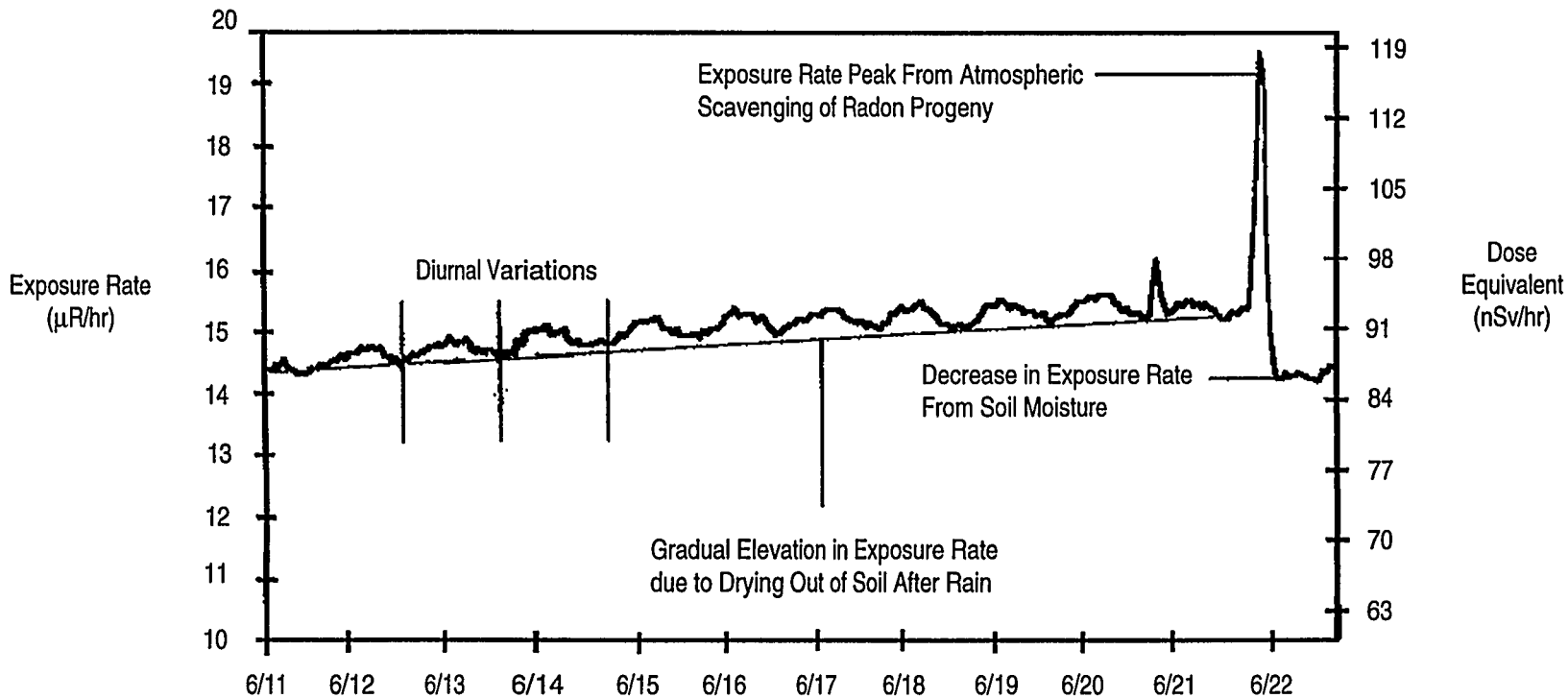
Figure 2.1 graphically illustrates the typical short-term variations observed in the rates of exposure from the penetrating component of background (gamma rays from terrestrial sources plus cosmic secondary radiation). These rates were measured hourly for a period of 11 days.

Several commonly observed effects on background gamma radiation are readily observable in this graph. The first feature to note is the somewhat wavering baseline, which represents the usual background level present at this site. This level gradually rose each day until some abrupt changes occurred at the end of the period. This rise resulted from the soil drying out, because this period of time was characterized by hot weather with no rainfall. (The effect of soil moisture is one principal factor in the variability of the external radiation levels. Water acts as a shield against the radiation coming from radionuclides contained in the ground, and dilutes the concentration of the radionuclides in the soil). The peaks toward the end of the period coincided with rainstorms. The quick rise in the radiation level resulted from a natural fallout process, one in which the airborne decay products of radon-222, primarily lead-214 and bismuth-214 (see Table 2.1) were scavenged (that is, washed out by rain). The radioactivity that was distributed throughout the lower region of the atmosphere caused the radiation level to rise when it was brought down to the ground. The second, larger peak in this graph shows the background exposure rate level increasing by approximately 30 percent or, in terms of effective dose equivalent, about 0.03 μSv per hour (equivalent to about 5 μR per hour in terms of exposure in air).

Natural washout events have been observed to double, and in rare cases even triple, the normal terrestrial gamma-ray level at a site during particularly heavy downpours associated with thunderstorms. These sharp increases from washout are not sustained, however, as the short-lived, gamma-emitting radon progeny decay away over the course of a couple of hours once the rain stops or the air is cleared of radioactivity. Also clearly evident in this graph is the return to more normal background levels with the addition of water to the soil. The first small peak represented in this figure was associated with a rather small rainfall event, but the second larger peak was associated with enough rain that the baseline level dropped markedly after the peak. The features shown in this particular graph can be repeated many times over the course of a season.

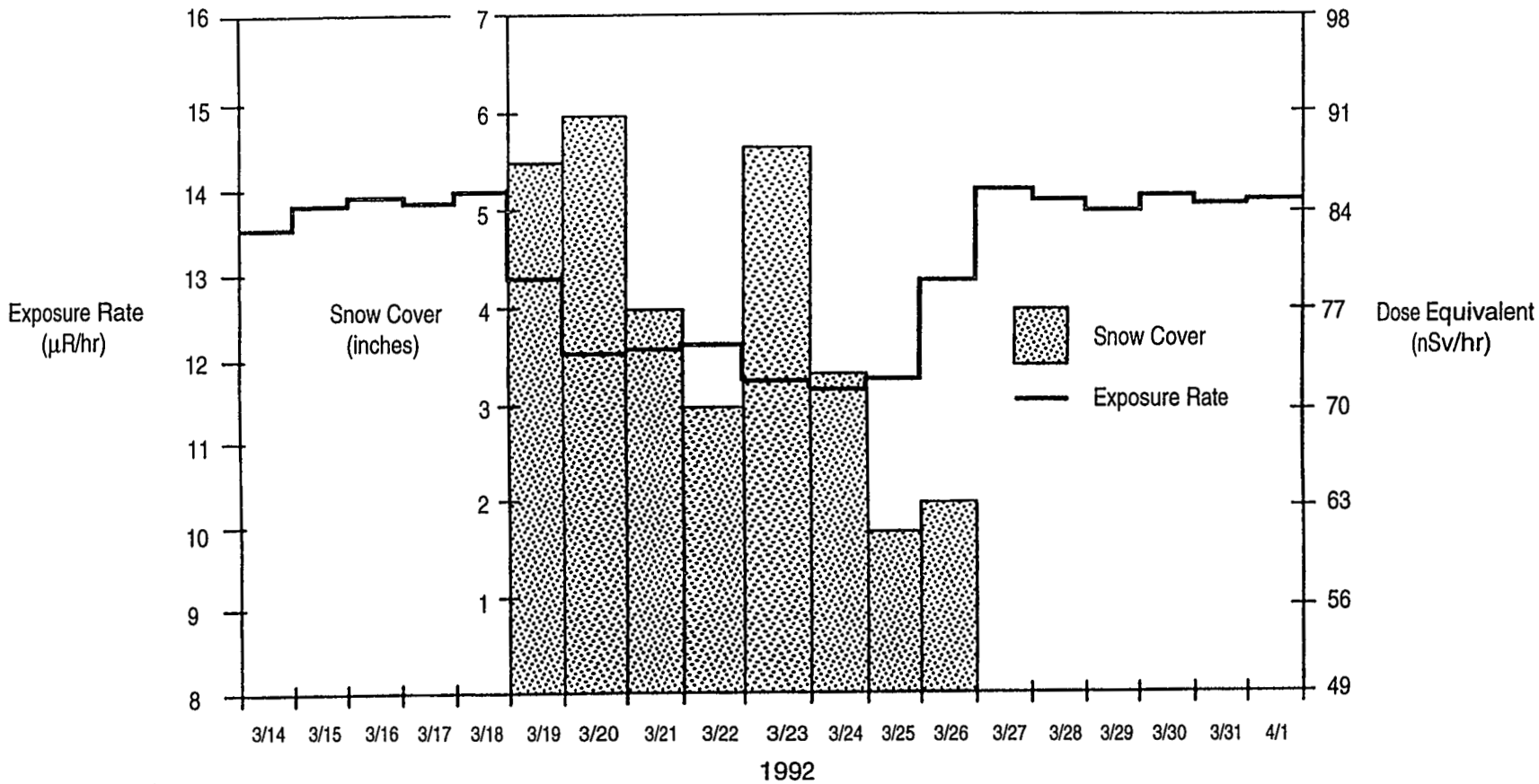
Another generally observable phenomenon in Figure 2.1 is that the waviness of the baseline during the first 10 days is not random. Rather, the cyclic action occurred on a daily basis as a result of changes in the radon progeny levels in the air which, in turn, arose from changes in the stability of the atmosphere. Extremely stable conditions produce what is known as an inversion layer (that is, the air temperature is lower at ground level than above, which is opposite to the norm). In the early morning hours before sunrise, conditions are typically calm, and the radon (which seeps from the soil into the air) stays near ground level, thus causing the radiation level to rise. When the sun rises, the ground warms up and air near it rises, producing a mixing effect that sweeps away the radon and its progeny to higher levels in the atmosphere, thus lowering the radiation level. The process cycles like this from day to day.

One of the most dramatic changes in gamma radiation levels occurs during periods of snow. While adding water to the soil decreases the radiation level to some degree, the shielding effect is much greater when water, in the form of snow or other frozen precipitation, accumulates on top of the ground. As shown in Figure 2.2, a period of snow cover with a depth of several inches reduced the radiation exposure rate by about 15 percent, or about 0.012 μSv per hour (2 μR per hour). The actual degree of shielding depends on the water equivalent of the snow, because a heavy wet snow is more effective than a dry light snow. After the snow melts away, the radiation returns to its usual



Note: Conversion of exposure to dose made by using 1R = 0.0087 Gy.
For environmental radiation, coversion of absorded dose in air to effective dose in the human body is 1 Gy = 0.7 Sv.

Figure 2.1 Typical short-term variations observed in the out door exposure rate.



Note: Conversion of exposure to dose made by using 1R = 0.0087 Gy. For environmental radiation, coversion of absorded dose in air to effective dose in the human body is 1 Gy = 0.7 Sv.

Figure 2.2 The effects of snow cover on the outdoor exposure rate

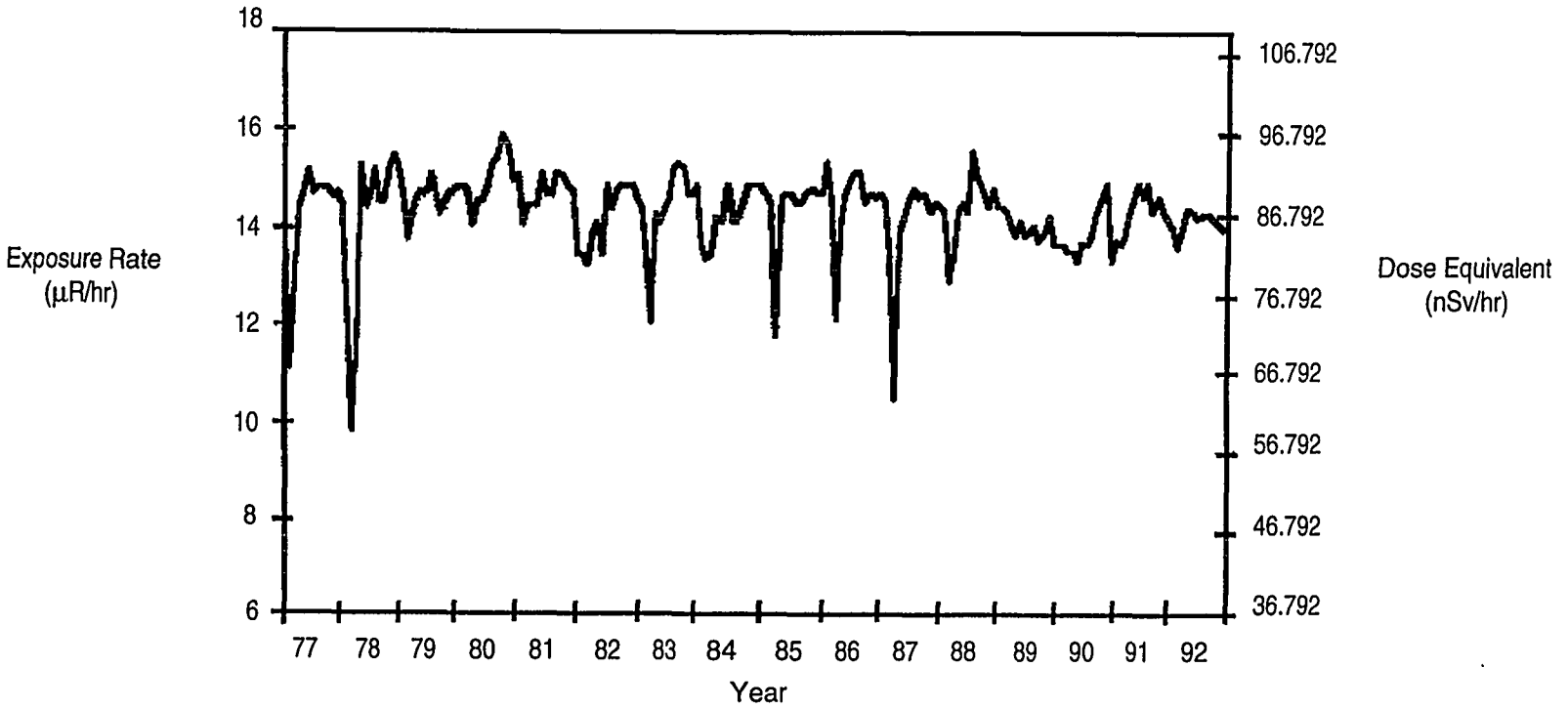
level. Calculations, supported by experimental data, have shown that 5 cm (2 inches) of water equivalent (that is, melted snow) would reduce the external gamma radiation level near the ground by almost 40 percent, while 15 cm (6 inches) would reduce it by nearly 70 percent (Saito, 1991). Mountainous areas that receive extremely heavy snowpack, say 50 cm (20 inches) water equivalent, would see the external gamma level drop by more than 95 percent. If this type of snowpack were sustained for a few months, it might lower the annual dose at a typical site by 0.1 mSv (10 mrem).

Variations in radiation levels from month to month primarily result from changes in soil moisture content and snow cover. Figure 2.3 shows a plot of average monthly outdoor exposure rates at a site over a period of 16 years. In this plot, seasonal trends can be seen as winter months tend toward lower radiation levels because of the higher soil moisture, while the summer months tend toward higher levels because of lower soil moisture. The sharp valleys in this plot correspond to those winter months where there was appreciable snow cover.

Average outdoor exposure rates over full–year periods show less variation as the seasonal effects even out the pattern. This can be seen in Figure 2.4, which shows the annual average along with the minimum and maximum daily average at a site over a 14–year period. The minimum daily value in any given year would generally occur on the day of heaviest snow cover, while the maximum daily value would generally occur on the day with driest soil or the day when a series of rainstorms produced many radon progeny washout events. For this site, over this time period, the typical daily high was about 10 percent or about 0.0085 μSv per hour (1.4 μR per hour) above the yearly average, while the typical daily low was about 25 percent or about 0.021 μSv per hour (3.5 μR per hour) below the yearly average.

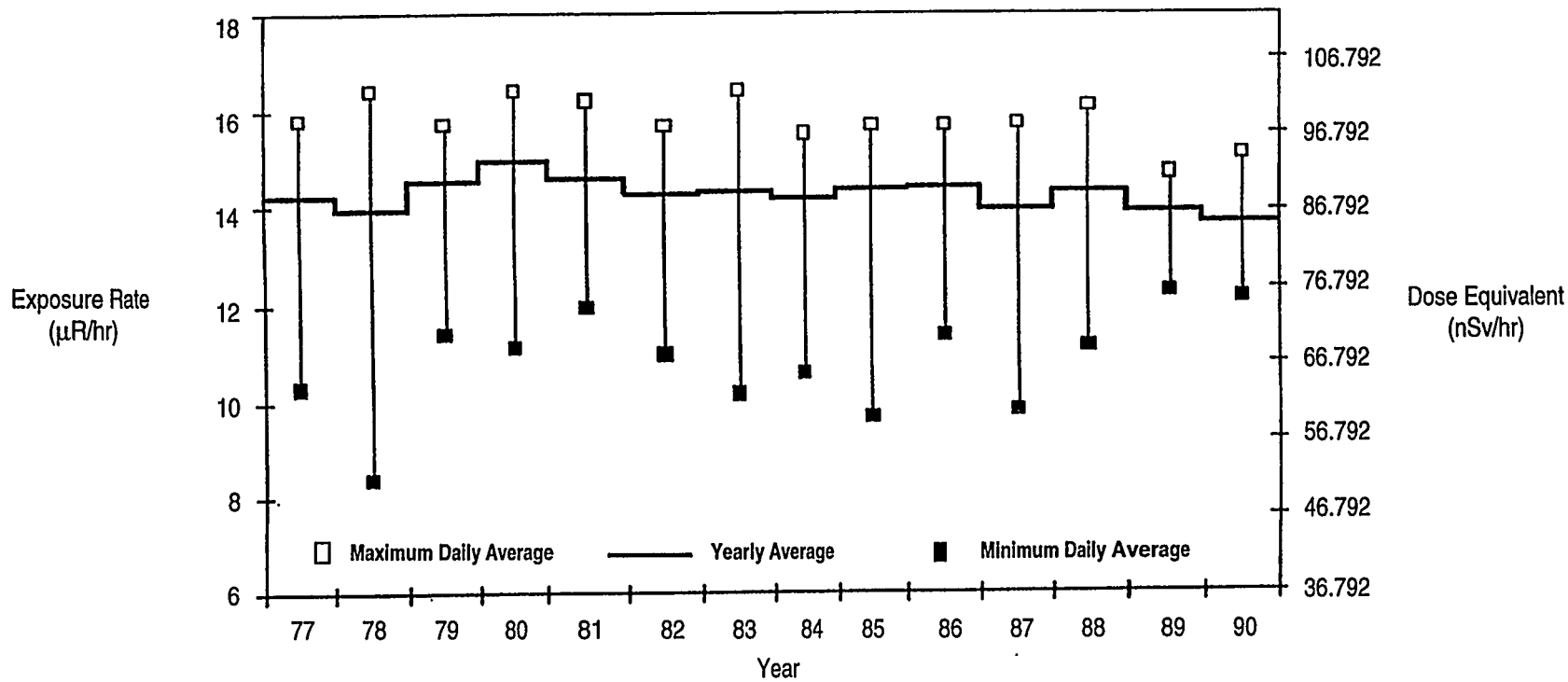
Over geological time frames, dramatic changes in the terrestrial radiation levels could take place in a region. If an area were covered by an ice sheet or a half meter (20 inches) or more of water, the gamma ray level could drop close to zero. On the other hand, upwelling of material from within Earth and erosional processes that transport soil and sediment could leave an area rich in mineralization, and the gamma ray level might quadruple from the extra uranium and thorium in the soil. In absolute terms, this would leave a range of about 0 to 1 mSv (0 to 100 mrem) per year, although there are some unusual areas that have been documented around the world where gamma levels are substantially higher. Climatic changes that lead to desertification of a region would lead to potential variations in background as areas become subject to wind erosion. Volcanic eruptions and the deposition an abrupt change in radiation of heavy amounts of ash in an area could causelevels depending upon the concentration of the natural radionuclides in the ash. The variation that is seen from place to place across the country (see next section) is a reasonable indicator of the degree of variation that might occur over long periods of time at any one location.

Human activities affect the local radiation level, and changes could therefore occur over time. On open ground, about two–thirds of the gamma radiation dose comes from radionuclides contained in the top 15 cm (6 inches) of soil out to a distance of 6 meters (20 feet) from where a person stands. Thus, changes in the radiation level could occur when the natural land is altered on a scale typical for home building and landscaping. The fact that building materials contain varying amounts of natural radioactivity means that background could be affected by any construction, including such work as building a house, making alterations to it, adding topsoil, or installing a swimming pool or patio. Public works, such as paving a road or parking lot, could also alter the radiation field. The magnitude of the change at any one site would depend upon the amount of material that is removed, added, or modified, and the relative radionuclide concentration in the old and new surroundings.



Note: Conversion of exposure to dose made by using 1R = 0.0087 Gy. For environmental radiation, coversion of absorded dose in air to effective dose in the human body is 1 Gy = 0.7 Sv.

Figure 2.3 Average monthly outdoor exposure rates at a site over 16 years



Note: Conversion of exposure to dose made by using 1R = 0.0087 Gy. For environmental radiation, coversion of absorded dose in air to effective dose in the human body is 1 Gy = 0.7 Sv.

Figure 2.4 Maximum and minimum daily averages as compared to the yearly average of the outdoor exposure rate over a 14-year period

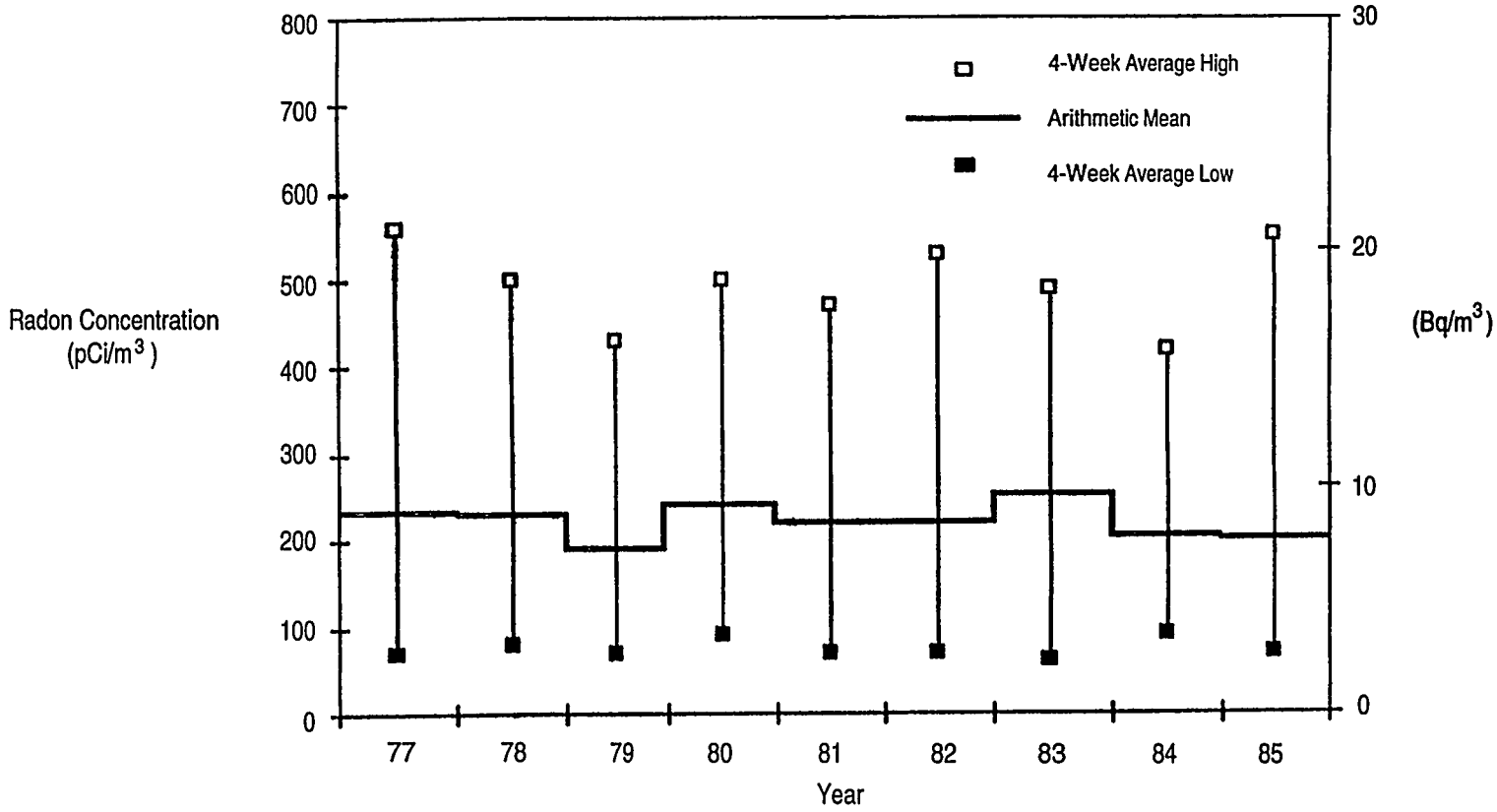
2.3.2.1.2 Inhaled Terrestrial Radionuclides. Although external terrestrial gamma radiation is highly penetrating and affects the entire body, the largest contributor to the total effective dose equivalent from background comes from the inhalation of radon gas and its short-lived decay products. This is because the radioactive particles are airborne and can be inhaled into the lungs, where the full energy of the emitted alpha particles associated with their decay is deposited in a small volume of tissue. As in the case of gamma radiation, various physical phenomena affect the concentration of radon in the environment and, consequently, variations occur over time.

Outdoor radon levels vary over time because of weather conditions. Data collected for many years at the station in Chester, New Jersey, demonstrate the degree of these variations (EML, 1978, 1979, 1980, 1981, 1982, 1984, 1985, 1988, 1991). In particular, the effect of atmospheric inversions, as discussed above, can cause ground level concentrations to increase by as much as 200 times those found during the day, although the average increase has been found to be about a factor of 2. Variations over longer terms show that the seasonal minimum in the winter is about three times lower than the seasonal maximum that occurs in August. Figure 2.5 shows a plot of average annual outdoor radon-222 concentrations for a 9-year period, along with the minimum and maximum averages over 4-week intervals in each year. In this figure, the annual average varies by up to 30 percent, or about 2.6 Bq per cubic meter of air (70 pico (one trillionth) curies per cubic meter), while the 4-week averages indicate that a single measurement over a month would only be within a factor of two or three of the annual average, again reflecting the seasonal differences that occur.

Indoor radon levels can be expected to vary over time as well. Since a principal source of radon entry into a building is the soil surrounding the building's foundation, weather can affect the air exchange rate between the soil and indoors. Wind, atmospheric pressure, andthe freezing and water logging of soil can all influence the movement of radon through the soil pore space and into a building. Variations can occur on time scales of hours, days, or months. Rapid changes in radon levels can occur from showering with well water containing dissolved radon gas, or from cooking with natural gas containing radon. Compared to outdoors, radon gas can build up to rather high levels indoors if there is a slow rate of air exchange with the outside.

Highly energy-efficient houses with snug-fitting windows and doors and other good weather stripping can fall in this category. In such situations, the radon level is subject to wide variations from changes in the ventilation rate, as would result from opening windows. Continuous monitoring of indoor air in houses has shown that the radon concentration can change by a factor of 10 or more (Nazaroff and Nero, 1988) from hour to hour. Seasonal differences are also found, as the concentration during winter months is generally higher than during the summer months, although there are exceptions to this rule. Another important process that influences the dose from radon is the attachment of its decay products (those that ultimately deliver the dose to the lung from being inhaled) to fine particles, or aerosols, in the air. The sizes of these particles and their removal from the air we breathe by attachment to walls and other interior finishes, called plate out, ultimately affect how much radioactivity we breathe in and retain. The aerosol concentration itself can vary with time depending upon such factors as cooking, smoking, and using kerosene heaters.

Radon decay products are not the only form of radioactivity that can be inhaled. Fine particles of soil, which contain all of the other natural radionuclides, can be suspended in air through the action of wind or human activities such as soil excavation. Dry periods and soil that lacks ground cover provide a ready environment for resuspension. Since wind conditions can abruptly change over short time periods, the amount of resuspended soil and the natural radioactivity that it contains can be



Note: 1 pCi equals 0.037 Bq.

Figure 2.5 Average outdoor radon-222 concentration in air at a site along with the average 4-week low and high values for a 9-year period

expected to vary accordingly. Seasonal changes related to wind as well as the dryness and vegetative cover of the soil can also be expected. Episodic increases from unusual natural or man-made activity in an area are also possible.

2.3.2.1.3 Internal Terrestrial Radionuclides. The intake of radioactivity to the body from eating food and drinking water can be expected to vary over time to some degree as well. Bananas and some other popular foods contain relatively high levels of potassium. However, the body maintains a fairly constant amount of this element, and the radioactive form, potassium-40, will not build up to higher levels even when larger than average quantities of these foods are eaten. The amount of potassium-40 will vary depending on body size and thus will change over time as adulthood is reached. On average, women would receive an annual dose that is about 25 percent, or about 0.05 mSv (5 mrem), less than men.

For some radionuclides such as uranium and radium, however, buildup within the body results from intake over time, and variations in diet therefore play a role. Also, geologic processes can influence the amount of natural radionuclides contained in well water in an area; if this is the primary source of drinking water, changes in intake and the dose from internal sources would result.

2.3.2.2 Cosmic Rays

Cosmic ray variations from day to day tend to be small, a few percent or about 0.001 μSv (0.1 μrem) per hour, and result primarily from changes in the barometric pressure. Under a high pressure system, for example, a larger mass of air above provides a greater shielding effect, compared to a low-pressure system in which there is less air and less shielding.

To a lesser degree, the temperature of the atmosphere plays a role as well. A higher temperature expands the atmosphere, which causes the cosmic ray level to decrease because there are longer path lengths that allow some of the cosmic ray secondaries more time to decay before reaching ground level. Cosmic ray intensity also changes over a period of years. The sun's 11-year cycle (as measured by sunspot activity) affects the cosmic ray intensity at ground level by raising or lowering it from its average value by up to 10 percent, or about 0.03 mSv (3 mrem) per year at sea level. The solar cycle is also related to the frequency of solar flares. Short-term increases in background from this source are possible, as was seen during the unusually energetic flare in September 1989, which produced an increase of about 200 percent in the neutron counting rate and an increase of about 35 percent or 0.01 μSv (1 μrem) per hour in the ionizing component at sea level (EML, 1992).

2.3.2.3 Cosmogenic Radionuclides

The cosmogenic radionuclide production in the atmosphere can be expected to vary according to changes in the cosmic ray intensity. From 1985 to 1990, a 30 to 40 percent decrease in the concentration of beryllium-7 was observed in surface air monitoring stations around the world (Larsen, 1993). This decrease coincided with the decrease in galactic cosmic ray intensity, which in turn coincided with the increase in the sun's activity during this time period. A more active sun, as evidenced by more sunspots, produces changes in the solar wind and magnetic field, which oppose the cosmic rays coming from outside our solar system. Seasonal changes also occur in the deposition of cosmogenic radionuclides to the surface of Earth. Deposition is greater during the spring months when air in the stratosphere tends to mix with air in the troposphere, where it can be washed out by precipitation.

2.3.2.4 Man-Made Radionuclides

Background variations can arise from the input of man-made radionuclides to ecosystems. Both nuclear weapon detonations and accidents dispersing nuclear material have the potential to cause radiation and radioactivity levels to increase at sites quite distant from the source. The large-scale testing of nuclear weapons in the atmosphere that took place during the 1950s and early 1960s resulted in the fallout of a variety of radionuclides that caused significant short-term increases in external radiation levels. Most of these have decayed away, although a few percent or less of the gamma radiation levels in many areas is still due to cesium–137, which has a 30-year half-life and can still be found in surface soils. Strontium–90, which has a 29-year half-life, has contributed significantly to internal dose through dietary intake over the past 30 years, although this source of exposure has gradually diminished over the years. Plutonium from fallout has contributed to internal dose through the inhalation pathway; however, the concentrations in surface air fell rapidly after the initial injection to the atmosphere. More recently, tests conducted by China in the late 1970s produced temporary increases in radiation and radioactivity levels. Immediately following the fallout, increases in gamma radiation were measured to be on the order of 20 percent or about 0.02 μSv per hour (3 μR per hour) above background, gradually declining over a period of a few weeks (HASL, 1976).

Temporal changes in the concentration of helium-3 in precipitation were considerable during the period of atmospheric nuclear weapons testing. The value of 360 Bq per liter recorded for the peak fallout year (1963) can be compared to the natural (pre-1952) level of only 0.6 for Ottawa, Canada (NCRP, 1987b). Changes of a factor of two or more were not unusual from year to year during the period 1953 through 1968.

Accidents at nuclear facilities, in particular the Chernobyl power plant in 1986, also produced measurable contamination around the globe, although the contribution to dose was quite small for people in the United States. The impact for an event of this magnitude would be abrupt and quite considerable for a local area, however. In a region about 160 km (100 miles) from Chernobyl, for example, measurements show cesium–137 concentrations in surface soil as high as 60,000 Bq per kg (Miller et al, 1991), which represents an increase of several orders of magnitude above pre-accident levels.

2.3.3 Spatial Variability

2.3.3.1 Terrestrial Radionuclides

The concentration of terrestrial radionuclides varies from place to place in much the same way that mineral deposits can be expected to vary from geologic processes that occur over time. Soils are mixtures of various chemical compounds, including major constituent elements such as silicon, aluminum, iron, carbon, hydrogen, and oxygen. Many other elements exist in either minor or trace quantities that can vary greatly. Elements that have naturally occurring radioactive forms (that is, potassium, uranium, and thorium) fall in this category. For instance, granitic rock is known to contain higher than average uranium concentrations, and monazite sand can have particularly high concentrations of thorium. Apart from naturally occurring variations, humans frequently alter the makeup of soil with the addition of amendments for cultivation. For example, one of the three principal components of fertilizer is potassium, most of which is in the stable forms, potassium–39 and potassium–41, but a fraction of a percent of which is the radioactive form potassium–40.

2.3.3.1.1 External Terrestrial Radionuclides. Surveys around the country have shown concentrations of uranium and thorium in the soil to range from as little as one tenth to as much as four times the average value (Myrick et al, 1983). In addition, aircraft mounted with radiation detectors have surveyed large tracts of land in various areas, and these measurements have been supplemented with a number of ground-based surveys. As a general rule, the Atlantic and Gulf coastal plains tend to average about half of the gamma ray level seen for middle America, although the distribution of the levels overlaps, and exceptional areas have been documented (NCRP, 1987b). For instance, the Denver, Colorado, area has gamma radiation levels about twice the average for Middle America. Measurements in sections of Nevada stretching into Utah contain similarly high natural gamma radiation levels (Miller et al, 1980).

The variation within a State, or even a smaller region, can be large. Monitoring stations operated by the Environmental Protection Agency in southern Nevada show background (combined cosmic and terrestrial gamma) to vary by a factor of three among the sites, or about 0.6 mSv (60 mrem or 100 mR) per year (EPA, 1990). While some of this variation results from differences in altitude and cosmic ray intensity, most of the variation arises from differences in the terrestrial gamma component. In certain regions (such as the Reading Prong formation that cuts across northwestern New Jersey), gamma radiation levels can be found to triple across a small field because of variations in the concentration of natural radionuclides in the soil. Venturing near rock outcroppings that may contain 100 times the average soil concentration will produce even larger fluctuations. In contrast to these areas of relatively high radiation in this part of the state, just 100 km (62 miles) to the southeast are sandy beach areas where the gamma radiation levels fall to less than 10 percent of the average measured over the Prong, which in absolute terms is only about 0.05 mSv (5 mrem) per year.

The variation in the total gamma radiation levels among sites relates directly to the concentrations of the principal gamma-emitting radionuclides in the local soil. Table 2.6 gives an example of the degree of variation that can be found in a local area, in this case, the vicinity of Three Mile Island. To some degree, soil cultivation by humans further adds to the natural variations in the radionuclide concentrations among different soil types in an area.

Areas where human activities have been known to alter background levels of radiation include the phosphate regions in northern and central Florida. In these regions, the phosphate rock is mined for fertilizer production, but the rock itself and the tailings contain elevated concentrations of radium. Backfilling operations in mined areas have led to areas of topsoil with higher concentrations than the original (NCRP, 1987b). Survey data show that gamma dose rate levels range from slightly less than to about double the national average.

Similar background variations can be found in western states where uranium mining and milling operations have produced tailings containing similarly and higher elevated concentrations of natural radionuclides. Of particular note are Uravan and Grand Junction, Colorado, where the gamma dose rate on top of tailings piles has been observed to be on the order of 100 times normal background (a few μSv per hour or a few hundred μR per hour) (NCRP, 1987b).

Another example of background alteration can be found on land where pipes from oil drilling operations are cleaned of scale containing relatively high concentrations of radium (Wilson and Scott, 1992). Concentrations in surface soil were found in the range of 5.3 to 62.2 Bq per gram, which is two to three orders of magnitude above normal background levels for the United States.

Table 2.6. *In Situ* Radionuclide Concentrations in the Vicinity of Three Mile Island[1]
(Bq per kg)

Site	Uranium-238	Thorium-232	Potassium-40
A	32	27	244
B	29	30	216
C	16	19	203
D	23	31	403
E	14	17	184
F	43	40	512
G	26	29	383
H	24	32	257

[1] From unpublished data collected by USDOE Environmental Measurements Laboratory.

Apart from outdoor variations in gamma ray levels, indoor variations occur because building materials vary among structures and even within the same structure. Measurements made in a variety of houses around the country in recent years show that in a typical wood frame house, gamma ray levels are generally about 50 percent, or on average 0.1 mSv (10 mrem) per year, higher in a basement than on a second floor (Miller, 1992). Rooms that contain stone or brick wall fireplaces tend to have gamma ray levels about 50 percent higher than those with normal drywall panels. Houses of full brick construction have average concentrations about 50 percent higher than wood frame houses without any brick. The use of cinder blocks, which are produced from ash residue in the combustion of fuels such as coal, also yields a higher than average radiation level. Within a large, concrete, commercial-type building, measurements have shown the gamma radiation level to vary up to 50 percent or about 0.15 mSv (15 mrem) per year among different floors, and on the order of 20 percent or about 0.05 mSv (5 mrem) per year on the same floor (Miller and Beck, 1984). In such situations, differing composition of interior partition walls and the effects of windows at the building edge can lead to variations in otherwise homogenous structural compositions.

The gamma radiation level inside a building results from the penetration of radiation from outside and the contribution from the building itself. It thus reflects the concentrations of radionuclides in the soil as well as in building materials. In light frame structures, the outside component is significant; however, in large massive buildings, it is generally quite small. In some sense, the concentration of the radionuclides in building materials relative to those outdoors is the determining factor in whether the building acts more as a shield against outdoor radiation or a source of radiation itself. Data presented in Table 2.7 indicate the variability in the concentration of the natural radionuclides in ordinary concrete samples from around the country (Ingersoll, 1981). As these data show, the variation among cities ranges from a factor of about 3 to 6 for the various nuclides. Variation can be expected even within a region, and the data of Eichholz et al (1980) showed variations of a similar range for concrete within the local area of Atlanta, Georgia. Available brick showed an even broader range (see Table 2.3).

Table 2.7. Natural Radionuclide Content of Ordinary Concrete[1]
(Bq per kg)

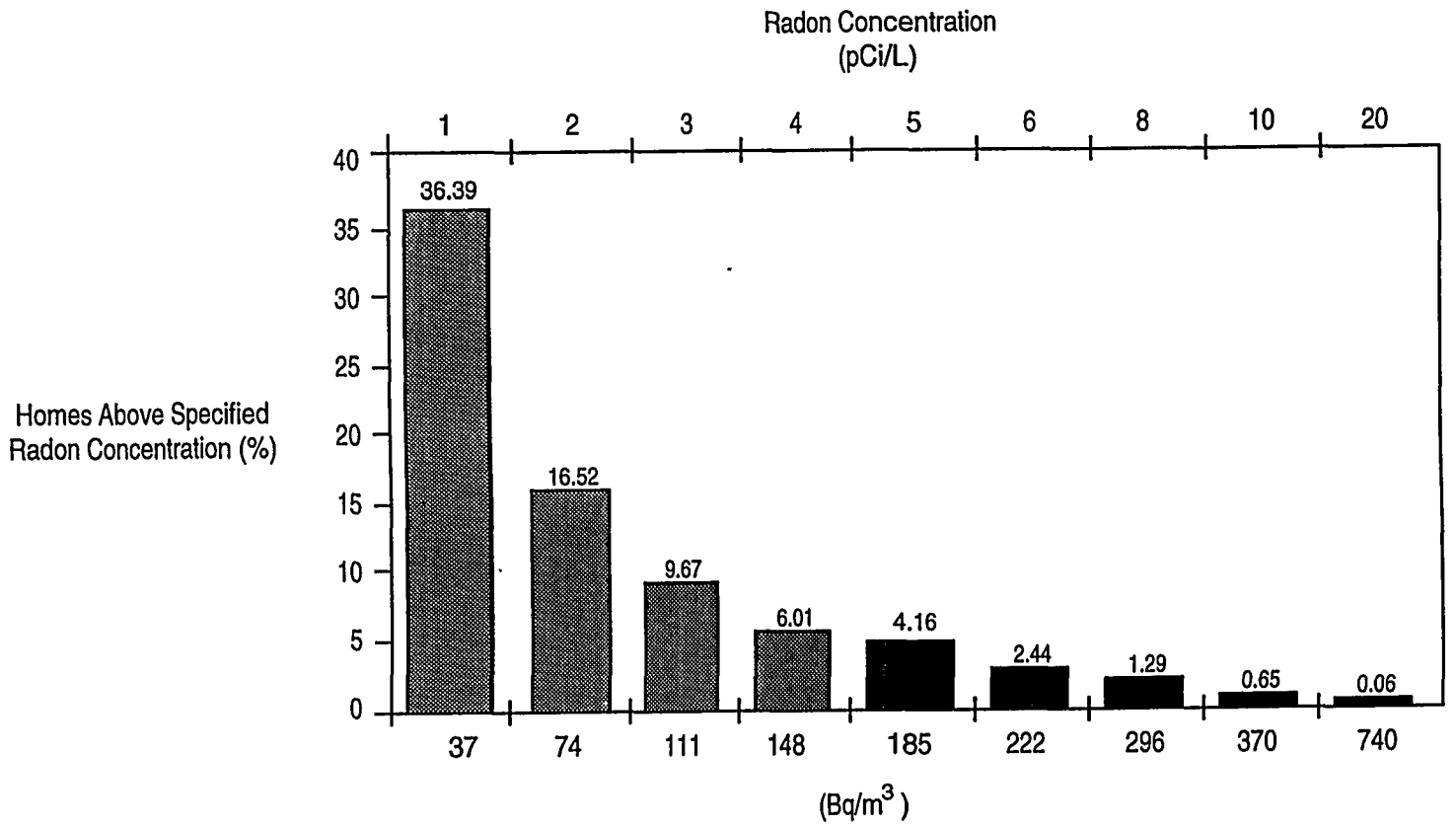
City, State	Uranium-238	Thorium-232	Potassium-30
Albuquerque, NM	31	24	461
Austin, TX	16	6	246
Chicago, IL	19	8	154
Kansas City, MO	13	8	215
Knoxville, TN	13	5	154
Philadelphia, PA	8	6	215
Salt Lake City, UT	25	16	184
San Antonio, TX	38	31	461
San Francisco-Oakland, CA	19	12	184
St. Paul-Minneapolis, MN	19	16	461

[1] From Ingersoll (1981).

2.3.3.1.2 Inhaled Terrestrial Radionuclides. The dose associated with the inhalation of terrestrial radionuclides is subject to spatial variations as well. Outdoor radon concentrations in air can be expected to vary according to the local radium levels in the surface soil. This is reflected in outdoor measurements around the country that range between 4 Bq per cubic meter of air (0.1 pCi per liter) in New York City to 44 (1.2 pCi per liter) in Colorado Springs (NCRP, 1987b). Coastal communities that receive air circulation off the oceans (where there is virtually no source of radon) tend to have lower concentrations than inland areas. Other local meteorological conditions, such as the degree and frequency of atmospheric inversions, play a role as well. Within a region, topography can be a factor, because it has been observed that the concentration of radon and its decay products in the air along a hillside can be five times lower than the concentration in a valley during a strong nighttime inversion (Porstendorfer, 1993).

Apart from outdoor variations from place to place, large differences can occur with indoor radon levels. Data collected from around the country indicate the average value for some counties can be several times the average for the state (Cohen and Shah, 1991). Individual homes can, in turn, have concentrations many times those of the county average. The results of the U.S. Environmental Protection National Residential Radon Survey are shown in Figure 2.6. About 6 percent, or roughly 6 million homes, exceed the EPA Action Level of 150 Bq per cubic meter (4 pCi per liter) (Marcinowski, 1992). Because of the highly variable nature of the radon source and entry pathways, it is possible for a house to have a concentration many times greater than a neighboring house. Within the same house, differences in concentration can occur, particularly when basement areas are closed off. As in the case of temporal variations, the concentration of aerosols to which the radon decay products attach can be expected to vary from place to place, as well as in the amount of plate out that occurs.

Variations in the dose associated with the inhalation of resuspended soil can be expected because radionuclide concentrations in the soil vary from place to place, as does the degree of resuspension that occurs in an area. In general, arid regions have higher resuspension. Within a local region, the degree of inhalation of radionuclides could depend upon the proximity to and frequency of use of dusty unpaved roads, and whether the population engages in agricultural, construction, or a similar type of work that produces resuspension.



Note: 37 Bq/m^3 equals 1 pCi/L

Figure 2.6 Results of the EPA National Residential Radon Survey program (Marcinowski, 1992)

The addition of natural radioactivity to the air can result from fossil fuel combustion where ash containing natural radionuclides is released directly to the air. For instance, in the process of burning coal, releases of ash as well as volatilized radionuclides such as lead-210, can lead to dose increases as high as a few percent above normal background levels in areas downwind of a large power plant with poor emission controls (Beck et al, 1980). Local variations relate to distance from such a facility, wind patterns, and other meteorological phenomena.

2.3.3.1.3 Internal Terrestrial Radionuclides. Although information on the variation of natural radioactivity contained within the body for people living in different places is not as extensive as that for external radiation, the available data indicate that variations do exist. Data have been collected from around the world for a number of the natural long-lived radionuclides that indicate the degree of variation in the concentration in human soft tissue, blood, and bone (Fisenne, 1993). For a nuclide such as lead-210, differences of about a factor of three have been measured among samples from various parts of the United States.

One potential source of variation among the population arises from the intake and retention of polonium-210 and lead-210 from cigarette smoking, because these radionuclides are volatile and are inhaled with smoke. For radium-226, somewhat larger differences can be seen for the mainland United States (NCRP, 1987b). In addition, variations in internal radionuclide levels result from differences in dietary intake, as well as the radionuclide concentration in foodstuffs in different areas of the country (NCRP, 1987b; Fisenne, 1993). Crops grown in different regions contain varying amounts of natural radionuclides because of differences in radionuclide concentration in the soil and uptake by the plant. To some extent, differences exist based on whether the diet is urban or rural in nature, because the relative proportion of foodstuffscontaining different concentrations of radionuclides varies according to market access. Also, intake of radionuclides can be expected to vary with concentrations in drinking water. People living in certain regions, such as those where there is a high concentration of uranium in well water used for drinking, develop higher body burdens over time. In contrast, intake is much lower where people rely on surface water for consumption. Measurements of uranium in water have shown that certain midwestern areas have concentrations 35 times greater than certain eastern states, while certain western areas have uranium concentrations in water 350 times greater than eastern states. Substantially higher intake of radium-226 has been documented for certain deep municipal wells in northern Illinois (NCRP, 1987b).

2.3.3.2 Cosmic Rays

Cosmic ray variations from place to place primarily result from variations in altitude, although some smaller variation results from latitude. In short, the higher the elevation, the higher the cosmic ray dose. Figure 2.7 shows the relationship between dose rate and altitude (Bouville and Lowder, 1988). The population in a city such as Denver, at an altitude of 1610 meters (5300 feet), receives an annual cosmic-ray dose about 0.2 mSv (20 mrem), or a factor two, higher than the average for the United States.

Since the magnetic field of Earth curves inward toward the north and south poles, the cosmic ray particles undergo less deflection and their intensity is stronger. At sea level, the cosmic ray dose is estimated to be about 10 percent lower in regions near the equator compared to high latitudes. At sea level, this amounts to a difference on the order of 0.03 mSv (3 mrem) per year in the effective dose equivalent. Given the range of latitude of the United States, the variations are just a few percent or

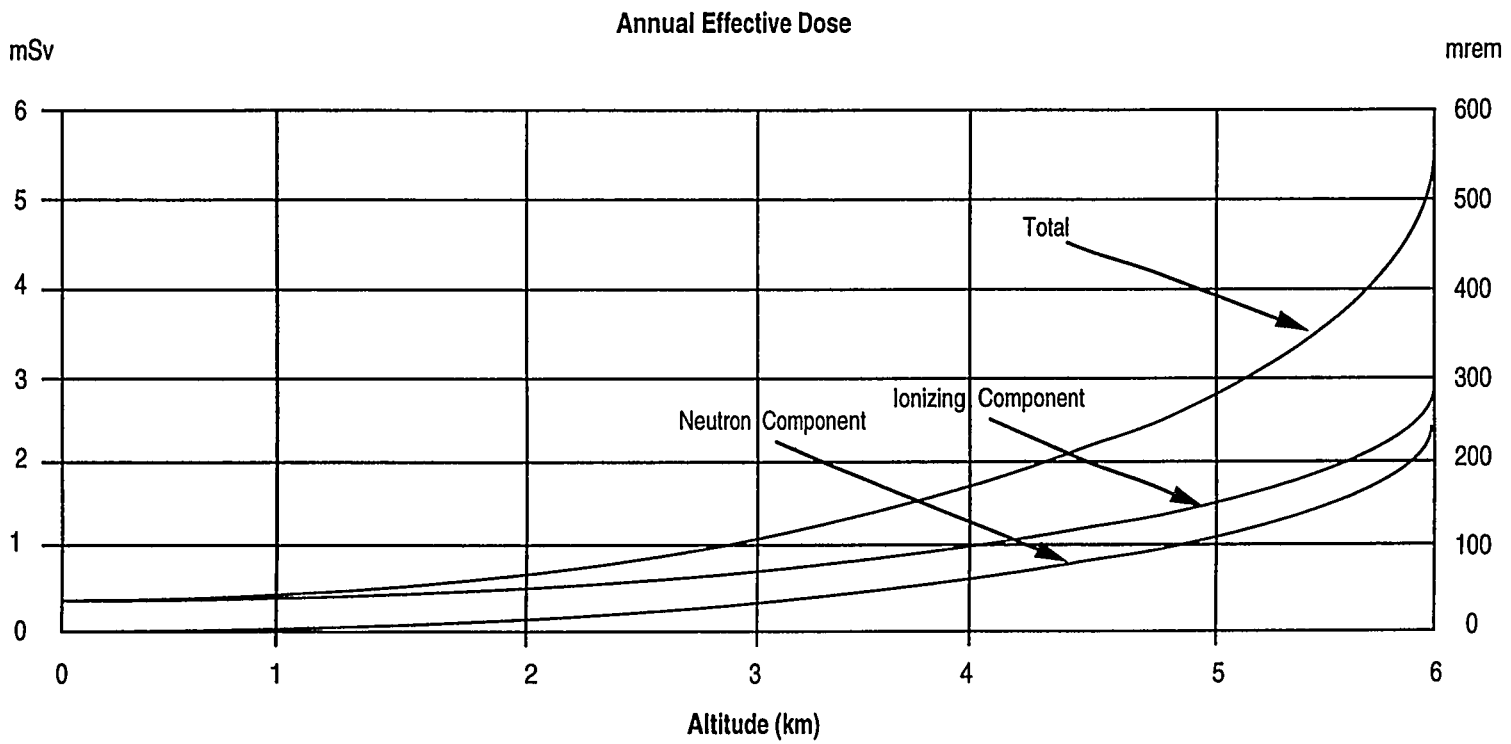


Figure 2.7 Annual dose from cosmic radiation as a function of altitude

about 0.01 mSv (1 mrem) per year about the average, with the exception of the northern regions of Alaska.

Cosmic radiation levels in small residential-type structures are only a few percent less than those outdoors, because there is little shielding provided by wood framing and roofing materials. However, in large buildings with relatively thick concrete ceilings and floors, significant shielding exists and the cosmic ray dose can drop sharply with the first overhead layer and more slowly with each successive layer thereafter. Measurements performed in a 12-story structure showed a 36 percent drop, or 0.1 mv (10 mrem) per year, on the top floor and a 73 percent drop, or 0.2 mSv (20 mrem) per year, at the basement level relative to the outdoor value (Miller and Beck, 1984).

2.3.3.3 Cosmogenic Radionuclides

Although the cosmogenic component of background is much smaller than that from terrestrial radionuclides and cosmic rays, the production of these radionuclides is nonetheless higher near the poles because of the greater cosmic ray intensity, as mentioned previously. However, many cosmogenic radionuclides are produced in the upper atmosphere, and the concentrations are therefore higher near the equator, since stronger convection leads to a much higher degree of mixing with surface air. For example, the concentrations of beryllium-7 in surface air show a clear trend toward higher values approaching the equator and lower values approaching the poles (Larsen, 1993). For the United States, the air in Miami, Florida, exhibits concentrations about 2 to 4 times higher than those at Point Barrow, Alaska. As for deposition to the ground, an additional source of variation occurs with climate, because arid areas receive less deposition than regions where there is more precipitation.

2.3.3.4 Man-Made Radionuclides

Differences in the distribution and deposition of fallout from nuclear weapon tests can be found across the United States. Globally dispersed fallout varies with latitude and, in particular, with the amount of precipitation an area receives. The arid southwestern portions of the United States have inventories of radionuclides from fallout in soils which are lower than average, whereas certain moist mountainous regions contain concentrations of fallout radionuclides that are a factor of two or three higher. Areas downwind of the Nevada Test Site are characterized by a heterogeneous distribution of local fallout from the tests conducted there.

Measurements of cesium-137 in undisturbed soil throughout Utah indicate that the deposition of fallout radionuclides varies by about a factor of three (Beck and Krey, 1980). However, because of differences in the degree of penetration through the soil layers and in density amongst soil types, the concentration in the top 2.5 cm of soil varies by a factor of 20. Even within the region around the Great Salt Lake, which is a more limited geographical area, the deposition varies by about 50 percent. This degree of variability is reflected in the data in Table 2.8, which gives the average concentration for a number of cities over a soil depth of 0 to 30 cm.

Table 2.8. Concentrations of Cesium-137 in Soil[1] in The Great Salt Lake Vicinity[2]

City	Concentration (Bq per kg)
Bountiful	15.3
Brigham	14.4
Layton	10.9
Layton	13.0
Logan	10.8
Ogden	13.7
Magna	12.3
Midvale	11.6
Salt Lake City	15.0
Salt Lake City	12.6
Salt Lake City	12.0
Toole	12.7
Tremonton	11.6
Tremonton	12.1

[1] Based on a soil depth of 0 to 30 cm.
[2] Computed from the data of Beck and Krey (1980).

Apart from regional differences in the original deposition, even larger variations can be found in the concentrations of fallout radionuclides in an area because of natural or man-made disturbances to the soil. Redistribution has occurred as a result of wind and water erosion, and many places have been plowed or had soil removed or brought in as fill. Thus, concentrations can span a range from nearly zero (or below detection limits) where runoff has occurred to several times the average for an area because of sediment accumulation. Despite these differences, the total dose from fallout radionuclides, like cosmogenic radionuclides, is quite small compared to terrestrial natural radionuclides and cosmic rays.

2.3.4 Summary of Background Variability

To give the reader a better understanding of the radiation environment, the preceding sections provide detailed information on the causes and magnitude of background variability. Temporal variability is affected by weather, climatic changes, geological processes, human activities, the 11-year solar cycle, and other naturally occurring processes. The most variable component of background over time is radon. Over the course of a day, or from season to season, outdoor radon concentrations can change by more than a factor of two, while indoor radon concentrations can vary even more as a result of building ventilation changes. Over the course of a day, changes in the distribution of radon decay products in the atmosphere cause changes in the external gamma exposure rate ranging from a few percent to 100 percent or more.

Temporal variability of background is affected by seasonal changes in soil moisture and snow cover, which typically lead to changes in external radiation levels of 10 to 50 percent. To a lesser extent, cosmic radiation and the production rate of cosmogenic radionuclides varies up to 10 percent throughout the course of the solar cycle. However, abrupt changes in background can occur from the

input of man-made radionuclides from fallout after a nuclear weapon test or distant reactor accident, which can increase background levels for a few months to a few decades.

The spatial variation of external radiation is largely related to the makeup of the soil in a locale. The greatest spatial variation in background arises from the differences in levels of radon gas, which can vary from one tenth the national average to more than ten times the average because of differences in the radium concentration in soil. Outdoor gamma radiation levels over sandy soil along a coast may be only one fourth the average for the whole country, whereas it might typically be three times the average in mountainous areas with a high degree of mineralization. Indoor gamma radiation levels vary by about 50 percent because of the use of different construction materials.

Human activities also affect spatial variability of background. Mining and milling have redistributed natural radionuclides, adding to the variation that occurs in some areas. Variations in the dose from internal radionuclides primarily results from differences in the concentration of natural radionuclides in drinking water. A significant fraction of internal dose arises from potassium–40; however, this is relatively constant, whereas the concentration of nuclides such as lead-210 in body tissues has been observed to vary by about a factor three throughout the United States. Cosmic radiation increases by a factor of two between areas above sea level, such as Denver, Colorado, and areas that are at sea level. Variations of a few percent also occur with latitude. On a local scale, cosmic ray levels are lower for residents and workers in tall, massive buildings because of the shielding effects of concrete floors. Measurements inside a building have shown a drop ranging between one to two thirds below that outdoors. Cosmogenic and man-made radionuclide concentrations vary in air and soil, although the overall effect on the total variation in dose from background is quite small.

When considered on a large scale, this widely variable and ubiquitous source of naturally–occurring radiation produces doses to the human population that are, in turn, widely variable as well. The magnitude and variability of radiation doses among a given population is directly proportional to the population's activities and the background level to which the population is exposed. Current estimates of the minimum, maximum, and average dose per year to a United States resident from background are provided in the next section, along with comparisons to worldwide estimates and doses from other sources of radiation.

2.4 Estimated Doses From Background

A comprehensive review of background sources and the resultant doses received by the population of the United States has been performed by the National Council on Radiation Protection and Measurements (NCRP, 1987b). Figure 2.8 shows a breakdown of the estimated total effective dose equivalent, with regard to the average contributions from each of the principal sources. Of the rounded total of 3 mSv (300 mrem) per year, two–thirds or 2 mSv (200 mrem) comes from inhaling radionuclides (by and large, the indoor radon decay products). The other radionuclides internal to the body from ingestion and inhalation contribute about 13 percent or 0.4 mSv (40 mrem) of the total dose. External terrestrial (gamma) radiation and cosmic ray components are about equal and together make up about 18 percent or 0.55 mSv (55 mrem) of the total, whereas the annual dose from the cosmogenic radionuclides is very small, on the order of 0.01 mSv (1 mrem) or less than one percent.

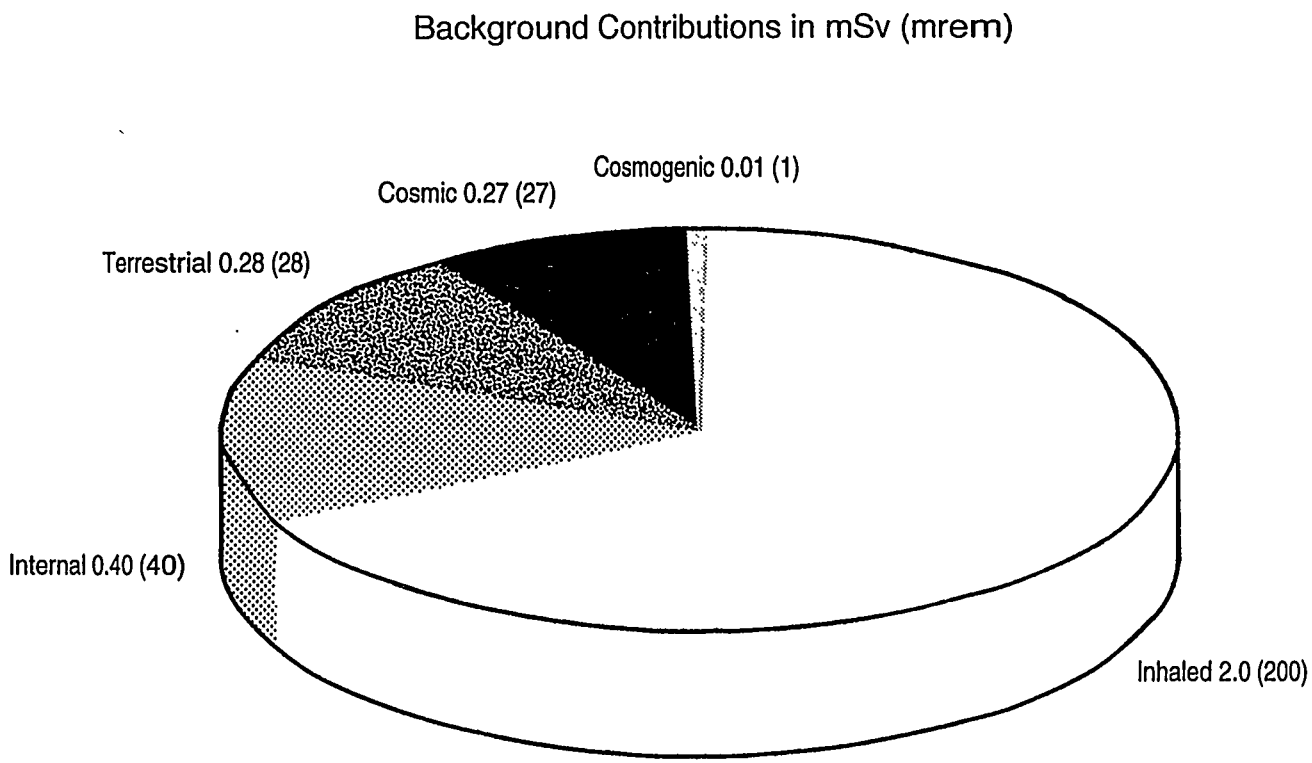


Figure 2.8 The average contribution to the total effective dose equivalent from various sources of background for the United States (NCRP, 1987b)

Given the previous discussion concerning the temporal and spatial background variations, it is imperative to remember that the estimated total dose of 3 mSv (300 mrem) is an annual average, and that the actual dose received by any one individual could be quite different. Figure 2.9 shows the average contributions of the four most significant components in perspective to the estimated typical maximums and minimums. These ranges are not to be taken as the absolute limits, but should indicate the variability generally encountered. In the inhalation category, the maximum of 8 mSv (800 mrem) per year is taken to be the dose corresponding to the current EPA Action Level of 150 Bq of radon per cubic meter of air (4 pCi per liter). Obviously, many United States homes exceed this level; however, indoor radon represents a category of natural radiation that is controllable by remediation. The minimum annual dose for radon, 0.2 mSv (20 mrem), corresponds to a level only one-tenth the national average, which is taken to be typical of well ventilated houses in areas with low radium concentrations in the soil. For internal radiation, about half of the average is taken to be constant, corresponding to the dose from radionuclides such as carbon-14 and potassium-40. The other half of the average internal dose is then varied from one-third to four times the average, based on data for the range of radionuclides measured in human tissues. This yields a minimum of somewhat less than 0.3 mSv (30 mrem) to a maximum of 1 mSv (100 mrem) per year.

The external terrestrial radiation maximum of three times the average is not unusual for areas in the western United States with a high degree of mineralization in the soil, whereas the minimum of one-fourth the average is representative of sandy soil along a coastline. This leads to a range of less than 0.1 mSv (10 mrem) to more than 0.8 mSv (80 mrem) per year for the gamma component. For cosmic radiation, the typical maximum is taken as twice that of the dose at sea level (a resident of Denver), while the minimum is half (a resident of New York City who lives and works in tall buildings). This corresponds to a difference of 0.4 mSv (40 mrem) per year in dose between the extremes for cosmic radiation.

The variability of major background components can average out in many cases so that many people receive similar total doses. Nonetheless, some degree of correlation exists among these components. High gamma levels can be found in mountainous areas, and accordingly, the higher levels of uranium in the soil lead to a larger source of radon gas in the soil, as well as higher concentrations of radionuclides in well water and food grown in those areas. The higher altitude also leads to a higher dose from cosmic rays.

As an example of the typical dose range, consider that people who live in well-ventilated wooden houses on sandy soil near the ocean would receive a minimal dose from radon — one tenth of the United States average — and a minimal external gamma dose — about one-fourth the average. With an internal and cosmic ray component of about average, the total dose to these individuals is only 1 mSv (100 mrem) per year. In contrast, people living in Denver, Colorado, could receive double the cosmic ray dose, triple the gamma dose, and quadruple the radon dose. With a somewhat higher intake of radionuclides from drinking water, the total dose is about 10 mSv (1000 mrem) per year. Although even higher doses are possible for people living in houses with very high radon concentrations, this value could be taken as an upper limit, allowing for extremes associated with unusual situations. Overall, this range of 1 to 10 mSv (100 to 1000 mrem) — a span of a factor of ten — is typical of the variation in background doses for most United States citizens in a given year.

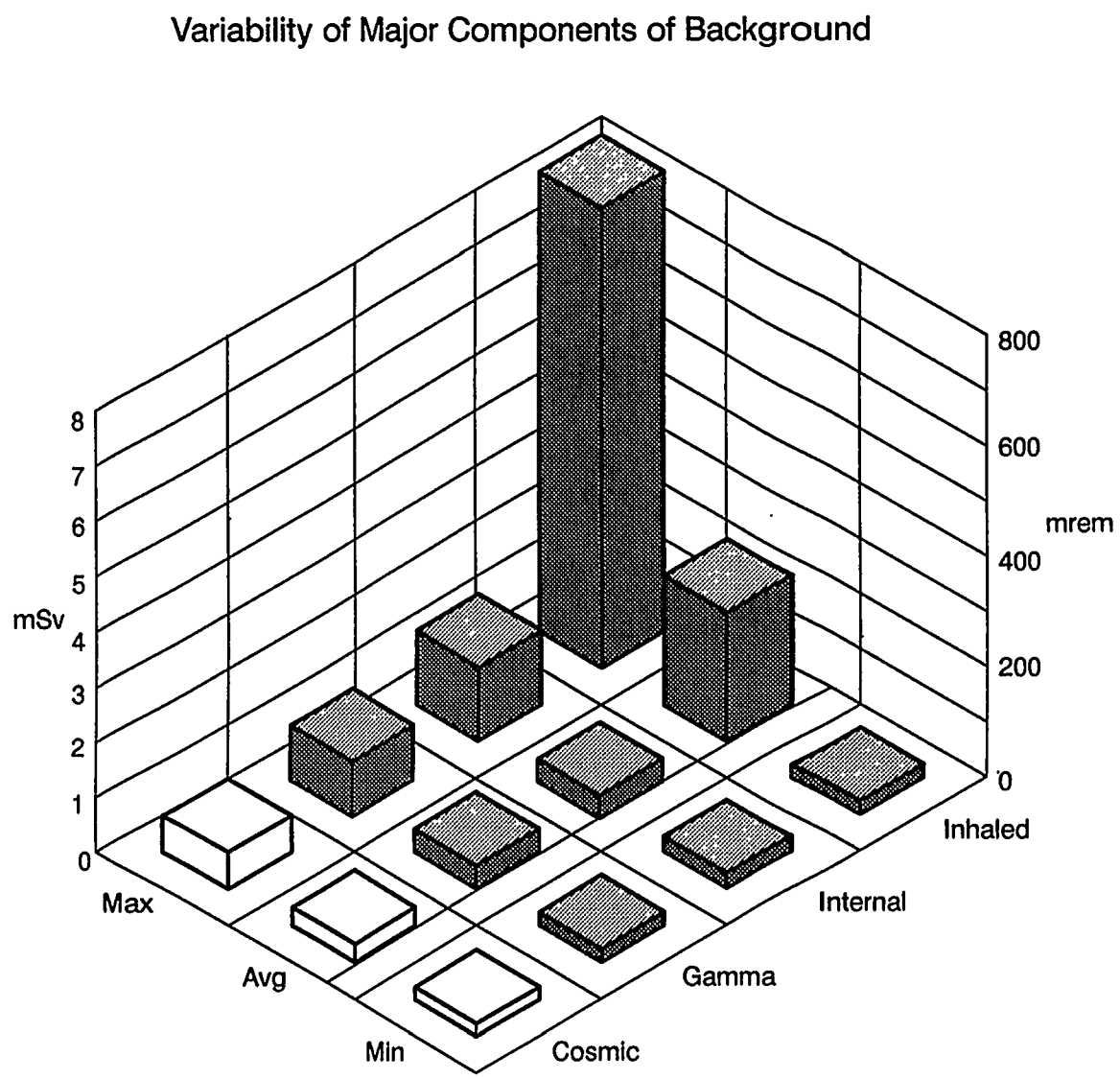


Figure 2.9 Typical maximum and minimum contributions of the major sources of background compared to their respective averages for the United States

2.4.1 Comparison to Worldwide Averages

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) issues a report every few years to update information on the sources, effects, and risks of ionizing radiation. The 1988 UNSCEAR report summarized data that was collected from around the world in the various categories of natural radiation exposure. Table 2.9 shows a comparison of the averages estimated by UNSCEAR and the range (excluding extremes) of effective dose equivalents as compared to the NCRP United States data that were published in 1987. As more information becomes available with each passing year, it is likely that both the worldwide and U.S.-specific values will be modified to some degree, particularly with regard to the radon component.

Table 2.9. Comparison of the Principal Components of Background Between Estimated Populations of the United States and the World

	Annual Effective Dose Equivalent(mSv)		
Component	U.S. Mean[1]	World Mean[2]	World Range[2]
Cosmic	0.27	0.36	0.3–2.0
Indoor radon and progeny	2.0	1.1	0.3–5.0
Internal (other inhaled, ingested)	0.4	0.5	0.2–1.0
Terrestrial gamma	0.28	0.41	0.2–1.0
Totals (rounded)	**3.0**	**2.4**	**1.5–6.0**

[1] From NCRP (1987).
[2] From UNSCEAR (1988).

2.4.2 Comparison to Some Man-Made Sources

After background, the next largest contributor of human exposure to ionizing radiation is medical procedures, such as those involving x-ray examinations and nuclear medicine. Table 2.10 compares the dose estimates for these, as well as a few other man-made sources, to dose estimates from background (NCRP, 1987a). All other sources are much smaller in magnitude. Included in consumer products are such contributions as ceramics, dental prostheses, and luminous watches and clocks, among others.

Again, these are average values; in other words, the total dose is distributed across the population. In fact, certain sub-population groups (such as sick or injured people who undergo the majority of the x-ray exams) are exposed to most of the radiation dose in various categories.

Table 2.10. Comparison of Average Background Doses to Those from Other Sources[1]

Source	Dose[2] (mSv)	% of Total
Background	3.0	82
Consumer products	0.05–0.13	3
Diagnostic x-rays	0.39	11
Nuclear medicine	0.14	4
Occupational	0.009	<1
Weapons test fallout	<0.01	<1
Rounded Total	**3.6–3.7**	**100**

[1] From NCRP (1987a).
[2] Annual effective dose equivalent.

3 METHODS FOR DISTINGUISHING BACKGROUND FROM NUCLEAR FACILITY SOURCES

3.1 Measurement Requirements

3.1.1 Unaffected Versus Affected Areas

The degree of effort expended in measuring radiation and radioactivity around and within a facility after it is decommissioned should be related to what is known about the past history of contamination at certain spots, as well as the potential for contamination from the type of operation that was conducted there. Likely affected areas therefore require more scrutiny, and the number of measurements performed and samples collected should be much higher than in unaffected areas.

An average concentration over a large area may be appropriate for determining if clean–up criteria have been met in unaffected areas; however, relatively small sections of ground, wall, or floor may have to be examined in affected areas. This could be accomplished using hand held scanning instruments or by collimating (or adjusting the line–of–sight of) detectors with a normally wide field of view. Contamination that exists on relatively smooth surfaces, such as walls and floors, can be measured using hand-held scanning devices that are sensitive to alpha and beta radiation. Removable radioactivity can be evaluated by swiping surfaces.

3.1.2 Site Characteristics

The analysis of radiation and radioactivity can be supplemented with a knowledge of the means by which material released into the environment is transported and deposited. For example, the direction and speed of the flow of surface and ground waters, as well as the sedimentation rate in ponds, lakes, and reservoirs, can be used to predict the degree of movement and accumulation of radionuclides. Similarly, wind speeds and directions and other atmospheric data are important in predicting the transport through the air and deposition to the ground. Terrain and ground cover (such as grass and trees) help in understanding and even predicting areas where maximum concentrations might be found. For instance, drainage channels and catchment areas tend to accumulate contamination.

Data from previous monitoring programs can be used if measurable quantities of substances from facility-related emissions were reported, especially in particular areas or during certain times of the year. Knowledge of population-related factors is potentially useful for dose assessment. Such factors, including geographical housing distribution, work and recreational areas, water sources, and land use characteristics, can help to establish the critical pathways to humans.

3.1.3 Instrumentation

The ability of radiation to ionize matter forms the basis for its measurement. For example, individual interactions of single particles or photons can result in a small pulse of electrical charge, a minute flash of light, or a damage track through a substance. Such effects can be observed and, in some cases, related to the type of radiation and its energy. The number of observed interactions, generally referred to as counts or events, that occur over a particular time interval provides a measure of the

intensity of the radiation or the amount of radioactivity. In some cases, a continuous flow of electrical charge (that is, a current) is measured.

A variety of instruments and analytical methods are used in the science of radiation and radioactivity measurement (e.g., see Chieco et al, 1990; Knoll, 1989). Many people are aware of devices such as Geiger counters and film badges, but there are a number of lesser-known instruments for measuring radioactivity, such as proportional counters, ionization chambers, scintillation detectors, semiconductor detectors, thermoluminescence dosimeters (TLDs), and track etch detectors. These are general categories of radiological instruments and there are a variety of different types, each of which is suited for measuring particular types of radiation, intensity levels, and energies.

Radiation can be measured directly at a point of interest, or samples taken from the environment at a site can be analyzed in the laboratory for their radioactivity content. In some cases, the radionuclides can be adequately measured by first chemically extracting them from a sample and then analyzing with a suitable radiation detector.

Radiation that the body receives from external sources can be measured directly with an instrument that is calibrated with similar radiation sources to infer dose. Radiation that results from sources internal to the body is generally determined less directly by measuring radionuclide concentrations in air, food, or water, and then computing the dose from the inhalation or ingestion of a certain quantity. Over the years, researchers have developed conversion factors that can be used to model these pathways and estimate radiation dose. It is also possible to determine radioactivity levels within the body directly with detectors. In keeping with occupational health and safety standards, this is routinely done for some people who work with particular types of radioactive material.

The general categories of radiation detectors can also be grouped according to whether they can be used on the spot (*in situ*), that is, over the course of minutes and hours in a survey mode or left in place for days or weeks in a monitor mode. Also, while some instruments can be used directly in the field, others are intended for laboratory-based analysis of collected samples. Some types can be adapted for either field or laboratory work. In addition, for thorough analysis, instruments are often used in conjunction with one another.

Table 3.1 lists some of the principal instrument types and their applications for assessing the radiation field from background. They include instruments for directly measuring radiation (gamma and cosmic) and those that are used to analyze samples for both external and internal dose assessment. As highly specialized scientific equipment, the costs of these instruments can be a sizable capital outlay for an organization outfitting a measurement group and laboratory. Table 3.2 gives approximate prices for radiation detectors and systems.

3.1.4 Spectrometry

Unambiguously identifying a radionuclide through the energy of its characteristic radiations is a far more sensitive way to distinguish background from radiation sources related to a nuclear facility, provided that the radionuclide to be measured is not found at measurable quantities as part of background. The analysis of radionuclides in this manner requires the collection of a spectrum, which comprises a channel-by-channel count rate. In some cases, thousands of channels are used, and each channel corresponds to an energy band of a selectable width. Channels where counts

Table 3.1 Selected Instrumentation and Applications for Background Measurement

Device	Application
Air sampler	Collection of particulates on filters or gases on traps (*in situ*) for subsequent analysis (at laboratory facilities)
Charcoal, track etch, electret	Analysis of radon in air
Germanium diode gamma spectrometer	Analysis of gamma emitters *in situ* or at laboratory facilities (high-energy resolution)
Ion exchange column	Removal of radionuclides in water (*in situ*) for subsequent analysis (at laboratory facilities)
Low-level survey meter (scintillator/GM counter)	Spot checks of external dose rate and alpha/beta surveys *in situ* (limited precision)
Liquid scintillation counter	Analysis of pure beta emitters at laboratory facilities
Mass spectrometer	Analysis of isotopes of elements extracted from *in situ* samples (at laboratory facilities)
PIC	Spot checks and continuous monitoring of external dose rate *in situ* (high precision);
Proportional counter	Analysis of alpha and beta emitters at laboratory facilities
Sodium iodide gamma spectrometer	Analysis of gamma emitters *in situ* or at laboratory facilities (low-energy resolution)
Silicon diode alpha spectrometer	Analysis of alpha emitters at laboratory facilities
TLD	Integrated measurements of external dose *in situ* (monthly or quarterly); can be used for site or personnel monitoring

accumulate to a higher degree than in neighboring channels produce peaks in the spectrum corresponding to characteristic energies that indicate which radionuclide is present and at what level of activity. In effect, each radionuclide has a fingerprint, as evidenced by these energy peaks, that positively identifies its presence.

Table 3.2 Estimated Costs of Radiological Instrumentation

Device	Estimated Cost
Alpha spectrometry system	$12,000
Continuous radon monitor	$3000
Germanium gamma spectrometer system	$25,000–75,000
Gross alpha/beta counter (manual)	$5000
Gross alpha/beta counter (automated)	$20,000
High–volume air sampling station	$3000
Liquid scintillation system (manual)	$20,000
Liquid scintillation system (automated)	$35,000
Low-level survey meter	$1000–2000
Mass spectrometer	$400,000
PIC	$13,000
Sodium iodide gamma spectrometer system	$15,000
TLD system (manual)	$10,000
TLD system (automated)	$40,000–70,000

3.1.4.1 Alpha Radiation

Alpha radiation is easily stopped and absorbed by the thinnest of material, even a small amount of air. For this reason, it is generally of no consequence unless the alpha-emitting nuclide is in the body, where its energy would be deposited in a very small volume and the dose would be large in that volume (as in the case of radon decay products inhaled into the lung). Radionuclides that can only be effectively identified and measured via their alpha radiation are generally chemically extracted from a sample, deposited on disks, and counted in a vacuum chamber close to a special detector. The chemical purification of the sample also removes other radionuclides that may have alpha particle energies close to those of the radionuclide under investigation, and that would otherwise interfere with the analysis.

3.1.4.2 Beta Radiation

Although somewhat more penetrating than alpha radiation, beta radiation is equally difficult to measure. It gradually loses energy as it traverses matter, making it difficult to detect the characteristic peak energy. Consequently, samples for beta analysis generally undergo some form of preparatory purification to reduce the matrix and concentrate the radionuclide. Samples in liquid form are well suited for beta detection. Liquid scintillation and gas proportional counters are employed to a large extent to quantify the beta particle emissions. In addition, it is sometimes possible to perform energy discrimination by examining individual events in the counter, and classifying and registering the counts in two or more channels. This can further improve sensitivities where interfering radionuclides contribute to the total count rate. For gross beta counting, absorbers of varying thickness can be used to filter out lower energy beta particles and establish a threshold above which counts can be attributed solely to the radionuclide of interest. In some sense, this can be considered a crude form of spectrometry.

3.1.4.3 Gamma Radiation

Gamma ray spectrometers are a very convenient tool for identifying and quantifying many radionuclides, because the analysis can be performed on whole samples, with minimal preparation, and in a non-destructive manner. Common fission and activation products such as cesium–137 and cobalt-60 are readily measured in samples using gamma ray spectrometry. Because of the highly penetrating nature of gamma radiation, spectrometry can even be performed directly at a site by examining the radiation emitted from a large area of ground. For radionuclides that don't have significant gamma radiations, it is sometimes possible to measure the x–rays that are associated with nuclear decay processes.

3.1.5 Sampling Needs

To fully assess the dose delivered to people from ionizing radiation and radioactivity in the environment, it is necessary to perform a complete pathway analysis that includes measurement and assessment of all radiation field components and, in some cases, individual nuclides. The penetrating component of background, which includes gamma and cosmic rays, can be measured directly at a site. To characterize other components, samples of soil and vegetation can be collected and returned to the laboratory for analysis. Sediment and water samples can be taken from surface water bodies. Drinking water samples can be drawn from taps, and subsurface water can be collected from existing wells or by drilling new wells. Samples of air can be taken whole, or filters and traps can be used to collect certain chemical species or particulate matter in the air. Rainwater or other forms of precipitation can be collected, as can fallout that comes down in dry form. Food can be sampled and may include locally produced milk, vegetables and fruit products from home gardens, fish, and game. Certain plant and animal organisms, such as mussels, serve as preferential accumulators of certain radionuclides, and these can be collected and examined.

A program to fully assess the radiation components that expose humans in a given area would best be extended over time to obtain an accurate average. Longer measurement periods would cancel out fluctuations that produce unusually high or low values over short time intervals. Gamma radiation could be assessed during this period by making spot measurements at a number of sites, characterizing the makeup of the radiation field, and identifying the radionuclides present. Continuous measurements at some of these sites would be appropriate. In the case of radioactivity associated with airborne particles, continuous sampling over monthly periods would not only provide a meaningful average, and would also result in higher sensitivity because the radionuclides would become more concentrated on the filters. A similar monitoring period would be useful for sediment, water, and food.

3.1.6 Methods

External radiation at normal background levels can be accurately determined with survey instruments that include energy-compensated Geiger-Müller (GM) and proportional tubes, dual-phosphor scintillators, and pressurized ionization chambers (PICs). Other survey meters of more simple design can be intercalibrated with these in the same type of radiation field, and used for spot measurements where less precise measurements will suffice. Over extended periods of time, such as a month or more, devices that integrate the dose are economical and more appropriate for use. An example is the TLD. Spectrometry can be employed wherever there is a need to characterize the relative

contributions of different radionuclides to the dose rate at a site. For large tracts of land, effective gamma-ray surveys can be performed by aircraft mounted with radiation detectors and position recording systems.

The cosmic ray dose contribution that is measured with these devices can be inferred from altitude or barometric pressure data when the devices are used outdoors or in small structures, such as houses. In larger structures, where the cosmic ray level is generally not known because of the significant shielding of the structure, specialized techniques for separating gamma and cosmic components may have to be applied (Miller and Beck, 1984). Whether the cosmic-ray level is known or not, it is usually possible to measure the gamma and cosmic doses as one quantity, treating them as a combined total of external penetrating radiation.

Particulate matter containing radioactivity can be effectively collected on filters through which air is pumped. The longer the sampling period, the more activity can be collected and thus the more sensitive the measurement. Measurements of radon gas in air can be performed with a variety of detectors such as activated carbon canisters, track etch detectors, and electret-type devices.

Ion exchange columns can be used to extract and concentrate certain radionuclides from water samples. Food items can be purchased at local markets. Included in a representative mix would be fresh and canned vegetables, grain products, fruits and juices, dairy products, meat, poultry, and fish. Food samples can be reduced to ash using a muffle furnace to provide concentrated samples for analysis of radionuclides that are not volatile.

Proper preparation of samples is an important aspect of a measurement program. Samples that are collected and returned to the lab (such as soil samples) are usually processed by weighing, drying, crushing, blending, and pulverizing. Smaller subsamples can then be partitioned and analyzed using specialized counters to determine the radionuclide activity present by detecting alpha, beta, or gamma rays. The samples can also be processed chemically to separate and concentrate the radionuclide before counting.

Estimated costs for particular types of radiation and radioactivity measurements are provided in Table 3.3. The services of a commercial laboratory for analysis represents only a part of the total cost of a measurement program. Cost estimates of survey measurements, given in Table 3.4, include the cost of manpower to obtain samples. Such tasks as overall management, development of a sampling program and strategies, site selection, servicing of monitors, data interpretation, and quality assurance would considerably add to the cost of a measurement program.

3.2 Measurement Considerations

3.2.1 Data Acquisition

The release of a decommissioned facility may require an extensive measurement program to ensure that radioactivity levels are at or near background levels. Key radionuclides for investigation can generally be identified through either the history of past operations or preliminary surveys to "scope out" the problem areas. It would be highly impractical and prohibitively expensive to sample and measure every square meter of land neighboring a facility. Rather, a sampling strategy can be

Table 3.3 Estimated Costs of Radiation/Radioactivity Measurements

Measurement Method	Estimated Cost (per location/sample)
Alpha spectrometry (with chemical preparation)	$300–1000
Beta analysis (liquid scintillation)	$50–100
Beta analysis (liquid scintillation with chemical preparation)	$250–750
External gamma exposure survey	$50
External gamma TLD measurement	$20
Gamma spectrometry (*in situ* spectrum)	$100–300
Gamma spectrometry (whole sample analysis at laboratory)	$100–300
Radon measurement (carbon, track etch, electret)	$10–20
Soil sample collection	$100–200
Soil sample processing	$100–400
Thermal ionization mass spectrometry (requires chemical preparation)	$1000

Table 3.4 Estimated Costs for Background Surveys

Background Component	Device/Method	Estimated Cost
External — 50 locations	*In situ* gamma spectrometry	$10,000
	PIC survey	$5,000
	Soil samples and lab analysis	$25,000
	Survey meters	$2,500
	TLDs (quarterly, one year)	$15,000
Inhalation (radon) — 100 locations (50 indoor, 50 outdoor)	Track etch (3 months)	$15,000
Internal (other) — one year	Analysis of food, water, and air (monthly composites)	$100,000

developed that combines radiation survey readings over fairly large areas with selective and intensive sampling and analysis at representative locations within an area, while incorporating the findings of past measurement programs where appropriate. It might be appropriate, for example, to sample land-based locations at 2 or 3 distances for each of the 16 compass points, as well as a few others at far away locations and at special areas of concern.

The selection of measurement and sampling points needs to meet pre-determined criteria designed to ensure that the sample is representative of the site category under investigation. Atypical situations, which themselves may require study, should be avoided in attempting to group like settings. Uniformity over a given area can be checked by scanning with hand-held survey instruments. In certain heterogenous situations, measurements can be performed along a fixed grid to provide an average. For affected areas, it may be necessary to scan entire surfaces a small area at a time.

The measurement of direct radiation or specific radionuclides can be performed with increasing levels of sophistication to detect ever smaller levels of residual radioactivity. As a first attempt, a standard survey meter could be employed to examine external radiation levels. Given the limited precision of such a meter and the variation of background over time and space, it would be possible to identify only gross changes in the radiation field that vary by a factor of two with any degree of certainty. Taking the level one step up, a continuous monitor could be installed at a site to document the variations that occur over time. When correlated with measurements of other phenomena, such as weather, this method increases sensitivity.

Measurements that distinguish the radionuclide by the type and energy of its radiation, or by its chemical behavior are far more discriminating. Here, the ability to positively identify and quantify the radionuclide exists, so that all other interfering or "background" radionuclides present in the sample or at the site can be excluded. This is possible for radionuclides that are unique to the facility and are not found at measurable quantities as part of background. For other radionuclides that are both facility-related and found in background, it is far more difficult to ascribe an increase above the average level as being facility-related, because such an increase may be within the normal variability of background. In this circumstance, a protocol involving many measurements and samples would be needed, and a statistical analysis would have to be applied with a resultant probability estimate and uncertainty. Gilbert and Simpson (1992) present a example of this approach.

The monitoring of environmental media, such as air and water, for contributions from a facility where decommissioning work has ceased could continue for a period of up to a year. After that period, it is likely that most particulate matter would have eroded from most impermeable surfaces and become fixed in the soil or washed into sediments. However, monitoring beyond a year might be indicated if soil excavation work is performed and resuspension is likely, particularly where there is evidence of subsurface soil contamination.

Care is needed in the collection, logging, and subsequent processing of data. Quality control is paramount, and a sound measurement program would include replicate, blank, and reference material analyses, along with frequent instrument performance evaluations, calibrations, and cross checks.

3.2.2 Data Interpretation

With the variability in collected data that is expected in any environmental sampling program, accurate interpretation of the results is essential. For instance, the presence of cesium–137 in soil, and the observation that it is not at the same level from place to place, does not necessarily indicate a local facility contribution. Such variations may have resulted from disturbance to the site through either natural or human action, which led to removal or addition of material containing fallout from atmospheric nuclear weapons tests, as well as differences in the spatial distribution of the original deposition.

Occasionally, data that fall outside the distribution of those collected need to be scrutinized. With further investigation, these data can be thrown out where there is justification, such as instrument malfunction. However, anomalously high or low values must not be dismissed without due cause, since these values frequently form the extreme ends of the distribution of results and may, in fact, be meaningful data. Increased ability to analyze data and ascribe changes to other than natural causes could also be accomplished with measurements performed at many different locations in an area under investigation if these measurements could be linked to other data, such as soil maps.

Databases comprised of measurement results from previous monitoring programs or surveys can be employed, provided that suitable quality assurance can be demonstrated. The performance record of the organization that made the historical measurements, and the inherent accuracy and precision of the methodology that was used, must be evaluated in such circumstances. It is also possible that archived samples, such as air filters, can provide useful information if re-analyzed. While the level of sensitivity may have been adequate during the initial analysis for regulatory purposes at that time, more sensitive techniques could be employed for re-analysis if desired.

3.3 Measurement Confidence Levels

3.3.1 Confidence Levels for Physical Measurements

Every measurement performed on radiation or radioactivity levels will entail some degree of uncertainty. Sources of systematic error in a measurement include the accuracy of the standard used to calibrate an instrument. Instability of electronic components that process the signal may produce an offset in the reading, as well as varying fluctuations from site to site or sample to sample. Inherent in the measurement of radioactive material is a statistical error that arises from the fact that a limited number of decay events are observed during sample counting time. The ability to reproduce a reading on an instrument by examining a sample a second time is limited by the precision of that instrument. In addition, measurements made at very low levels of radioactivity vary widely when the sensitivity limits of an instrument are approached. The total of these errors for typical measurements leads to an uncertainty that ranges from as small as 1 percent to more than 100 percent. Frequently, when errors become that large, a lower limit of detection is reported, indicated by the "<" (less than) sign.

Of particular relevance in radiation measurement is the ability of the instrument to respond equally to radiation of different energies. This "energy response" is never truly constant, and any given instrument can read somewhat different from the true dose rate, depending upon the makeup of the energy spectrum at a site and the energy spectrum of the radionuclide source that was used to calibrate the instrument. Another problem is that different types of radiation can contribute to the instrument reading (such as gamma, beta, and cosmic rays), and each may have its own calibration factor. As such, the makeup of the radiation field at a site may have to be determined to properly interpret instrument readings. With these complications, it is possible that readings from different instruments may not perfectly agree at the same site.

Given the uncertainties associated with various measurements, allowances must be made for disagreement. Generally, two measured values are said to agree if they are within the estimated uncertainty.

3.3.2 Confidence Levels In Data From Temporal Extrapolation

Data collected over a limited period may not provide a true average of radiation and radioactivity levels. Extrapolation of a measurement to longer time intervals involves uncertainties. These may only be a few percent in some cases, but a factor of two or more in others. If an external radiation reading is taken at a soil-covered outdoor site and periods of rain and snow cover are avoided, one could expect to be within 10 to 20 percent of the annual average, given the typical degree of temporal variation. In very dry climates, where there is little soil moisture variation, this might be reduced to between 5 and 10 percent. Barring any unusual physical disturbance to the site, extrapolation of an annual average to periods of a few decades would likely have an uncertainty of between 5 and 10 percent.

The changes in radiation levels will be reflected in changes in the soil concentrations of the radionuclides. *In situ* measurements will therefore show concentration changes that result from soil moisture variations. Samples that are collected and then processed and analyzed in the laboratory allow concentrations to be reported on a dry basis.

Variability in collected data can be explained by referencing other data, such as weather and geological data. At the same time, it must be understood that these other data have their own sources of uncertainty. In addition, these supplemental data can sometimes lack the spatial or temporal detail needed to correlate with radiation and radioactivity data collected in a survey.

3.3.3 Confidence Levels In Data From Spatial Extrapolation

A significant source of uncertainty in deciphering changes in radiation levels and radionuclide concentrations is likely to arise from their spatial variability in the environment (see Section 2.3.3 of this document). In the case of natural radionuclides, local geological features and patterns of soil type result in gradients in their concentrations. Micrometeorological effects and erosion that produces runoff and accumulation cause man-made radionuclide concentrations to exhibit potentially significant variations. In both cases, human activities, such as soil excavation, must be considered. Thus, measurements within the same region, and even those only meters apart, must be carefully interpreted. Differences of more than 100 percent would not be unusual in certain situations.

Perhaps most significant in spatial extrapolation of radionuclide data is the site selection process. For example, it would be inappropriate to compare uranium concentrations in soils collected from two sites of different geology, such as a sandy beach area and an inland region with heavy clay soil. In the case of the fallout radionuclide cesium-137, concentrations in surface soils could only be extrapolated to other local plots of land that have received the same deposition (rainfall) and have the same history (for example, plowed agricultural land, forest, or undisturbed lawn).

3.4 Methods for Assessing Background Doses From Doses Attributable to a Nuclear Facility

3.4.1 External Exposure

The simplest and most direct method for determining external exposure is to measure the total radiation level at a site. In order to distinguish background from a nuclear facility component, one could compare this reading to others made at sites throughout the area. As discussed previously, given the wide spatial variability of background, this method would only highlight a large facility-related radiation component, such as a radiation level that doubles the background reading. If information on the background level is available for the given site for years prior to the facility construction, one could compare the present day reading and perhaps decipher an increase of 50 percent with a reasonable degree of certainty. With knowledge of soil moisture conditions and the cosmic ray component, perhaps a 25 percent increase could reasonably be ascertained.

A significant increase in sensitivity could be obtained by collecting a gamma-ray spectrum. Depending upon the radionuclides involved, a facility-related component that would lead to an external dose of just a few percent of that from background could be determined. In certain cases, performing radiochemical and/or mass isotopic analysis would allow the detection of trace quantities of radionuclides that contribute a fraction of a percent to the dose.

Potential methodologies for distinguishing radiation doses attributable to a decommissioned nuclear facility from those associated with background are given in Table 3.5. The hypothetical radionuclide considered in Table 3.5 is cobalt–60, which is a strong gamma-emitting man-made isotope that arises from neutron activation of stable cobalt–59. Cobalt–60 is not found in measurable concentrations in normal environments; thus the analysis assumes that the contamination is uniformly mixed in the surface soil layer, and that the dose to the body results principally from external gamma radiation.

For this particular radionuclide, the lowest dose increment in Table 3.5, 0.0003 mSv (0.3 μSv or 0.03 mrem), is measurable in principle. This is only one hundredth of one percent of the total effective dose equivalent from average background. Both the instrumentation and methods that are applied at these levels could vary depending on such factors as the particular radionuclides and their distribution in the environment. Detector sizes and sensitivities also affect the length of counting time that would be required. In the case of a mixture of radionuclides, each of which makes some contribution to external exposure, the ability to measure a given total increment is proportionately reduced.

Given the estimated costs for various types of measurements, Figure 3.1 presents a rough correlation between the measurement cost and the measured dose increment for cobalt–60. The relationship indicates that smaller doses are measurable with increasing costs as more sophisticated techniques are employed. A large cost jump occurs when the limit is reached for the sensitivity of measurements that can be made onsite. To reach lower dose increment levels, samples must then be taken for laboratory-based analysis. Once the work is done to collect and prepare a sample, the cost for analysis can continue to rise if longer counting times are needed to attain a certain level of precision in the measurement. For some radionuclides, the limits of detection of standard laboratory instruments can be reached, in which case, the cost to measure lower levels would rise astronomically as highly specialized research techniques are employed.

Table 3.5 Methodology for Assessing Facility-Related External Radiation Dose Component

Level (mSv)	Instrument/Technique	Methods (comments)
1.00	Survey meter	Quick spot measurements
0.60	Survey meter	Quick spot measurements
0.30	Survey meter	Quick spot measurements
0.10	Survey meter with PIC	Careful readings averaged at each location; use of knowledge of background variability for land and construction type
0.03	PIC with *in situ* spectrometry	10-minute measurements at each location
0.01	PIC with *in situ* spectrometry	10-minute measurements at each location
0.003	PIC with *in situ* spectrometry	60-minute measurements at each location
0.001	Above plus lab sample analysis	Gamma spectrometry on samples (500-minute counts)
0.0003	Above plus lab sample analysis	Gamma spectrometry on samples (5,000-minute counts)

In the case of cobalt-60 and many other radionuclides, the protocol for assessing compliance with clean-up criteria would involve comparing the measurements that are made onsite to a background that is essentially zero, or one that is below the detection limit of the instrumentation. A confounding factor for verifying that clean-up criteria have been met involves radionuclides associated with facility operations that are the same as those already present in the environment, whether natural or man-made. In this case, the distribution of onsite measurement values would be compared to those offsite (that is, in some background reference area or region that represents background with no contamination from the facility). The selection of this background reference area and the measurement sites within it would have to meet strict criteria, in order to avoid introducing biases in the comparison.

To further avoid biases, the very same measurement techniques and instrumentation would be used both onsite and offsite.

The comparison for a particular radionuclide would take into account some threshold value above which it would be deemed to be unacceptable and would require remediation. For measurement values that are close to background, the distribution of values onsite would be tested against those in the background area using statistical techniques such as a "t test," if it could be verified that data are distributed normally or are in a form (such as log-normal) that could be transformed to a normal distribution. More likely, the data will not fit a standard distribution, in which case it would be best

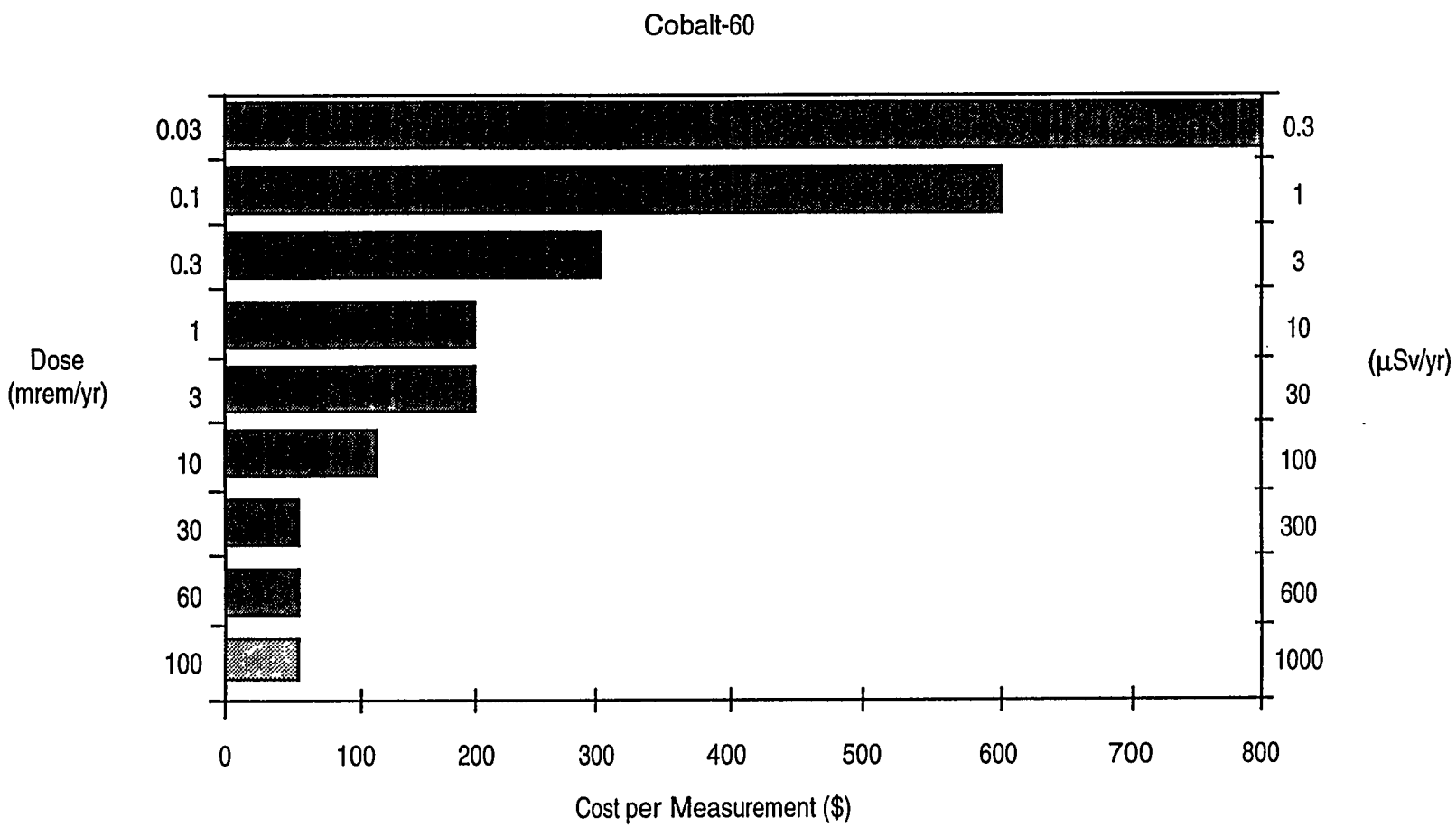


Figure 3.1 Estimated approximate cost for a single measurement of cobalt-60 in soil as a function of the dose increment above background

to apply a non-parametric statistical test, such as the Wilcoxon Rank Sum (Mann-Whitney) test (Gilbert and Simpson, 1992). This type of test will allow the inclusion of "less than" values that may arise in the site assessment program. In performing such a test, a null hypothesis (the area tested has achieved clean-up criteria) and an alternative hypothesis (the area tested has not achieved clean-up criteria) are stated. Certain "error rates" must then be set. For instance, a Type I error of $\alpha = .05$ would mean that there would be a 5 percent chance that the tested area would be incorrectly labelled as being above background. A Type II error rate of $\beta = .05$ would mean that there was a 5 percent chance that the tested area would be incorrectly labelled as being at background. In addition, the greater than one inpower of the test is affected by the number of measurements made and a probability, P (greater than 0.5 and less than 1.0), must be specified that a random measurement value in the tested area is greater than one in the background area. This probability relates to the amount of "shift" one is willing to accept in the measurement distribution of the tested area above that of the background area.

If small values of α and β (such as 0.01) and a value of P close to 0.5 (such as 0.55) are specified, thousands of measurements will be required for each test. More realistically, values of 0.05 can be accepted for α and β, and a value of perhaps 0.75 for P. In terms of shift, these values of P would correspond to about one standard deviation for normally distributed data. Furthermore, the site can be divided into a number of subsections, each of which is tested against the background reference area. Based on the methodology discussed in Gilbert and Simpson (1992), a site that was divided into 50 subsections would then require about 120 measurements in the background area and about 15 in each of the subsections for a total of 750 onsite measurements. With less stringent criteria (that is higher values of α, β, and P), fewer measurements are required. Different background reference areas may have to be chosen for different radionuclides if their distributions in the region are not correlated.

Depending upon the distribution of the measurements in both the background reference area and the onsite area, another non-parametric statistical test, the Quantile Test, can be performed (Gilbert and Simpson, 1992). This may require adjustment in the selection of the values of α and β, and may change the number of measurements required, but it would add to the sensitivity in determining whether tested areas have been reduced to background. In summary, the number of measurements required depends upon the nature of the facility, its size, and the probabilities one is willing to accept that clean-up standards have been achieved. Of course, the potential dose increment above background would depend upon the degree of variability in the background values of the radionuclide being investigated.

Figure 3.2 gives the cost estimates for determining an increase in dose from cesium-137. These costs estimates are based on the same methodology given in Table 3.5 to determine cobalt-60 cost estimates. However, for cesium-137, the doses correspond to different radionuclide concentrations in soil than for cobalt-60. As a result, different measurement techniques must be applied to account for the differences in dose rates between cobalt-60 and cesium-137. Whereas the ability to measure cobalt-60 is ultimately limited by the detector sensitivity and the contribution of other gamma emitting radionuclides to instrument background, a limit in the measurement of cesium-137 is reached because a small increase above levels already present in the environment would not be detectable, based on the methodology discussed above. Given typical fallout levels and the degree of variability that could be expected in a local area, dose increments of 0.001 mSv (1 μSv or 0.1 mrem) per year or less would be indeterminate.

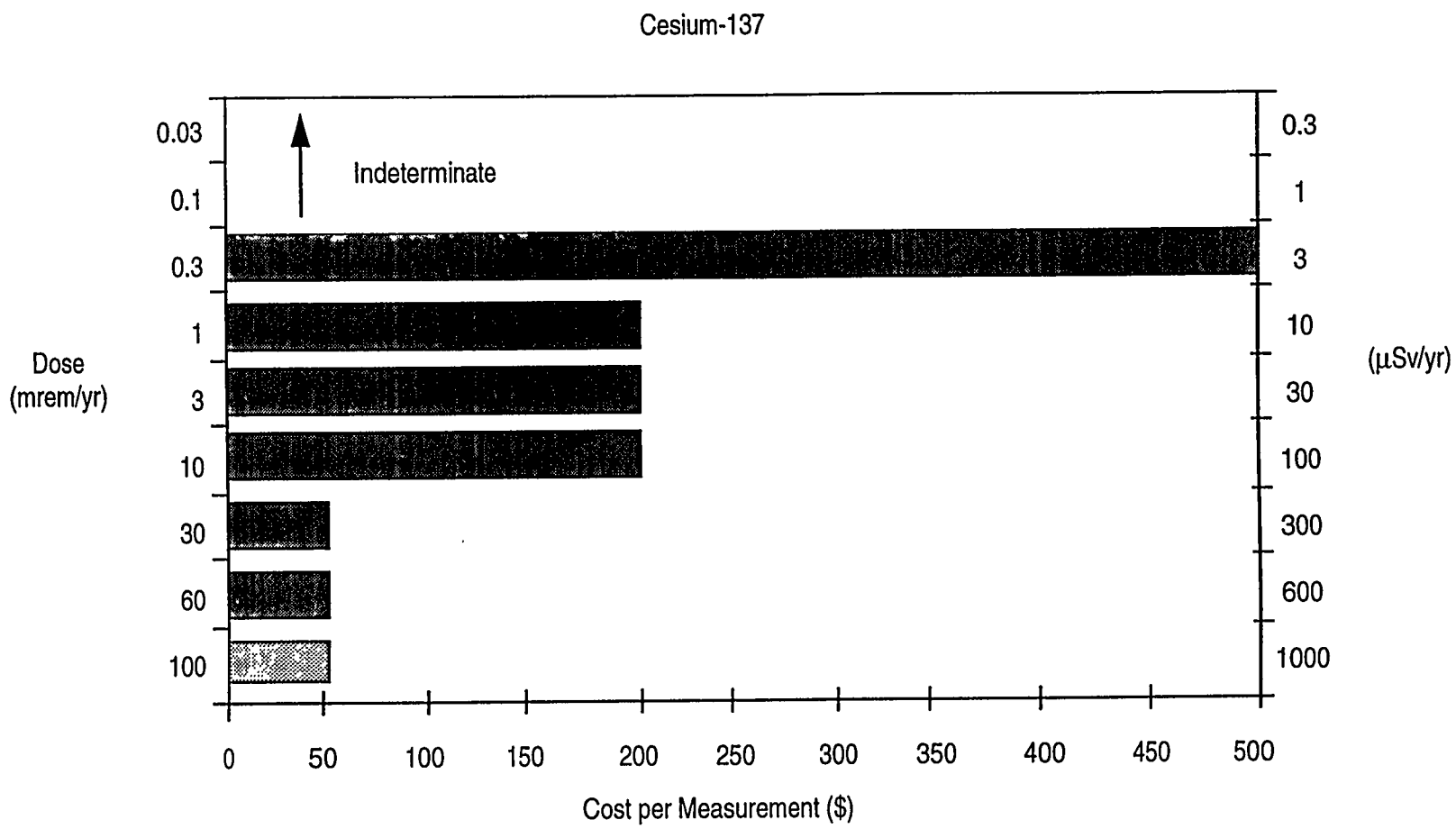


Figure 3.2 Estimated approximate cost for a single measurement of cesium-137 in soil as a function of the dose increment above background

Figure 3.3 presents cost estimates for the measurement of strontium-90. Here, survey techniques can not generally be used since this nuclide is a pure beta emitter and the dose arises mainly from an internal contribution to the body. Samples must then be collected and processed in the laboratory. This leads to an essentially constant cost. As with cesium-137, strontium-90 is a weapons test fallout product that can be found in soils, and a similar limitation is reached in the ability to detect an increment above what is already present in the environment.

Figures 3.4 and 3.5 show cost estimates for thorium-232 and natural uranium. It is assumed that all of the decay products of thorium-232 are present in equilibrium. Since some of these are gamma emitters, survey techniques can be used effectively; however, a limitation is reached at doses corresponding to thorium-232 concentrations near those typically found in soil. Given the degree of variability that might be expected in soils in a local area, a 10-percent increase would generally not be detectable. Natural uranium exhibits similar characteristics and limitations, with the exception that gamma emissions are relatively low, and a given dose increment corresponds to a higher concentration of uranium in the soil.

The ability to distinguish a facility-related dose increment varies according to the overall background level from all sources in the local area, the average concentration of the particular radionuclide under study, and the variability in concentration about that average. The higher the background level and the wider the range in concentrations of a background reference area, the higher the dose at which a facility component can be determined with a given level of confidence. Areas with a high degree of variability may require more sampling and a careful selection of background reference locations to compare with facility sites.

3.4.2 Internal Exposure

Internal exposure from inhalation and ingestion can be assessed by sampling various media, such as soil, water, and air, for specific facility-related radionuclides, and then applying the appropriate conversion factor to internal dose based on models of intake and retention in humans. In the measurement cost analysis presented above, a pathway analysis was used to compute the dose per unit concentration of a radionuclide based on a residential scenario (that is, a scenario in which people live on a decommissioned site).

Of particular relevance to site decommissioning is the drinking water pathway. This pathway may be significant for certain radionuclides that are soluble and can penetrate to groundwater that is ultimately consumed by the local populace. However, the same radionuclides may not be of consequence if they can are bound in soil, therefore incapable of entering groundwater. As in the case of external radiation, the ability to identify particular radionuclides substantially improves the sensitivity of the measurement, such as the application of spectrometry when analyzing environmental samples. Experimentally, it is also possible to directly measure the radionuclide content of a *person* by using a shielded vault and radiation detectors placed over the body. Using 10-minute counts, a radionuclide such as cobalt-60 could be detected at levels in the body that could give a committed dose on the order of 0.005 mSv (5 μSv or 0.5 mrem). Particular organs (such as lungs) can be measured for radionuclides (such as plutonium) when there is a known critical pathway and source in the environment.

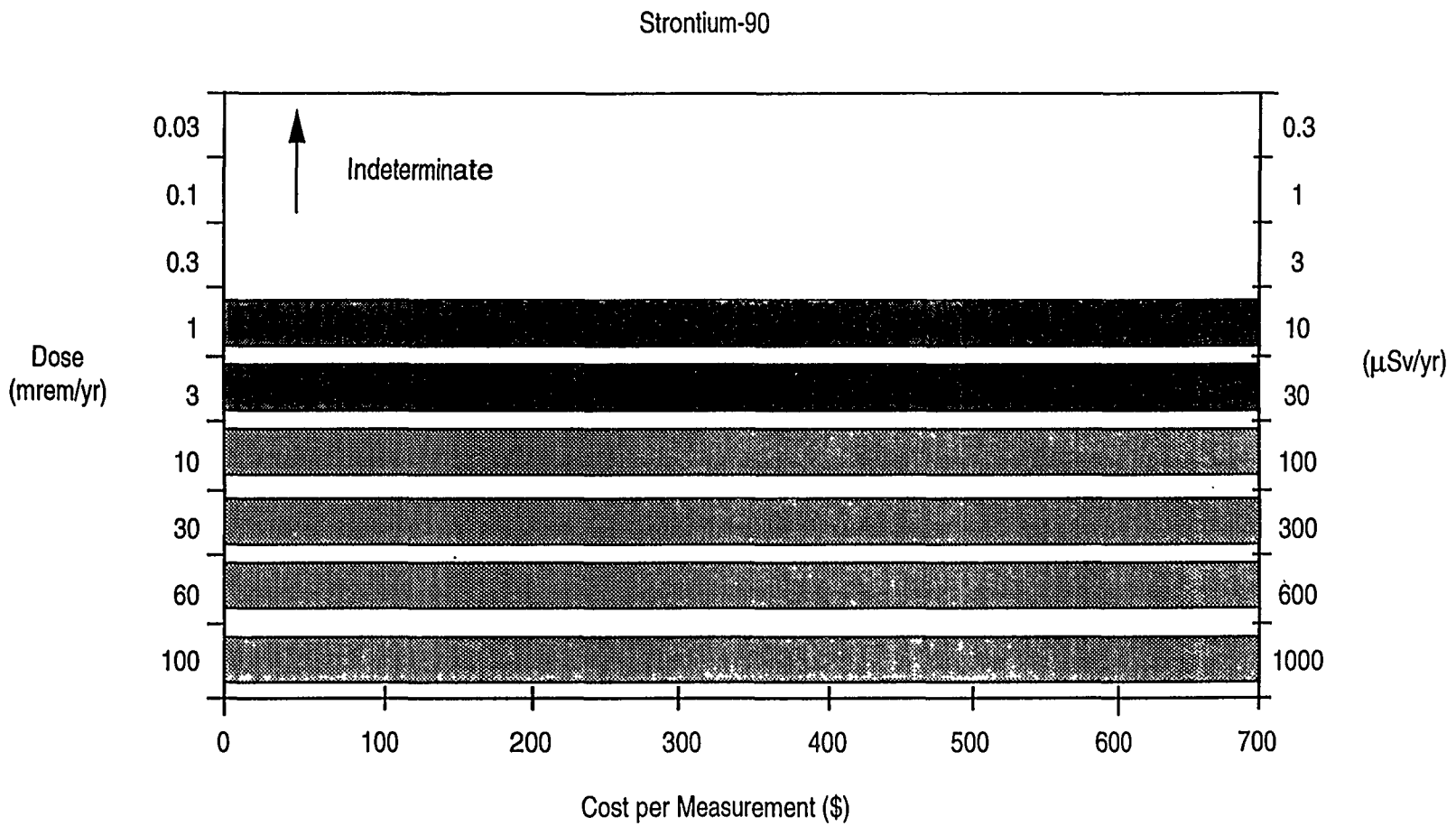


Figure 3.3 Estimated approximate cost for a single measurement of strontium-90 in soil as a function of the dose increment above background

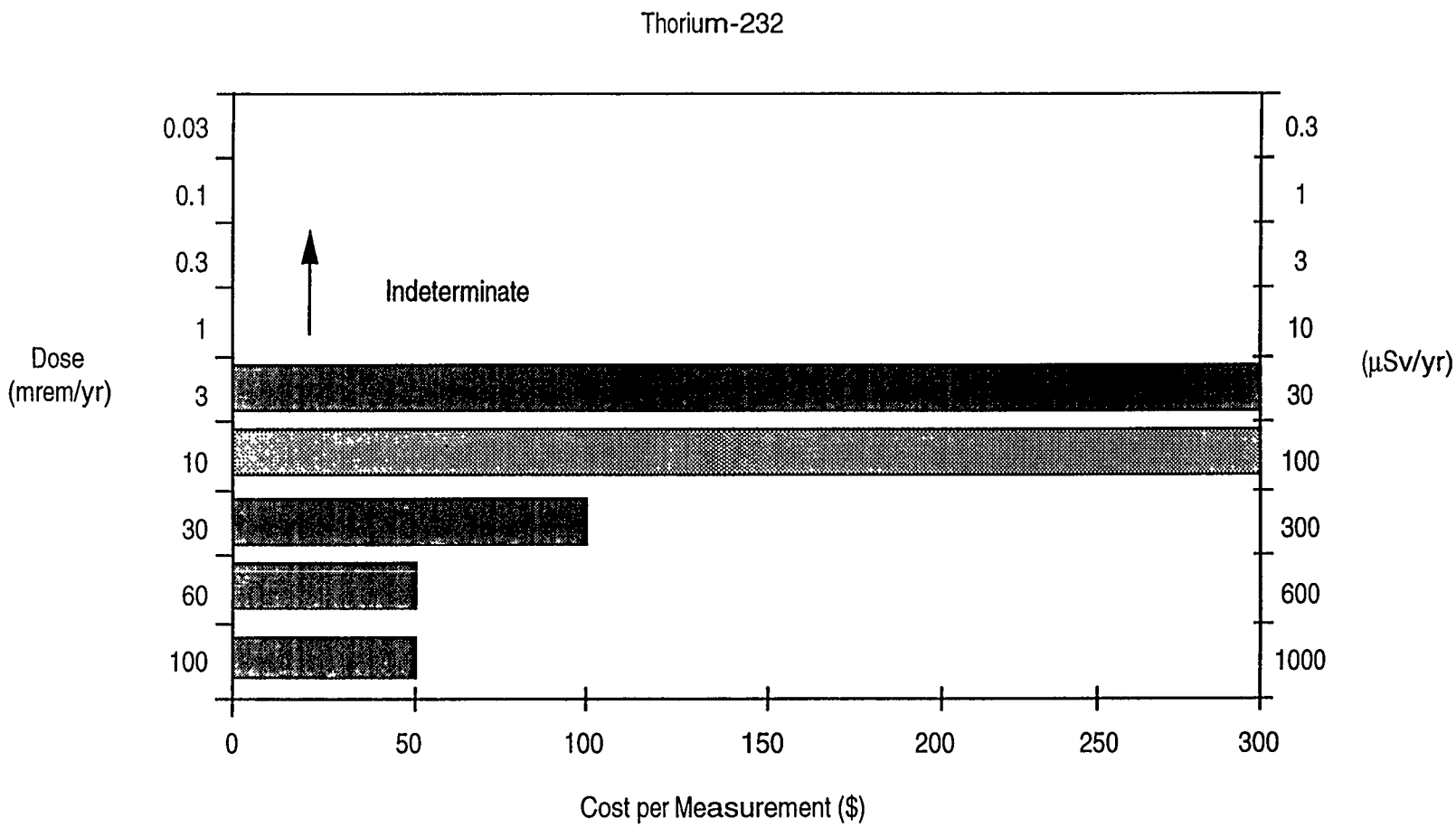


Figure 3.4 Estimated approximate cost for a single measurement of thorium-232 (and progeny) in soil as a function of the dose increment above background radiation

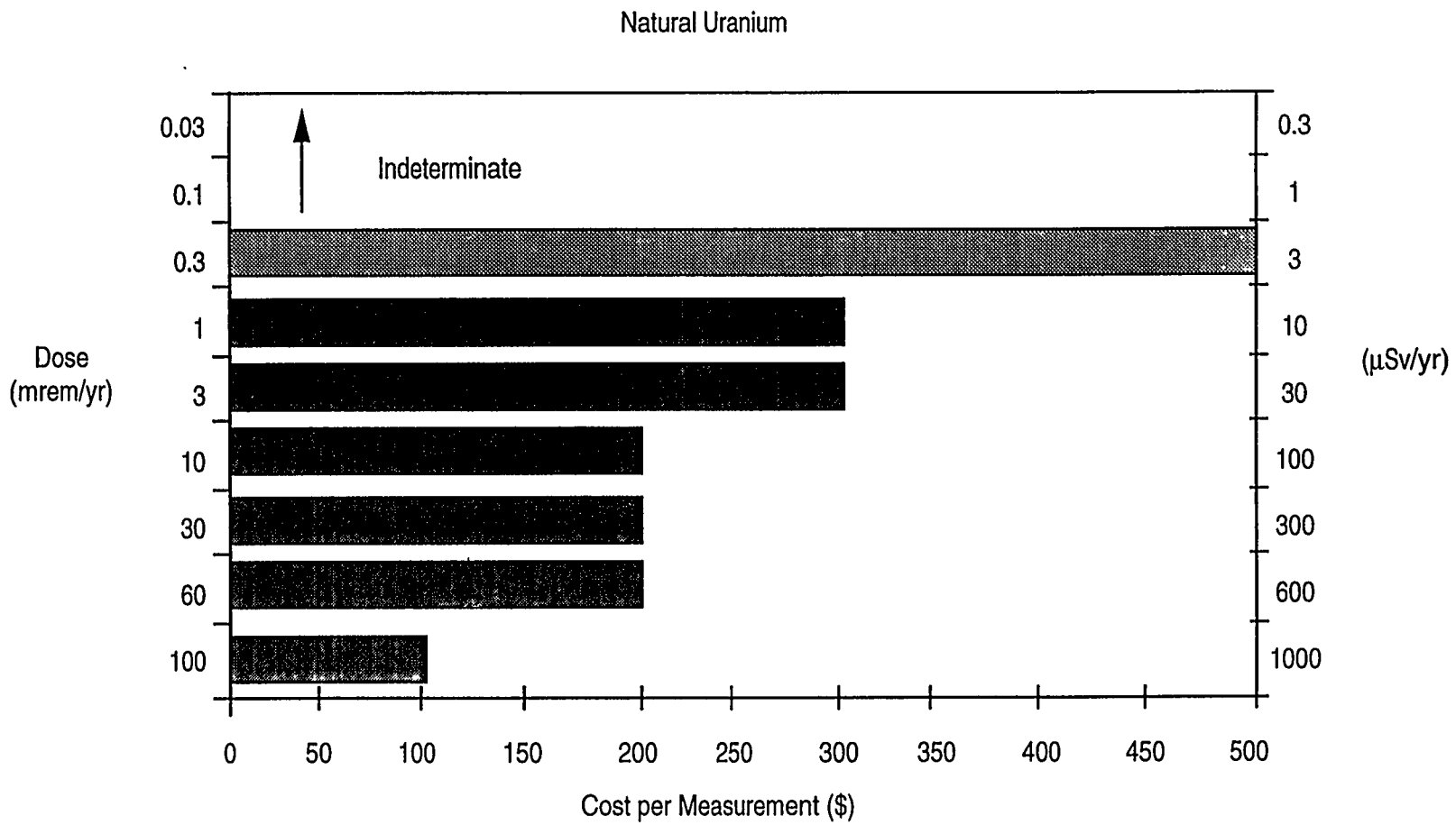


Figure 3.5 Estimated approximate cost for a single measurement of natural uranium in soil as a function of the dose increment above background

The sensitivity of a measurement for a radionuclide in air is essentially related to the flow rate and length of time that an air sampler is run. Collection of monthly samples using a pump with a flow rate of 1 cubic meter per minute, and subsequent analysis using radiochemical preparation and alpha spectrometry, allows the detection of environmental plutonium down to concentrations corresponding to committed doses on the order of 0.001 mSv (1 μSv or 0.1 mrem). A gamma-emitting radionuclide (such as cesium–137) that could deliver a committed dose of the same magnitude could, in turn, be measured in only a few hours using gamma spectrometry, given the same flow rate during collection of the air sample.

It is problematic to distinguish between facility–related radiation and radionuclides already present in the environment when they are both normally found in humans. In addition, it must be recognized that, in many cases, radionuclide content builds up over a long period of time. During any finite sampling period, the measurement of inhalation and diet does not necessarily correlate with the current body burden, which better reflects the cumulative intake over the person's lifetime.

3.5 Complete Survey Measurement Costs for Specific Radionuclide Concentrations

Rough estimates of complete survey measurement costs for specific radionuclide concentrations can be calculated by applying data requirements from the hypothetical case described in Section 3.4.1 of this document. These cost estimates are based on the decommissioned facility requiring a total of 870 measurements to test for compliance with a particular clean–up criteria for a specific radionuclide. Data provided in Figures 3.1 through 3.5 can be applied to estimate sample measurement costs. However, it must be noted that savings over a single measurement are achieved when multiple measurements are conducted adjacent to each other, because setup time can be substantially reduced. For example, the survey cost is reduced when certain tasks are repetitive (such as instrument readings and soil sampling). Table 3.6 summarizes the hypothetical soil concentration limits for five relevant radionuclides at two clean–up levels, and Table 3.6 lists the limiting hypothetical exposure scenario and pathway for each.

Table 3.6 Hypothetical Clean–up Criteria for Five Radionuclides

		Soil Concentration (Bq per kg)	
Radionuclide	**Scenario (Pathway)**	**0.15 mSv/yr**	**0.03 mSv/yr**
Cobalt-60	Residential (external)	111	22
Cesium-137	Residential (external)	396	78
Natural Uranium	Residential (drinking)	714	143
Strontium-90	Drinking water (ingestion)	296	59
Thorium-232	Residential (ingestion)	32	6

The general measurement techniques employed include direct dose-rate measurements with PICs, *in situ* gamma-ray spectrometry, and soil sampling with subsequent laboratory processing and analysis. These techniques can be used individually or in combination. When possible, direct measurements in

the field are preferred to speed up and reduce the cost of the survey; however, some soil sampling is still required to ascertain the radionuclide distribution with depth and to provide a quality assurance component to the field measurements in the survey. For each area measured, a composite soil sample would be taken that consists of several cores of soil totaling about 200 cm^2 in area and sectioned in at least two different depth increments (0 to 5 cm and 5 to 30 cm, for example). Additional quality control would be provided by an independent measurement of total dose rate in air with a PIC. This could be compared to the sum of the individual radionuclide contributions to the dose, with the cosmic ray component estimated from altitude or barometric pressure added in. Also, a statistical analysis of the data may be required when the radionuclide concentrations listed as clean-up criteria approach those already present in the environment.

For purposes of consistency, the spectrometer or PIC can be positioned at grid points corresponding to those where a soil sample would normally be taken. Following guidelines established by the EPA, a triangular spacing with points 5 meters apart can be used (Gilbert and Simpson, 1992). With the detector at a height of 1 meter above the ground, approximately 80 percent of the gamma radiation from nuclides that are homogeneously distributed with depth in the soil originates from within a circle with a radius of 5 meters. This grid spacing thus provides some degree of overlap. For examining areas with larger dimensions or where lower spatial resolution is desired, spectrometer or PIC measurements can be spaced at 10 meters or more. Also, the amount of ground area viewed by the spectrometer can be adjusted by positioning the detector at different heights above the ground. For purposes of this analysis, only affected areas in open land are considered. Measurements with much greater spatial separation would be appropriate in unaffected areas, and other techniques would be employed for measurements in buildings, water covered areas, and sites where there is buried contamination.

3.5.1 Specific Measurement Methods

3.5.1.1 Cobalt-60.

For the 0.15 mSv (15 mrem) annual dose value (corresponding to 111 Bq per kg of soil), the gamma dose rate in the field would be high enough to produce a measurable change above background. As such, it would be possible to perform 750 measurements onsite and 120 in a background reference area using a PIC to measure total dose. The statistical comparison would then be required where the distribution of onsite measurements, minus the dose rate corresponding to that concentration of cobalt-60, would be tested against the distribution in the background reference area.

For measurements at the 0.03 mSv (3 mrem) annual dose value (22 Bq per kg), however, the total dose rate approach would not be sensitive enough, and the combination of *in situ* spectrometry and selective soil sampling would be required. However, except in an unusual situation, it could be assumed that the concentration of cobalt-60 would be essentially zero for background areas, so no comparison to a background reference area would be made. Thus, the concentration value of 22 Bq per kg listed in Table 3.6 becomes an absolute standard.

3.5.1.2 Cesium-137

The same approach can be used for cesium-137 as for cobalt-60, because it too is a gamma emitter for which the dose to humans is dominated by the external pathway. At the 0.15 mSv (15 mrem) annual dose value (396 Bq per kg), the total dose (as measured by a PIC) can be compared to background reference areas.

Although cesium-137 is normally found in the environment as a result of weapons test fallout, the concentration in most areas averaged over a soil depth down to 15 cm will be several times less than that of the criteria at the 0.03 mSv (3 mrem) annual dose level (78 Bq per kg). However, it is important to consider that some surface samples (0 to 5 cm, for example) in undisturbed areas where the fallout cesium-137 has not penetrated far into the ground could have concentrations on the same order as the clean-up criteria. Since an *in situ* spectral measurement is influenced mostly by the concentration in the surface layers, the depth profile becomes especially important to avoid misinterpretation of results. Despite these complications, it is estimated that the combination of *in situ* spectrometry and selective soil sampling would be the method of choice. As in the case of cobalt-60 at the 0.03 mSv (3 mrem) annual dose level, the associated concentration of cesium-137, 78 Bq per kg, becomes an absolute standard.

3.5.1.3 Thorium-232

Survey measurements at both the 0.03 mSv (3 mrem) annual dose level (6 Bq per kg) and 0.15 mSv (15 mrem) annual dose level (32 Bq per kg) would require spectrometric techniques, as in the previous cases for this dose level. A concentration of 32 Bq per kg of thorium-232 (in secular equilibrium with its daughters) in soil is on the same order as that which can be found for background, so that background reference area measurements would be required along with the statistical testing of onsite versus offsite distributions. However, survey measurements at the 0.03 mSv (3 mrem) annual dose level (6 Bq per kg) would require longer counting times to attain increased measurement sensitivity.

3.5.1.4 Strontium-90

Strontium-90 measurements require a strict soil sample approach because there is no effective survey instrument for concentrations at these levels in soil (296 Bq per kg at 0.15 mSv (15 mrem) per year,and 59 Bq per kg at 0.03 mSv (3 mrem) per year). Unless there is an unusual background situation, however, these concentrations for a soil depth of 0 to 15 cm are sufficiently above those normally encountered from weapons test fallout. As in the case of cesium-137, the concentration values become an absolute standard to measure against.

3.5.1.5 Natural Uranium

Soil concentrations for the 0.15 mSv (15 mrem) annual dose level (714 Bq per kg) can be measured with *in situ* spectrometry by analyzing the gamma emissions of the short-lived immediate decay products of uranium-238 as well as the direct gamma emissions associated with uranium-235. This concentration is sufficiently above background in most situations to be used as an absolute standard. As in all cases involved with *in situ* spectrometry, selective soil sampling is also required.

At the 0.03 mSv (3 mrem) annual dose level (143 Bq per kg), the same technique can be used with the exception that longer counting times are required in the field to attain the proper counting statistics, because the gamma emissions associated with natural uranium (radium-226 and decay products not present) are relatively weak compared to those of cobalt-60, cesium-137, and the thorium-232 decay products. As an alternative to long gamma spectrometric counts in the field, it would be possible to use a purely soil sampling approach as in the case of strontium-90. Although sample collection and processing would remain the same, the analytic techniques employed for natural uranium determination would cost less that those for strontium-90. With either field or lab-based measurements, background reference area values are needed to perform statistical testing since a concentration of 143 Bq per kg approaches that found for background in certain areas of the United States.

3.5.2 Estimated Costs

Table 3.7 presents the cost estimates for the five radionuclides under consideration in the above methodologies. In addition to the basic measurement costs, quality control measurements in the form of blank, duplicate, and reference material analysis would add an additional 10 percent to the number of measurements required, and an estimated additional 10 percent would be required to repeat measurements judged to be of questionable reliability. The complete survey program would of course involve other costs, such as laying out gridpoints, prescreening, management oversight, among others. The cost for a particular facility would also have to be scaled according to its size and, in particular, the number and extent of affected areas.

Table 3.7 Estimated Survey Costs for Five Radionuclides

	Annual Dose Rate	
Radionuclide	**0.15 mSv/yr**	**0.03 mSv/yr**
Cobalt-60	$50,000	$90,000
Cesium-137	$50,000	$90,000
Natural Uranium	$100,000	$220,000
Strontium-90	$300,000	$300,000
Thorium-232	$140,000	$220,000

4 STATUS OF BACKGROUND IN CURRENT REGULATORY PRACTICE

4.1 Introduction

Existing clean-up criteria for nuclear facilities are a patchwork of applicable regulations, guidance, and practices that have been developed since the beginning of the atomic energy program by the U.S. Atomic Energy Commission (AEC) and, more recently, by the NRC, the EPA, and other Federal regulatory agencies. The scope of this section is limited to existing NRC and EPA clean-up criteria to illustrate how background is currently applied in clean-up criteria that are germane to the majority of NRC-licensed decommissioning cases. Other Federal agencies and State and local governments may have established their own clean-up criteria that account for background differently than those discussed in this section.

NRC's requirements for decommissioning and termination of licenses are contained in 10 CFR 30.36, 40.42, 50.82, 70.38, and 72.54. However, these regulations do not explicitly state which radiological criteria to apply to demonstrate that a site has been adequately remediated. The Commission's current positions on residual contamination criteria, site characterization, and other related decommissioning issues are outlined in an NRC document entitled "Action Plan to Ensure Timely Clean-up of Site Decommissioning Management Plan Sites," which was published in the Federal Register on April 6, 1993 (57 FR 13389). Pending the establishment of generic decommissioning criteria through rulemaking, NRC continues to consider existing guidance, criteria, and practices listed in the April 1993 Action Plan. The criteria listed in the Action Plan were developed independently in the past for specific decommissioning applications. For example, NRC staff provided site-specific clean-up criteria for release of the Safety Light Corporation site in Bloomsburg, Pennsylvania, where soil and groundwater showed evidence of radioactive contamination (57 FR 6136; February 20, 1992).

Historically, clean-up criteria have been applied on a site-specific basis with a common emphasis on attaining residual contamination levels that are "as low as is reasonably achievable" (ALARA). However, the contribution of background has not been accounted for uniformly among existing decommissioning criteria — some include background to establish an absolute standard that accounts for the total radioactivity present, whereas other clean-up criteria exclude background, thus establishing an incremental standard that addresses only the radioactivity in the contaminant under investigation. The clean-up criteria discussed in the following sections include those contained in the April 1993 Action Plan. It is apparent that the manner in which background is implicitly or explicitly accounted for in these criteria appears to be a function of the intended purpose of each individual criterion and the practicality of its measurement when conducting radiological surveys.

4.2 NRC and EPA Criteria and Standards Relating to Release of Sites and Buildings

4.2.1 Regulatory Guide 1.86 and Policy and Guidance Directive FC 83-23

Two documents, "Termination of Operating Licenses for Nuclear Reactors," Regulatory Guide 1.86 (June 1974), and "Termination of Byproduct, Source, and Special Nuclear Materials Licenses," Policy and Guidance Directive FC 83-23 (November 1983), contain surface contamination limits for unrestricted use at reactors and materials facilities by listing radionuclides in groups that are roughly based on their relative radiotoxicity. Both documents provide surface contamination limits in terms of disintegrations per minute per 100 square centimeters, but Policy and Guidance Directive FC 83-23 provides additional surface contamination levels in terms of average and maximum radiation levels for beta-gamma emitters.

Background is *not* included in these limits because the maximum acceptable contamination refers to the rate of emission by the residual radioactivity alone. In practice, radiological surveys to determine compliance with these limits account for the contribution of background by correcting the counts per minute observed by the survey instrument for background and other factors, such as detector efficiency and source-to-detector geometry.

4.2.2 NRC Office of Nuclear Reactor Regulation Letter to Stanford University, NRC Docket No. 50-401 (April 1982)

Enclosure 1 to this letter provides NRC guidance on acceptable levels of cobalt-60, cesium-137, and europium-152 that may exist in concrete, components, and structures for release for unrestricted use. This guidance recommends that residual radiological contamination be removed such that the indoor exposure rate at 1 meter from surfaces is less than or equivalent to 5 μR per hour (in terms of exposure in air)[1] *above* background, with an overall dose objective of 0.1 mSv (10 mrem) per year.

In this document, the term background means radiation from naturally occurring radionuclides, as measured at a comparable uncontaminated structure or exterior soil surface. Therefore, it is necessary to first survey uncontaminated buildings or outdoor locations at a decommissioning site to determine background exposure rates, and then subtract the contribution of background from exposure rate measurements made in contaminated areas.

4.2.3 NRC Waste Disposal Regulations

NRC regulations allow licensees to dispose of radioactive wastes on their own property and at locations other than licensed commercial disposal facilities. The methods for obtaining approval of proposed disposal procedures are contained in 10 CFR 20.2002 (formerly 10 CFR 20.302), which requires NRC authorization based on an evaluation of the proposed burial. Applications submitted under 10 CFR 20.2002 must include a description of the waste, the manner and conditions of waste

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[1] **Conversion of Exposure to dose made by using 1R = 0.0087 Gy. For environmental radiation, conversion of absorbed dose in air to effective dose in the human body is 1 Gy = 0.7 Sv. Thus, 5 μR per hour in air is equivalent to 0.044 μGy per hour in air or 0.03 μSv per hour in the human body.**

disposal, an analysis and evaluation of environmental information, information on other potentially affected licensed and unlicensed facilities, and procedures and analyses to ensure that doses are maintained ALARA and within the dose limits of 10 CFR Part 20.

Existing NRC guidance for academic, medical, and industrial licensees seeking authorization to dispose of radioactive material by onsite subsurface disposal is provided in three volumes of NUREG-1101, "Onsite Disposal of Radioactive Waste." This document provides guidance on the contents of applications for disposal under 10 CFR 20.2002, such as limiting conditions for total radioactivity, frequency of burials, and waste package requirements, which are based on a maximum annual whole body or critical organ dose of 0.25 mSv (25 mrem). NUREG-1101 also contains methods for performing radiological assessments of the disposals and an approach for estimating potential groundwater contamination.

Radioactivity limits for onsite disposal that are contained in NUREG-1101 do *not* include background. Additional NRC guidance for evaluating licensee applications for onsite disposal or storage of radioactive material is contained in the 1981 Branch Technical Position (BTP) 46 FR 52601, "Disposal or Storage of Thorium or Uranium Wastes From Past Operations" (see Section 4.2.4 below).

4.2.4 "Disposal or Onsite Storage of Thorium or Uranium Wastes from Past Operations," NRC Branch Technical Position, 46 FR 52601 (October 1981)

The "1981 BTP" discusses five options for NRC approval of disposal or onsite storage of thorium or uranium contaminated wastes. Currently, the NRC staff considers Disposal Options 1 and 2 acceptable for release for unrestricted use, whereas disposals under Options 3 and 4 are considered unacceptable for unrestricted use because of required land deed restrictions. Option 5 is for storage of more concentrated uranium and thorium wastes.

Option 1 uranium and thorium concentration limits are based on EPA recommendations contained in "Persons Exposed to Transuranium Elements in the Environment" (November 1977) and "Proposed Disposal Standards for Inactive Uranium Processing Sites" (January 1981). Under Option 2, uranium and thorium wastes are buried under prescribed conditions and are limited in concentration so that an individual would not receive a radiation dose exceeding that discussed under Option 1, as long as intrusion into the burial ground did not occur.

For uranium contamination in soils, inhalation and ingestion of contaminated soils produce the greatest radiological dose; for natural thorium contamination in soils, external exposure to gamma radiation is of primary concern. Under Option 1, radionuclide concentrations are set so that external exposures from thorium contamination do not exceed 0.06 μSv per hour or 10 μR per hour (in terms of exposure in air)[2] *above* background. For depleted and enriched uranium contamination, Option 1 concentration limits are based on limiting bone doses to 0.6 mSv (60 mrem) and lung doses to 0.2 mSv (20 mrem); however, for natural uranium, concentration limits are based on a lung dose equivalent to exposure from radon daughters from 0.19 Bq (5 pCi) per gram of radium-226.

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[2] Conversion of Exposure to dose made by using 1R = 0.0087 Gy. For environmental radiation, conversion of absorbed dose in air to effective dose in the human body is 1 Gy = 0.7 Sv. Thus, 10 μR per hour in air is equivalent to 0.087 μGy per hour in air or 0.06 μSv per hour in the human body.

Assuming intrusion into the burial ground, Option 2 concentration limits for uranium contamination are based on lung or bone doses of 1.7 mSv (170 mrem), and for thorium contamination, external "whole body" exposures are limited to 1.7 mSv (170 mrem).

Radionuclide concentration limits contained in the 1981 BTP do *not* include the contribution of naturally occurring background levels of uranium and thorium. When applying this guidance at sites undergoing decommissioning, it may be necessary to assess the contribution of naturally occurring uranium or thorium in soils to determine compliance with the appropriate concentration limit, which is for licensee-produced uranium or thorium only. It follows that a comprehensive assessment of naturally occurring uranium and thorium in soils near the site may not be necessary if the total (natural plus licensee-produced) concentration of uranium or thorium is sufficiently below the 1981 BTP limit.

4.2.5 "Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material From Ores Processed Primarily for Their Source Material Content" (10 CFR 40, Appendix A) and Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings (40 CFR 192, Subparts D and E)

These regulations, issued by the NRC and EPA, establish technical criteria related to the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings. Both regulations provide design requirements for closure of the mill's waste disposal area, which requires an earthen cover over tailings or waste piles to control radiological hazards from uranium and thorium tailings for 200 to 1,000 years, according to Technical Criterion 6 of Appendix A to 10 CFR Part 40.

The principal radiological hazards from uranium milling operations and mill tailings disposal are radon from uranium and thorium daughters. The release rates of these gaseous radionuclides to the atmosphere are limited to an average rate of 0.74 Bq (20 pCi) per square meter per second. This radon release rate is applicable to any portion of a licensed and/or disposal site unless land areas do not contain radium concentrations, averaged over 100 square meters, greater than (i) 0.19 Bq (5 pCi) per gram of radium averaged over the first 15 centimeters below the surface and (ii) 0.56 Bq (15 pCi) per gram of radium averaged over 15-centimeter thick layers more than 15 centimeters below the surface. Criterion 6 of Appendix A to 10 CFR Part 40 specifies that such concentrations of radium are *above* background levels.

It should be noted that Criterion 6 allows radon release rates to be averaged over a period of at least 1 year (but much less than 100 years) to account for the wide variability in atmospheric radon concentrations over short time periods and seasons. In addition, this criterion applies only to emissions from uranium daughters and does not include radon emissions from earthen materials used to cover the tailings piles. Radon emissions from cover materials are evaluated when developing a closure plan for each site to account for this additional contribution from naturally occurring radon, if appropriate. However, direct gamma exposure rates from the tailings or wastes should be reduced to background levels according to this standard.

4.2.6 National Primary Drinking Water Regulations (40 CFR Part 141)

In accordance with Policy and Guidance Directive FC 83-23 (see A.4.2.1 above), the NRC staff applies the EPA's national primary drinking water regulations as reference clean-up standards for protection of groundwater and surface water resources at or near decommissioning sites. This regulation establishes limits (maximum contaminant levels) for radioactivity in public drinking water and classifies radionuclides into two categories—natural and man-made.

These regulations consider naturally occurring radionuclides to be those that emit alpha particles when undergoing radioactive decay. As such, the EPA's interim national primary drinking water regulations (40 CFR 141.15) provide maximum contaminant levels for alpha particle-emitting radionuclides such as radium-226, radium-228, and other naturally occurring radionuclides. In its proposed rule for final national primary drinking water regulations (Federal Register notice dated July 18, 1991), EPA identified radon-222, radium-226, radium-228, and uranium as the more significant naturally occurring radionuclides in terms of occurrence in drinking water and potential to cause adverse health effects. However, these contaminant levels are for the "total" or "gross" concentration of the radionuclide, whether from natural or man-made sources. Therefore, the EPA limits the concentration of all alpha particle-emitting radionuclides so that an overall dose objective can be met, regardless of whether the alpha particle-emitting radionuclides are naturally occurring or man-made.

In turn, these regulations consider man-made radionuclides as those that emit beta particles and photons when undergoing radioactive decay. The maximum contaminant levels for limiting the average annual concentration of beta particles and photons in drinking water to meet a dose objective of 0.04 mSv (4 mrem) per year are provided in 40 CFR 141.16. However, any beta and photon radioactivity from naturally-occurring radionuclides is included in these drinking water limits since the maximum contaminant levels are based on an overall dose objective. It follows that beta and photon radioactivity attributable to background is not subtracted from beta and photon radioactivity from man-made sources. For example, hydrogen-3 (tritium) and carbon-14 can be produced either naturally or by man-made sources, but the EPA limits the concentration of tritium and carbon-14 in drinking water by establishing a single maximum contaminant level for each, regardless of origin. In summary, the EPA's national primary drinking water regulations *include* background.

4.2.7 Environmental Radiation Protection Standards for Nuclear Power Operation (40 CFR Part 190)

This regulation limits radiation doses to members of the public from radioactive materials introduced into the general environment as the result of operations that are part of the nuclear fuel cycle. 40 CFR Part 190 establishes the following radiological emission standards for the uranium fuel cycle during normal operations: (1) 0.25 mSv (25 mrems) to the whole body, (2) 0.75 mSv (75 mrems) to the thyroid, and (3) 0.25 mSv (25 mrems) to any other organ of any member of the public. It also establishes quantity limits of radioactive materials entering the general environment based on the amount of electrical energy produced by the fuel cycle. For this regulation, the uranium fuel cycle is defined as the operation of uranium milling, conversion, enrichment, fuel fabrication, electricity generation by power reactors, and reprocessing of spent uranium fuel. Uranium mining, waste disposal, transportation of uranium, and the reuse of recovered non-uranium special nuclear and byproduct materials are excluded from the definition.

At a given site, the estimated radiological dose received by a member of the public is calculated based on the applicable potential exposure of the nearest resident in the offsite area surrounding the site. In practice, internal and external radiological doses are summed and then doses attributable to background and extraneous sources (that is, nearby uranium mining or radioactive material transportation activities) are subtracted from this sum to yield an estimate of the total radiological dose from the facility. Radiological standards established by 40 CFR Part 190 do *not* include background. In addition, this regulation specifies that doses from radon and its daughters are excluded from the uranium fuel cycle environmental radiation protection standards.

4.2.8 "Persons Exposed to Transuranium Elements in the Environment," 42 FR 60956 (November 1977)

This guidance provides recommendations on protection of the public health from exposure to transuranium elements in the environment. The recommended radiation dose limits are applicable to individuals in the general population outside the boundaries of a Federal facility, Federally licensed facility, or other site under the direct control of a Federal agency. When developing this guidance, the EPA considered inhalation and ingestion of transuranium elements and established a maximum dose rate to the lung (10 μGy or 1 mrad per year) and the bone (30 μGy or 3 mrad per year) for members of the general population exposed to these radionuclides. The recommended radiation dose limits were above fallout levels found in the environment at that time.

Although this guidance addresses transuranium element contamination in the general environment, it does not consider the contribution of transuranium elements that are caused by the testing of nuclear devices. Therefore, fallout radionuclides and other components of background are *not* included in this guidance.

4.2.9 Standards for Protection Against Radiation (10 CFR Part 20) — Dose Limits

Standards for protection against ionizing radiation resulting from activities conducted under NRC licenses are established in 10 CFR Part 20. The purpose of this regulation is to control the receipt, possession, use, transfer, and disposal of licensed material by any licensee in such a manner that the total dose to an individual does not exceed the radiation protection standards. According to 10 CFR 20.1001, the total dose to an individual includes doses from licensed and unlicensed radioactive material and from radiation sources *other than* background radiation. Therefore, 10 CFR Part 20 occupational and public dose limits do *not* include those radiological doses caused by background radiation.

The term "background radiation" is currently defined in 10 CFR 20.1003 as radiation from cosmic sources, naturally occurring radioactive materials including radon (except as a decay product of source or special nuclear material), and global fallout as it exists in the environment from the testing of nuclear explosive devices.

4.2.10 Various NRC Regulations Concerning Effluent Releases (10 CFR Parts 20, 40, 50, and 70)

A licensee is prohibited by 10 CFR 20.1301 from releasing radioactive materials to an unrestricted area in concentrations that exceed the limits specified in 10 CFR Part 20 or that exceed limits otherwise authorized in an NRC license. For nuclear power reactors, Appendix I of 10 CFR Part 50 provides numerical guidance for keeping radioactive materials in liquid and gaseous effluents released to unrestricted areas "as low as is reasonably achievable" during normal operations of a nuclear power reactor. These guides are provided in units of mrem and mrads per year and do *not* include background. For the purpose of Appendix I, "background" is defined as radioactive materials in the environment and in the effluents from other power reactors. Typically, nuclear power reactor licensees subtract the background component from the gross radioactivity level monitored in effluents so that only reactor effluents, without background, are reported to the NRC.

For materials facilities licensed by the NRC, 10 CFR 40.65 and 10 CFR 70.59 impose requirements for licensees that possess and use either source material for producing uranium hexafluoride or special nuclear material for processing, fuel fabrication, scrap recovery, or conversion of uranium hexafluoride. Specifically, these regulations require the licensees to submit semiannual reports to the NRC specifying the quantity and concentration of principal radionuclides released to unrestricted areas. This information is used to estimate radiation doses from liquid and gaseous effluents. For the majority of materials licensees required to submit semiannual reports, applicable NRC guidance indicates that gross radioactivity measurements are acceptable for reporting purposes. Thus, background is normally included in the measurements reported to the NRC. For example, at a facility that possesses or uses uranium, the contribution of naturally occurring uranium from environmental background is included in the gross radioactivity measurements and typically is not subtracted from the reported effluent releases.

However, if the gross radioactivity measurements approach NRC effluent release limits, background is usually subtracted from gross radioactivity measurements so that radioactivity levels from only NRC-licensed activities can be evaluated for compliance with appropriate limits. Consistent with the occupational and public dose limits contained in 10 CFR Part 20, NRC's effluent release limits do *not* include contributions from background.

4.3 Summary of the Role of Background in Regulatory Applications

Although the clean-up criteria discussed in Section 4.2 represent only a partial listing of all of the Federal, State or local regulations, guidance, and practices that may be applicable during the decommissioning of a nuclear facility, they are the ones most frequently applied at NRC-licensed facilities and illustrate the differences in how background is addressed therein. Of the nine criteria discussed previously, eight exclude background and the one that does include background (drinking water) embodies neither the total dose from background nor all components of background. Rather, only the component of background that applies to that criterion is incorporated.

For clean-up criteria that exclude background, the contribution of background can be critical for determining compliance with the criteria, especially for those that have limits at or near background levels. One example is NRC guidance contained in the April 1982 NRC letter concerning acceptable levels of cobalt-60, cesium-137, and europium-152 for release for unrestricted use (Section 4.1.2).

This guidance recommends that residual radioactivity be removed so that the indoor exposure rate at 1 meter from surfaces is less than 0.03 μSv per hour (5 μR per hour in terms of exposure in air) above background. With background exposure rates typically averaging twice that level indoors, it is imperative to account for background; without subtracting background from gross radioactivity measurements, the criterion's limit would be exceeded. Similarly, accounting for radiation levels produced by background is common practice in other regulatory applications, such as when evaluating and recording exposures to radiation workers using personnel dosimeters. Because background is excluded from radiation dose limits contained in NRC standards for protection against radiation (10 CFR Part 20), background is subtracted from gross radiation measurements before an exposure is assigned to an individual's exposure record. In the case of personnel monitoring using thermoluminescent dosimeters, this is accomplished by assigning a small number of dosimeters to measure back-ground at the facility and during transit, while the majority of dosimeters are assigned to personnel for recording gross radiation exposures. The dosimeters assigned to measuring background are processed and the background exposure is then subtracted from the gross radiation exposures measured on the personnel dosimeters before personnel exposures are recorded.

Regarding the temporal and spatial variability of background, most of the existing clean-up criteria do not explicitly address how to account for this inherent characteristic of background. An exception is the NRC and EPA regulations concerning the operation, decontamination, decommissioning, and reclamation of uranium or thorium mills and mill tailings (Section 4.2.5). These regulations allow radon release rates to be averaged over a period of at least 1 year to account for the wide variability in atmospheric radon concentrations over short time periods. The method of handling temporal and spatial variability of background in other clean-up criteria is not specifically addressed, but may be implied by the context of the individual criterion. For instance, in criteria that exclude background, it is implied that similar methods may be used to measure both the contaminant under investigation and background—the same survey instruments, sample collection and laboratory procedures, and quality controls would be common to both sets of measurements. However, none of the criteria specify the number and locations of background measurements to address spatial variability, nor do they specify an acceptable time period for collecting measurements or between making background and residual radioactivity measurements to address temporal variability. Depending on the criterion, it may be implied that background measurements should be taken in the general locale of the facility during the time that contamination measurements are made. In practice, for most of the NRC criteria discussed in Section 4.2, a representative number of background measurements would be made each day a contamination survey is conducted.

It follows that the cost of making background measurements varies for each of the existing clean-up criteria and depends on several factors, including the number of measurements needed and the quality of those measurements. In general, the end use of the background measurement dictates the quality and associated cost of the measurement. For most of the existing criteria, the number of representative background measurements needed is small compared to the number of contamination measurements needed, but the cost for individual measurements would be comparable. At the radioactivity levels associated with many of the criteria, the background level is well below the criterion's radioactivity limit, thereby requiring only relatively simple and inexpensive background assessments for these applications. However, if background were to be used as *the* clean-up criterion in the future, its measurement would become paramount. Unfortunately, most of the existing criteria do not address the role of background or how to acceptably quantify it and, at the lower radiation levels associated with a return-to-background criterion, existing survey methodologies may not be applicable anyway. Because background is not an absolute entity, it is likely that more extensive and expensive surveys would be needed in order to achieve the increased sensitivity and accuracy for demonstrating compliance with a return-to-background clean-up criterion.

5 OPTIONS FOR APPLYING BACKGROUND AS A RESIDUAL RADIOACTIVITY CRITERION FOR DECOMMISSIONING

5.1 Two Basic Options

There are two basic options for applying background as a residual radioactivity criterion — one based on the radiological dose rate produced by background and the other based on radionuclide concentrations that occur naturally in the environment. Under the first approach, the dose rate from background would be used as the yardstick for comparing the dose rate produced by residual radioactivity at the facility, whereas the second approach considers the radionuclide concentration in the environment that existed before a facility was built. For background to be applied judiciously as a residual radioactivity criterion, however, both approaches must incorporate those factors that affect spatial and temporal variability.

5.1.1 Dose Rate From Background

Section 2.4 of this document contains estimates of annual radiological doses to a United States resident from background, which range from 1 to 10 mSv (100 mrem to 1,000 mrem) with an average dose of about 3 mSv (300 mrem). About two-thirds of the total annual radiological dose from background is from inhaled radon decay products, 9 percent (0.25 mSv or 25 mrem) is attributable to external gamma radiation, with another 9 percent from cosmic rays, and about 13 percent (0.4 mSv or 40 mrem) is from other sources internal to the human body from ingestion and inhalation. Relatively minor contributors to the radiological dose from background (less than 1 percent each) are cosmogenic radionuclides created by the interaction of cosmic rays on otherwise stable elements present on Earth and man-made fallout radionuclides from nuclear weapons testing.

The radiological dose rate from background may be used as a reference dose rate for which site-specific clean-up criteria can be established. A residual radioactivity criterion for decommissioning based solely on the total annual dose from background would exceed current NRC regulatory limits for members of the general public exposed to licensed activities (1 mSv or 100 mrem) by a factor of three for the average United States resident. A clean-up criterion that would correspond to an annual background dose rate exceeding 1 mSv (100 mrem) would likely be considered unacceptable.

Rather than using the total dose rate from background as a residual radioactivity criterion, an alternative is to consider only certain components of background in order to establish a criterion with a lower radiological dose. It follows that it would be necessary for this application to estimate the radiological dose produced by the various components of background. Defining and understanding all components of background and the factors that influence its measurement and variability at a particular facility location is a formidable task requiring much time and resources to accurately determine individual dose rates.

For example, subtracting the relatively large and highly variable radiation dose produced by naturally occurring radon from the remaining components of background would decrease the clean-up criterion to about 1 mSv (100 mrem) per year. However, accurately quantifying radon levels could be complex because radon concentration is influenced by many variables, such as location, barometric pressure, soil moisture, temperature, and building design and construction. Measurement of naturally

occurring radon would be even more complex for sites where uranium or thorium was authorized and used under NRC license because of radon gas production from licensed materials. Therefore, it would be necessary to differentiate between the sources of radon if the dose rate from radon was excluded from the dose rate criterion at such sites.

If measurable, radiological doses from other components of background could be applied as the residual radioactivity criterion. The dose estimated from terrestrial gamma radiation could be used if cosmic radiation could be measured separately. Since it cannot, special measurement techniques need to be employed to separate the terrestrial gamma radiation component from the cosmic radiation component. Estimating the internal dose from radionuclides ingested or inhaled would require measuring the radionuclide composition of food, water, and air and then modeling the resulting doses.

In contrast to applying doses produced by individual components of background, a residual radioactivity criterion could be based on some fraction of the total dose from background. The appropriate fractional multiplier could be established on a site-specific basis or for all decommissioning sites by rulemaking. This approach would also need to take into account the spatial and temporal variability of background in a locale or region, which is discussed in Section 5.3 of this document.

In addition to the difficulties in measuring the background dose rate, another disadvantage to this approach concerns the use of modeling for estimating the risk to future populations from residual radioactivity. The modeling process may contain inherent uncertainties in predicting future radiological doses because the assumptions and factors that are incorporated into the model are based on present scientific knowledge. The model may not accurately represent future residual risks because future site usage may differ from the exposure scenarios that were used to estimate the residual risks. For sites that are released for unrestricted use, it is impossible to predict with great certainty what the actual future site usage will be. Although such scenarios incorporate conservative assumptions about future site usage, there may be different, more limiting scenarios in the future than the current ones that are used to establish residual radioactivity criteria.

Regarding other factors that affect modeling, such as radionuclide release and transport models to simulate radionuclide movement in the environment, current assumptions and parameter values may not accurately reflect future technological improvement or land use of populations that work or live on the site. For example, assuming present day agricultural yields for future farms may not be accurate because improved farming techniques could be developed in the future. This could result in an inaccurate estimate of the dose to future populations from current farming models. Similarly, assumptions such as food chain transfer may not be applicable to future populations working or living on this site.

The main advantage in establishing a residual radioactivity criterion based on the background dose rate is that it facilitates risk comparisons, which is preferable for implementing health protection regulations. Dose can be converted to risk relatively easily, but there is a point at which the risk to future populations from residual radioactivity is lower than the risk from the remedial action. In other words, the clean-up may do more harm than good. Having a residual radioactivity criterion that allows this type of risk comparison is beneficial because it facilitates determining the trade-off between protecting future populations and protecting the people affected by the remedial action.

5.1.2 Naturally Occurring Radionuclide Concentrations

An alternative approach is to establish a residual radioactivity criterion based on radionuclide concentration. Under this approach, the concentration of residual radioactivity at the site would be compared to the concentration of radionuclides present in background to establish a site-specific criterion for individual radionuclides. The concentration limits would therefore be greatly dependent on the local variability of background. An approach based on radionuclide concentration would require that residual radioactivity be reduced to a level that is indistinguishable from background concentrations of individual radionuclides in the vicinity of the facility.

This approach would not require the removal of each atom authorized or used by a nuclear facility. Rather, there could be a distribution of residual radioactivity that is measured onsite, but when compared to the distribution of naturally occurring radionuclides measured offsite, the difference between the two distributions is not statistically distinguishable. The implementation of this approach would vary substantially depending on a number of factors, including the background level for all radionuclides at the site, the temporal and spatial variations in background at the site, and the radionuclide(s) under investigation.

It is recognized that it would be a complex task to demonstrate that the concentration of residual radioactivity at a site is indistinguishable from background concentrations. This task would involve more sophisticated sampling, measuring, and statistical analysis techniques than are currently recommended in the draft report NUREG/CR-5849. Section 3.5.1 of this document briefly discusses a statistical approach that is applicable to this methodology. The amount of data required is dependent on whether the residual radioactivity is part of background as well.

To illustrate how a residual radioactivity criterion based on radionuclide concentration could be applied, examples of two facilities with different types of residual radioactivity are discussed below. The first example is a facility with residual radioactivity that is not part of background, and the second example is a facility with uranium or thorium contamination from licensed activities.

At a facility that used only cobalt-60 during operations, it is expected that residual radioactivity at the facility is not present in background and that it could be assessed using direct external exposure measurements from a general radiological survey, although more comprehensive radiological data may be necessary to assess site locations containing large amounts of residual radioactivity. Because cobalt-60 is not normally a component of background, only limited data would be needed from offsite areas to confirm the absence of cobalt-60 in background in the vicinity of the facility. If the clean-up criterion was based on radionuclide concentration alone, demonstration of compliance would then be relatively straightforward for this type of facility because the background concentration of the radionuclide used by the facility was essentially zero.

By contrast, at a facility that is contaminated with uranium or thorium, more comprehensive radiological data from both onsite and offsite locations would be required for an adequate site assessment. With a sufficient number of high-quality measurements, uranium or thorium concentrations measured onsite could be compared to naturally occurring uranium or thorium concentrations offsite. The variability of uranium or thorium concentrations offsite would have to be compared statistically to the range of uranium or thorium concentrations measured onsite. A similar situation exists for radionuclides that are present in soil from nuclear weapons test fallout, such as cesium-137

and strontium-90; the magnitude of variation found in nature would make identification of a facility-related component difficult, unless it was a significant fraction of that already present in the local environment.

As another reference, the EPA allows for the statistical comparison of onsite samples with background concentrations to identify the offsite related chemicals that are found at or near a site being remediated. The type of statistical comparison is determined on a site-specific basis. With this method, background samples are collected at or near the hazardous waste site in areas not influenced by site contamination and are collected from each medium of concern in offsite areas. Site-specific background information may be supplemented with information obtained from other sources; however, care is taken in using such data because it may represent nationwide variation in a particular parameter rather than variation typical of the geographic region or geological setting in which the site is located.

In appropriate circumstances, background sample size is evaluated in the EPA process by statistical methods, which should be sufficient to accept or reject with a specified likelihood of error the hypothesis that "there is no difference between contaminant concentrations in background areas and onsite." This comparison is made by using the geometric mean concentrations of the background and site data sets, but other statistical methods may be used as appropriate. If there is no statistical difference between onsite and offsite chemical concentration, these chemicals are eliminated from remedial action.

Employing a radionuclide concentration criterion has certain advantages and disadvantages. The main advantage is that the additional radiation risk following clean-up is assured to be very low because the difference between background and residual radioactivity levels is indistinguishable. A site meeting this criterion would remove concern about future site use and would ensure that future populations are protected against radiation risk. Regarding implementation, it appears that measuring radionuclide concentrations would be less difficult than measuring total background dose rates, as discussed in the following section.

The main disadvantage to this approach is that it considers only the risk from future land uses and precludes risk comparisons and trade-offs. For example, cobalt-60 does not generally exist in surface soils naturally or from fallout at measurable levels, but it can be detected in contaminated soil at levels as low as 0.3 μSv (0.03 mrem) per year (see Figure 3-1). Table 5-1, presented in Chapter 5 of the NRC staff's draft "Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities" (July 1994), shows that the mortality risk resulting from 0.3 μSv (0.03 mrem) per year residual dose to the people living and working onsite after decommissioning a generic nuclear facility is 2.02×10^{-4}. Table 5-1 also shows that restoring the site to this risk level will cause 116 times more risk to the people performing the restoration. Establishing a criterion based on returning the site to close to its original radionuclide composition ensures that future populations are protected, but does not consider the risks from performing the remedial action.

5.2 Establishing Background at a Nuclear Facility

5.2.1 Establishing Data Needs

At present, guidance for conducting radiological surveys to demonstrate that residual radioactivity satisfies *existing* decommissioning criteria is contained in the draft report NUREG/CR-5849, dated June 1992. On the basis of the survey methodology contained in this version of NUREG/CR-5849, the type and amount of radiological data needed to demonstrate compliance with clean-up criteria is determined on a site-specific basis, taking into account the radiological characteristics of both the residual radioactivity and background at the facility. Although specific guidance on performing radiological surveys to satisfy a return-to-background clean-up criterion has not yet been developed, it is anticipated that the type and amount of radiological data needed for determining compliance with such a criterion would also be established on a site-specific basis, given the wide variability of background from facility to facility, and the diversity of radionuclides authorized by the NRC at nuclear facilities located throughout the United States. The process for establishing site-specific data needs is currently performed by the licensee; however, in the future, data needs may be negotiated with local, State, or Federal regulatory entities, as discussed in Section 5.2.4.2 of this document.

Section 3 contains a brief overview of radiation detection equipment and analytical methods for identifying and quantifying background and its inherent variability. The equipment and methods discussed in that section may be used to obtain sufficient radiological data on all sources of background at a nuclear facility undergoing decommissioning. This would include collection of data on direct external exposure and radon concentration, as well as radioactivity levels in soil, air, water, and in certain cases, food sampling. As discussed in Section 3, the ability to distinguish naturally occurring radioactivity from radioactivity contributions produced by the nuclear facility will depend greatly upon the radionuclides involved and the radioactivity measurement methods chosen. In general, the amount of radiological data needed to assess a nuclear facility that used radionuclides that are already present in the environment will most likely be greater than for a facility that did not use such radionuclides.

It should be noted that the survey methodology described in the draft version of NUREG/CR-5849 is applicable to decommissioning criteria that are typically well above background radiation levels. However, the survey methodology described in NUREG/CR-5849 may not be applicable for determining compliance with a return-to-background decommissioning criterion because of statistical limitations and the need for additional radiological data on background. An alternative process, described briefly in Section 3.4.1, is based on information reported by Gilbert and Simpson (1992). When using this approach, it is prudent to specify the type and quality of radiological data early in the decommissioning process, along with an acceptable confidence level that the specified objectives of the radiological survey will be attained. This process entails early specification of sample collection and analysis procedures, the method of comparing site areas to reference areas, the null and alternative hypotheses and Type I and Type II error rates, the quality assurance procedures, and other parameters.

Included in this process is the establishment of a "reference area," which is defined as an area that has physical, chemical, radiological, and biological characteristics similar to those of the site area being remediated, but which has not been contaminated by site activities. The reference area is where background would be measured and defined for the purpose of decommissioning. Understandably, the

distribution and concentration of background in the reference area should be the same as that which would be expected onsite if the site had never been contaminated. However, it may be necessary to select more than one reference area for a specific site, if the site exhibits so much physical, chemical, radiological, or biological variability that it cannot be represented by a single background area. Thus, such an approach would require the development of a site-specific survey design to produce sufficient radiological data for the assessment of the radiological characteristic of both the site and background. The distributions of background and residual radioactivity levels would then be compared statistically to determine whether the two distributions are distinguishable.

It is evident that increased sensitivity in distinguishing a facility-related radionuclide from background requires more comprehensive radiological data, which are obtained through more sophisticated analytical techniques. In areas where background is both high and widely variable, the ability to assess facility–related radionuclides becomes increasingly difficult. Even with the application of state-of-the-art measurement techniques and the collection of large amounts of radiological data, radiological dose limits for some radionuclides cannot be measured with sufficient certainty using current survey techniques.

5.2.2 Data Interpretation

An understanding of the radiological characteristics of both facility-produced residual radioactivity and the variability of background in the vicinity of a decommissioning site is necessary to properly interpret data, particularly where the facility-produced residual radioactivity under investigation is a component of background. Use of data from past monitoring programs, the reanalysis of archived samples, the history of radioactivity releases, and preexisting site characteristics are potentially useful for interpreting radiological data collected at the time of decommissioning. If available, historical site information should be compared to more recent site information to identify trends in radionuclide migration, as well as to identify previous burials of radioactive waste, so that they can also be assimilated into the site assessment process.

An important objective of collecting radiological data at the time of decommissioning is to obtain a realistic estimate of both the residual radioactivity and background that exist at the site. In addition to interpreting actual site measurements, predicting such levels may also be accomplished through modeling, which is an important tool for sites where site-specific information is not available. In the absence of site-specific information, generic modeling parameters can be selected in a conservative manner to calculate potential radiological doses under hypothetical exposure conditions. The NRC staff typically estimates doses from residual radioactivity by constructing and executing a computer model or analytical solution that simulates the release and transport of radionuclides and radiation in the environment. These assessments are performed on a site-specific basis and reflect differences in the characteristics of the residual radioactivity and background.

The modeling description and calculational methodology described in Volumes 1 and 2 of NUREG/CR-5512 have been developed to evaluate the total effective dose equivalent to the average member of a critical group, and can be used as a screening model which employs generically derived conservative assumptions and factors. If it can be demonstrated that the criteria have been met using the default parameters and assumptions in the screening model, it would be acceptable to release the site for unrestricted use. However, assumptions and factors that are more appropriate to a particular site could be substituted if it can be demonstrated that these factors and assumptions reasonably reflect

the conditions at the site. Other models or methods could be used for estimating the total effective dose equivalent, provided that it can be demonstrated that they provide reasonable estimates for the site to be decommissioned.

To properly assess the adequacy of radiological data, the uncertainties associated with all radiological data collected from the site should be estimated. As discussed in Section 3.4, many sources of error contribute to the overall uncertainty in radiological data. Uncertainties should be considered when evaluating all data and should be determined through statistical evaluations. The first step in the evaluation is to validate the data by identifying invalid data and then qualifying usable data. The second step is to determine whether the uncertainty in the data itself is acceptable for decision-making purposes. Section 5.2.4 discusses uncertainties and the importance of establishing an acceptable confidence level to attain specified objectives of the decommissioning program.

5.2.3 Costs and Practicality of Survey Methods

Section 3.5 of this document provides cost estimates for measuring cobalt-60, strontium-90, cesium-137, thorium-232, and natural uranium at residual radioactivity concentrations corresponding to the following annual dose levels: (1) 1 mSv (100 mrem), (2) 0.6 mSv (60 mrem), (3) 0.3 mSv (30 mrem), (4) 0.1 mSv (10 mrem), (5) 0.03 mSv (3 mrem), (6) 0.01 mSv (1 mrem), (7) 1 μSv (0.1 mrem), and (8) 0.3 μSv (0.03 mrem). As illustrated in Figures 3.1 through 3.5, measurement costs increase with lower doses; when increased sensitivity at levels approaching background is required, the cost of residual radioactivity measurements increases significantly.

In addition to the data contained in Section 3.5 of this document, an independent and more detailed series of survey cost estimates was developed for 10 generic nuclear facilities using 5 radionuclides at the same radiological dose levels prescribed in Section 3.5. These cost estimates support the technical basis of the GEIS and are based on survey methods contained in the draft report NUREG/CR-5849. However, at low residual contamination limits, certain modifications and assumptions to this survey methodology are necessary to demonstrate compliance with the low dose guidelines, such as limiting counting times to 20 hours per sample and collecting less than 3,000 soil samples per 100 square meter grid. Although survey cost estimates for residual contamination limits approaching background concentrations may not be absolute, this study confirmed that radiological survey costs increase with decreasing residual contamination limits and that, for radionuclides that are not naturally occurring, survey costs increase significantly at residual contamination limits that are less than 0.01 mSv (1 mrem) per year. For naturally occurring radionuclides such as uranium and thorium, survey costs increase significantly at higher residual contamination limits.

In general, measurement costs increase with decreasing dose because of the need for increasingly sophisticated survey methods that rely heavily on laboratory analyses of samples collected from a site. For example, Table 3.5 indicates a factor of 10 increase in cost for measuring external radiation by means of laboratory analysis of soil samples compared to an *in situ* measurement using a survey meter. Depending on the radiological characteristics of the site and the residual radioactivity criterion, decommissioning surveys could require hundreds of radiological measurements costing several hundreds of dollars to more than one thousand dollars per measurement. However, for certain radionuclides, there are residual radioactivity limits that cannot be measured practically with current survey techniques because of the exorbitant costs associated with extremely long counting times or the need to employ highly specialized research techniques to analyze radiological samples.

Another practical and possibly limiting factor that must be considered when planning radiological surveys is the time needed for sample analysis. For increased sensitivity at very low dose levels, a single radiological sample may need to be measured or "counted" in the laboratory for several days. Although this amount of time may be required to obtain sufficient measurement accuracy to ensure that a site meets a return-to-background residual radioactivity criterion, it may not be practicable to conduct surveys that require such long count times because of the large number of samples that would be collected and analyzed at such low radioactivity concentrations. Under these circumstances, several well-equipped laboratories would have to dedicate all of their radioanalytical equipment for several months to analyze samples from a single decommissioning survey with sufficient accuracy.

5.2.4 Establishing Acceptable Confidence Levels

5.2.4.1 Confidence Levels Established by the NRC

One of the basic considerations in designing survey plans for site decommissioning is that the collected and analyzed radiological data is sufficient and of adequate quality to meet an overall uncertainty, or confidence level, that is acceptable for decision-making purposes. A variety of errors are associated with making site remediation decisions, and the term "confidence level" is used to describe the likelihood of all types of errors associated with a particular decision. The use of statistical methods allows for controlling the probabilities of making decision errors.

When using statistical methods, an acceptable level of confidence should be established early by the decision maker. In so doing, consideration should be given to the amount of "error" that is acceptable in incorrectly determining that a site meets or does not meet the clean-up criterion. For example, the selection of a 0.05 probability of a Type 1 error means that it is considered acceptable to be wrong 5 percent of the time in labeling a site that actually meets the clean-up criterion as being contaminated above background. Likewise, a 0.05 probability of a Type II error means that it has been considered acceptable to be wrong 5 percent of the time in labeling a site that does not meet the clean-up criterion as being at or below background.

In determining such "error rates," consideration must also be given to the number of radiological data points that are necessary to satisfy the specified level of confidence. The greater the level of confidence and the lower the corresponding error rates, the greater the number of radiological measurements that will be required. The number of measurements required also depends on the power of the statistical test that is specified by the decision maker.

In many environmental applications, the NRC staff considers the 95-percent confidence *interval* appropriate for assessing radiological data. The "confidence interval" refers to a method of quantifying the likely range of fluctuation of the data, and is a function of the way the data are distributed. Blanket specification of a standard confidence interval may not be appropriate given the diversity of radiological conditions at decommissioning sites located throughout the United States. By establishing a standard confidence interval, certain sites may be required to make an unwarranted number of radiological measurements. For example, a large uranium or thorium processing site that has a highly variable background level could be required to make more radiological measurements than would be accommodated by a realistic decommissioning budget.

An alternative to applying an NRC-established confidence level would be for licensees and the NRC staff to jointly define an acceptable confidence level on a site-specific basis. In this manner, local radiological conditions and other modifying factors could be taken into account while ensuring that an appropriate site-specific confidence level was attained. A process such as the one discussed in Section 5.1.1 could be applicable to this approach.

5.2.4.2 Confidence Levels Negotiated by Site-Specific Advisory Board

As an alternative to setting confidence levels by either establishing a single NRC standard or defining many individual site-specific ones through negotiations limited to the licensee and NRC staff, confidence levels could be negotiated with a site-specific advisory board convened to obtain advice from affected parties regarding the proposed decommissioning. It is envisioned that local citizens' groups would participate early in the decommissioning process, especially where residual radioactivity at the site is above background levels and in cases that could result in an additional radiological dose to the average member of a critical group.

If a site-specific advisory board is convened, the recommendations provided by the board may include determining the level of residual radioactivity that is to be considered ALARA. In defining the site-specific ALARA level, it would be prudent to establish an acceptable level of confidence for decision-making purposes. As discussed above, the confidence level that is agreed upon through negotiations would have an immediate impact on the decommissioning process because of its direct relationship to survey requirements and costs and, where the residual radioactivity is long-lived, there could be future impacts as well because of the associated level of confidence in projecting future radiological doses.

5.3 Options for Accounting for Temporal and Spatial Variability of Background

Section 2.3 of this document discusses the sources and magnitude of temporal background variability and concludes that the variation is greater over short time periods than longer time periods. Figure 2.4 shows that on a daily basis at a given location, background exposures vary by almost a factor of 2, but on a yearly basis, they vary by only about 10 percent. This apparent decrease in temporal variability is due to averaging daily and seasonal effects, such as rainstorms and winter snow cover, over longer time periods. It is therefore recommended that background be measured over periods ranging from several months to more than 1 year to obtain sufficient data to quantify temporal variability at a particular site.

Section 2.3 also discusses the sources and magnitude of spatial background variability on a nation-wide, regional, and local (site-specific) scale. Surveys around the country have shown that concentrations of uranium and thorium in soil vary by a factor of 40 between the highest and lowest survey points and that certain regions have external gamma ray levels that are 4 times higher than others. Background can vary by a factor of 10 within a State, and on a smaller scale, wide variations can occur within a locale because of the location of mineral deposits. Because spatial background variability can be characterized with greater certainty over smaller areas, it is recommended that measurement and application of background data be limited to the locale of the facility undergoing decommissioning. Identifying the local variation also provides the most meaningful information for direct comparisons of facility radiation levels to the radiation levels adjacent to the facility.

There are several approaches for incorporating background variability in a residual radioactivity criterion, some of which are discussed below. The temporal and spatial variability of background must be taken into account in both the radiation dose and radionuclide concentration approaches discussed in Sections A.5.1.1 and A.5.1.2 above. Without accounting for these variations, quantification of the differences between residual radioactivity and background levels cannot be ascertained reliably.

5.3.1 Average of Background

The average background level or some other measure of central tendency, such as a sample mean, could be incorporated into a return-to-background criterion. The average value of background will fluctuate from site to site and its value is dependent on the data collected at a particular site. As discussed in Section 5.2.4.1, confidence intervals are a method of quantifying the likely range of the site-specific data. To determine a confidence interval, the distribution of the sample mean needs to be known and is described by its shape, the estimated sample mean, and the variance of the sample mean. The application of confidence intervals is also used by the EPA in their "Superfund" program for comparing background concentrations of hazardous substances to onsite levels.

Unless the confidence interval is specified before collection and analysis of site samples begin, it is possible to overestimate the true upper limit of the confidence interval when using this approach. This would occur if an insufficient number of rather variable measurements formed the basis for calculating the confidence range. The calculated upper limit of this range could then be greater than the true upper limit of background onsite. To prevent this situation, statistical methods should be employed when planning, conducting, and analyzing the results of the background survey.

5.3.2 Maximum Measured Background Value

Another approach for incorporating background variability in a return-to-background criterion is to apply the maximum measured value of background as the criterion. However, this approach could overestimate or underestimate actual background conditions, depending upon the sufficiency and quality of the data. An insufficient number of measurements or poor quality measurements could indicate erroneously high or low values for the maximum background level. For example, if measurements were made only from an area of low-bias conditions, the maximum measurement would carry this low bias, thereby underestimating background. Likewise, if natural variability is not adequately assessed, anomalously high or low measurements could be set as the criteria because of temporal or spatial variability. Again, to ensure that the maximum measured value adequately represents the upper limit of background, statistical methods should be employed when planning, conducting, and analyzing the results of the site survey.

5.3.3 Average Variation of Background

The quantity of the average variation of background could also be used as a residual radioactivity criterion. For this application, the average variation, or resolution, of background is the smallest radioactivity level detectable above background while accounting for its variability. Quantifying the average variation requires the averaging of measurements aimed at assessing temporal and spatial variability and uncertainties in the data, such as those associated with analytical procedures.

This approach would require a survey that would produce a large database and, for analysis of the database, statistical methods should be applied to estimate the confidence level. A survey program would need to produce numerous measurements over long periods of time under this approach, which would be costly in both time and effort. As with other approaches, specification of the statistical method and level of confidence to quantify background variability should be made when planning the survey. Section 3.5.1 suggests parametric tests (such as a "t" test) or nonparametric tests (like the Wilcox Rank Sum or the Quantile test) for these applications.

5.3.4 Incremental Addition Applied to the Measurement of Background

Background and its inherent variability could be quantified by any of the above methods and an additional increment could be added to the background level to establish a site-specific residual radioactivity criterion. Justifications for applying an incremental increase and for defining its magnitude may be based on the reasonableness of the decommissioning measures to be taken (ALARA). For example, if an analysis of a proposed decommissioning action concluded that the remediation activities would result in excessive adverse onsite impacts to reach a background level, an incremental addition to the background level may be chosen that justifies the reduction of onsite impacts. A justification for the incremental addition to the background level may be the reduced immediate impacts from remediation activities compared to the increased risk to future populations from a higher level of residual radioactivity. The magnitude of the incremental addition to the background level would be determined on a site-specific basis and would therefore be greatly dependent on the local variability of background. Further information on the application of such an approach is provided in Section 6.3 of this document.

6 SUMMARY AND CONCLUSIONS

6.1 Summary of Doses From Radionuclides as a Criterion for Decommissioning

Background is composed of various sources of ionizing radiation that collectively produce an average total effective dose equivalent of about 3 mSv (300 mrem) per year to the United States resident. Annual radiological doses from background typically range between 1 and 10 mSv (100 and 1000 mrem) in the United States. Although greater doses are possible for people living in houses with very high radon concentrations, 10 mSv per year could be taken as a practical maximum, except in unusually extreme situations. For comparison, the estimate of the average United States dose from background is similar to the world average estimate of 2.4 mSv (240 mrem) per year.

The largest source of exposure comes from terrestrial radionuclides, which have been present on Earth since its formation and are incorporated in soil, water, air, and the human body itself. About two-thirds (2 mSv or 200 mrem) of the total annual dose from background is from inhaled radon decay products, 9 percent (0.25 mSv or 25 mrem) is attributable to external gamma radiation, with another 9 percent from cosmic rays, and about 13 percent (0.4 mSv or 40 mrem) is from other sources internal to the human body from ingestion and inhalation. Relatively minor contributors to the dose from background (less than 1 percent each) are cosmogenic radionuclides created by the interaction of cosmic rays on otherwise stable elements present on Earth, and man-made fallout of radionuclides from nuclear weapons testing. Figure 2.8 illustrates the estimated total dose from background and the individual doses from its principal components.

Background produces doses to the United States population that are highly variable between locations (spatial) and also over time at the same place (temporal). For example, cosmic radiation is modulated by the 11-year solar cycle and typically varies about 10 percent at the same location, but at different times. Temporal variability of background is also tied to atmospheric circulation and precipitation patterns that affect the distribution of cosmogenic and fallout radionuclides. Short-term changes in external gamma exposure arise from redistribution of radon decay products in the atmosphere and washout with precipitation, resulting in changes ranging from a few percent to more than 200 percent over the course of a day or season. Even larger variations in indoor radon concentrations can occur because of building ventilation changes. Indoor levels of gamma radiation typically vary by about 50 percent from the use of different construction materials. Outdoors, changes in soil moisture and snow cover cause external gamma radiation levels to vary seasonally by 10 to 50 percent at the same location. The concentration of radionuclides that produce internal doses, such as lead-210 in body tissues, has been observed to vary by about a factor of 3 throughout the United States. Spatial variability of cosmic radiation is observed to be as much as 200 percent, depending greatly on altitude and to a lesser extent on latitude.

In addition to naturally occurring sources of radiation, nuclear technology has also led to the creation of man-made radionuclides that contribute to the background dose. Man-made sources of ionizing radiation exposure account for 18 percent of the total dose to the United States population. Of the man-made sources, medical x-ray examinations are the largest source of exposure, producing 11 percent of the total annual dose (0.39 mSv or 39 mrem). Nuclear medicine procedures account for 4 percent of the total population dose, followed by consumer products (3 percent), weapons test fallout

(less than 1 percent), and occupational exposures (less than 1 percent). On average, however, 82 percent of the total dose to the United States population comes from naturally occurring radiation sources. The magnitude and variability of radiation doses is directly proportional to the background level to which individuals are exposed, and the activities in which they are engaged. Because of its widely variable and ubiquitous characteristics, radiation doses to United States residents from background are, in turn, widely variable as well.

Applying the dose from background is one option for establishing a decommissioning criterion that is tied to background radiation levels. Understandably, a residual radioactivity criterion for decommissioning based solely on the total dose from background would likely be considered unacceptably high for releasing a nuclear facility for either unrestricted or restricted use. For comparison, the annual variation in the background dose rate to the United States population alone is greater than current NRC regulatory limits for members of the general public exposed to licensed activities (1 mSv or 100 mrem). Because of the relatively high and variable radiation dose from radon, it is also considered unlikely that a residual radioactivity criterion that incorporated radon from unlicensed activities would be considered acceptable. Furthermore, given its large spatial and temporal variability, implementation of a clean–up criterion that incorporated radon appears impractical as well.

As discussed earlier, rather than applying the total dose from background, it may be preferable to apply dose rates produced by individual components of background, such as the external terrestrial component or the internal (human) terrestrial component, as reference dose rates for decommissioning. For example, Table 2.9 lists the average annual dose to United States residents from the terrestrial gamma component as 0.28 mSv (28 mrem) and 0.40 mSv (40 mrem) for the internal component. Thus, decommissioning criteria could be set at lower dose rates by applying dose rates from individual components of background instead of the total dose rate from background. It follows that such an application of background would require accurate determinations of doses produced by the various background components. Further discussion of the use of the background dose rate as a basis of a decommissioning criterion is provided in Section 6.3.

6.2 Summary of Radionuclide Concentrations as a Criterion for Decommissioning

Nearly all materials contain naturally occurring radioactivity because of the presence of terrestrial radionuclides (such as potassium-40, rubidium-87, thorium-232, and uranium-238) and cosmogenic radionuclides (such as carbon-14, hydrogen-3, beryllium-7, and sodium-22). The concentration of these radionuclides in soil, water, air and living matter can vary widely throughout the United States because of geological processes, climatic changes, weather, and human activities. For example, concentrations of uranium and thorium in the soil range from as little as one-tenth to as much as four times the average value. Data contained in Table 2.2 of this report illustrate a typical range of natural radionuclide concentrations in soil throughout the United States and the world.

The concentration of the principal gamma emitting radionuclides in soil is directly related to the external gamma radiation levels in a locale. On a nationwide scale, the concentrations of terrestrial radionuclides vary widely, as reflected in the grouping of external gamma radiation levels into three regions: (1) the Atlantic and Gulf coastal plains, which average about half of the level seen for Middle America (230 microgray per year or 23 mrad per year); (2) Middle America, which has an average level of 460 microgray per year (46 mrad per year); and (3) the Denver, Colorado area,

which has an average level about twice that of Middle America (900 microgray per year or 90 mrad per year). Throughout the United States, concentrations of naturally-occurring radionuclides in groundwater can also vary widely. In certain midwestern areas, for example, the concentration of uranium in water (13 Bq per cubic meter or 0.35 pCi per liter) is 35 times greater than in some eastern states (0.4 Bq per cubic meter or 0.01 pCi per liter). Even greater concentrations are reported in western areas of the United States, where natural uranium concentrations in groundwater (130 Bq/m^3 or 3.5 pCi/L) are 350 times that of eastern groundwater.

On a smaller scale, such as within an individual State, background radioactivity levels can vary even more. For example, in a particular location in northwestern New Jersey, external gamma radiation levels triple across a small field and, at a nearby rock outcropping, the average soil concentration of naturally occurring radionuclides increases 100 fold; yet 62 miles away from this location, gamma radiation levels fall to less than 10 percent of the regional average because of the presence of sandy beaches. This local variability can also be seen in the data contained in Table 2.6 of this report which lists concentrations of potassium-40, thorium-232, and uranium-238 in soil sampled from southeastern Pennsylvania.

Spatial variability in the concentration of background radionuclides can also be caused by human activities. Fallout from a nuclear weapon test can cause abrupt changes in background that require a few months to a few decades to decay away. Such testing has correspondingly increased the spatial variability of background because the distribution of fallout radionuclides in the United States is not homogeneous. Mining and milling have also increased the spatial variability of background by redistributing the preexisting concentrations of naturally occurring radionuclides in a locale. Another human activity that affects the spatial distribution of background is the combustion of fossil fuels, which produces ash that redistributes natural radioactivity from the ground to the air.

In summary, background concentrations in environmental media are highly variable in both space and time because of natural processes and human activities. Measuring the concentration of background radionuclides can be costly and complex for the purpose of calculating the dose to a local population. However, as discussed previously, it may not be necessary to quantify all components of background to distinguish radiological contributions, if any, from a decommissioned nuclear facility. Thus, for decommissioning purposes, radiological assessments in a given locale should be capable of accurately distinguishing between facility contributions and those radiological contributions that are attributable to background.

6.3 Conclusions

There are numerous ways to apply background as a basis for a decommissioning criterion. The two approaches considered in this report are background dose rates and background radionuclide concentrations. In the first approach, an acceptable background dose rate would be used to measure the efficacy of the decommissioning effort by comparing it to the dose rate produced by the facility. In the second approach, the concentration of background radionuclides would be compared to the concentration of residual radioactivity at the site. Application of either approach may be associated with a radiological risk that is dependent on either the selected background dose rate or background radionuclide concentration. In addition, to further reduce the radiological risks from decommissioning, it is possible to use as a basis individual components of the background dose rate or background

concentrations of only certain radionuclides, rather than applying total background dose rates or total background radionuclide concentrations.

For regulatory purposes, it is prudently assumed that all exposures of an individual to ionizing radiation, including background, incrementally increase the risks of adverse health effects. Consequently, risks from radiological exposures are weighed against the benefits. In establishing decommissioning criteria, the benefit is the future use of lands and structures. In the United States, the regulatory acceptability of radiological risk usually has been in terms of the calculated incremental lifetime risk of fatal cancer. This risk has ranged in regulations from 1 in 1,000,000 to 1 in 100, but usually is approximately 1 in 10,000. A calculated incremental lifetime risk of fatal cancer equal to 1 in 10,000 corresponds to a dose to an individual of approximately 0.03 mSv (3 mrem) per year over a 70-year lifetime. For comparison, 0.03 mSv per year is well below the variability of average background dose rates in the United States (1 mSv to 10 mSv).

Given the previous discussions on background variability, it is apparent that there is no single value of background dose or background concentration that can be applied universally because of its wide variability in both time and space. Although a decommissioning regulation could, in concept, establish a single maximum dose limit that is based on the total background dose rate for the United States, the radiological risk associated with such a proposition would likely be considered unacceptably high because the average background dose rate is about 3 mSv (300 mrem) per year to the United States resident and varies annually in the country between 1 and 10 mSv (100 and 1,000 mrem). For comparison to risk, an average background dose rate of about 3 mSv (300 mrem) per year to the United States resident produces a lifetime risk of fatal cancer of approximately 1 in 100. A background dose rate that varies annually between 1 mSv and 10 mSv (100 and 1000 mrem) produces a lifetime fatal cancer risks ranging from approximately 3 in 1,000 to 3 in 100. However, even on a localized basis, implementation of a background dose rate criterion in the calculated risk range of 1 in 10,000 would be difficult because of the temporal and spatial variations in background that exist in local areas throughout the United States. Thus, it is difficult to establish a single background dose rate for regulatory purposes based directly on either a national or local background dose measurement.

The consideration of directly applying the concentrations of background radionuclides as a regulatory basis leads to some, but not all, of the same difficulties as attempts to directly apply background dose rates. As discussed above, concentrations of background radionuclides in the United States vary too much to establish a single value as a regulatory basis for all decommissioning sites. However, in the locale of a site being decommissioned, it is possible to quantify the variability in the concentration of background radionuclides and then compare those radionuclides to the concentration of residual radioactivity at the decommissioned site. Because spatial variability of background radionuclide concentrations can be characterized with greater certainty over smaller areas, application of background data can best be utilized if it is limited to the locale of the facility undergoing decommissioning.

Identifying the local variation provides the most meaningful information for direct comparisons between facility radiation levels and radiation levels adjacent to the facility, while also increasing the certainty of correctly extrapolating data from nearby offsite areas to onsite areas. For example, if a decommissioned facility is located in a certain county in Ohio, it is more appropriate to apply background data from neighboring lands in that county than from either a highly mineralized county located in Colorado or a county located in a coastal plain State where background levels are

significantly lower. Another advantage of applying background data is that, in general terms, its variability is less than the nationwide variability of background. Application of local background data would likely result in lower doses than if nationwide background data were applied with its greater range of radionuclide concentrations.

In order to relate radionuclide concentrations to a dose rate or risk level, exposure pathway modeling can be performed for a decommissioned facility. Because exposure pathway modeling and dose-risk relationships can relate concentration to risk for all radionuclides, a return-to-background regulatory alternative can be considered on the basis of radionuclide-specific contributions to individual dose or risk. In comparing the effects of residual radioactivity with background radionuclides, it is noted that risk is a reasonable basis for comparison for both sources of radioactivity. A regulatory basis can be the calculated risk associated with concentrations of residual radioactivity compared with risks from background. Thus, given the wide variability of background and the wide variation of radiological risk to the United States population, the manner in which background is defined as a reference radioactivity level directly affects the level of risk associated with its application as a decommissioning criterion.

Compliance with a return-to-background decommissioning criterion could be determined based on the objective of reducing residual radioactivity to a level that is indistinguishable from background, while taking into account the reasonableness of the decommissioning measures to be taken (ALARA). This approach would demonstrate that the concentration of individual radionuclides that contribute to residual radioactivity at the site would be reduced to a level that is indistinguishable from background concentrations of the individual radionuclides in the vicinity of the facility. The concentration limits for individual radionuclides would be determined on a site-specific basis and would therefore depend greatly on the local variability of background.

Based on information presented in Section 3.5 of this report, the ability to distinguish between background and residual radioactivity decreases with lower concentrations of residual radioactivity. It follows that the costs to determine compliance with a return-to-background decommissioning criterion increase rapidly with lower concentrations of residual radioactivity. Likewise, the trend is for remediation costs to increase significantly with smaller amounts of residual radioactivity. This information, combined with the wide variability of background at all locations throughout the United States, leads to the finding that an additional increment of risk could be added to the average background level to establish a reasonable and realistic site-specific residual radioactivity criterion. The magnitude of the increment could be based on an acceptable level of incremental risk from residual radioactivity while taking into account the ALARA concept. As discussed earlier in this section, a frequently applied risk level of 1 in 10,000 for a calculated incremental lifetime risk from fatal cancer corresponds to a dose of 0.03 mSv (3 mrem) per year.

It is recognized that demonstrating that residual radioactivity levels at a site are indistinguishable from background is a complex task involving relatively sophisticated techniques for sampling, measuring, and statistical analysis. The difficulty of the task can vary substantially depending on a number of factors, but with sufficient planning it is possible to use background as the basis for a decommissioning criterion.

A limitation of a background radionuclide concentration basis is that not all radionuclides found at a contaminated site necessarily occur in nature. For radionuclides that are produced by a licensee but are not part of background, such as cobalt-60, a return-to-background alternative could be interpreted

to mean that no atoms of the licensee-produced radionuclide should remain on site. However, measurement of every atom at a site is not practicable because of physical and financial limitations, for naturally occurring and man-made radionuclides alike. However, as discussed above, exposure pathway modeling and use of a dose-risk relationship can relate radionuclide concentrations to risk for all radionuclides, including those that do not occur in nature. As stated previously, the regulatory basis can be the calculated risk associated with concentrations of residual radioactivity compared with risks from background.

In conclusion, a decommissioning criterion based on return-to-background can be considered to have a basis in two parts. One part is for naturally occurring radionuclides in common with licensed activities that could contribute to radioactive contamination. The basis is a direct comparison of contamination concentration to local concentrations of the same radionuclides, resulting in a net risk from decommissioning. The second part is for radionuclides that are not part of background. For the latter radionuclides, the basis is a comparison of the risk from licensee-produced radioactivity to the risk from variations of background concentrations of radioactivity.

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This report was originally published as an appendix to the draft U.S. Nuclear Regulatory Commission (NRC) document entitled, "Generic Environmental Impact Statement in Support of Rulemaking on Radiological Criteria for Decommissioning of NRC-Licensed Nuclear Facilities." Because of the great interest in this report by members of the public, citizen and environmental organizations, academicians, licensees, and regulators, the NRC staff is publishing this report separately, so that it can be readily available to a diverse audience. This report was created to assist both the NRC staff and interested members of the public in evaluating background radiation (background) as a decommissioning criterion, by serving as a primer on background and providing information on the existing applications of background in regulatory criteria and standards. This report also discusses some of the methods available to measure and distinguish between the very low radiation levels associated with background and man-made sources of radiation.

Two approaches are considered for applying background as a decommissioning criterion; these are the use of background dose rates and background radionuclide concentrations. This report concludes that the temporal and spatial variability of background produces a wide range of doses to United States residents, which prevents the application of background dose rates as a decommissioning criterion. Instead, this report recommends that local background radionuclide concentrations serve as a benchmark for decommissioning criteria, while taking into account the concept of reducing residual radioactivity to a level as low as is reasonably achievable.

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