ORP/SID 72-1

NATURAL RADIATION EXPOSURE IN THE UNITED STATES

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs

NATURAL RADIATION EXPOSURE IN THE UNITED STATES

Donald T. Oakley

June 1972

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs
Surveillance and Inspection Division
Washington, D.C. 20460

FOREWORD

The Office of Radiation Programs of the Environmental Protection Agency carries out a national program designed to evaluate population exposure to ionizing and non-ionizing radiation and to promote development of controls necessary to protect public health and safety.

Within the Office of Radiation Programs, the Surveillance and Inspection Division conducts programs relating to sources and levels of environmental radioactivity and the resulting population radiation dose. Reports of the findings are published in the monthly publication *Radiation Data and Reports*, appropriate scientific journals, and Division technical reports.

The technical reports of the Surveillance and Inspection Division allow comprehensive publication of the results of intramural and contract projects and, as in the case of the present report, of studies supported by the Division. The reports are distributed to State and local radiological health agencies, Office of Radiation Programs technical and advisory committees, universities, libraries and information services, industry, hospitals, laboratories, and other interested groups and individuals. They are also included in the collections of the Library of Congress and the National Technical Information Service.

Readers of these reports are encouraged to inform the Office of Radiation Programs of any omissions or errors. Comments or requests for further information are also invited.

W. D. Rowe
Deputy Assistant Administrator
for Radiation Programs

ACKNOWLEDGMENTS

My deepest gratitude is extended to my thesis advisors: Dade W. Moeller, principal advisor, Abraham S. Goldin, and Robert B. Reed, members of the faculty of the Harvard School of Public Health. Special thanks are due Dr. Moeller for his patient guidance which led to the thesis topic and for his attention to my problems and progress throughout the preparation of the thesis. I am especially grateful to Dr. Reed for his numerous suggestions for improving the interpretation and presentation of the data. and to Dr. Goldin for his thorough review of my work and for his wise counsel that helped me to steer clear of contradictions and other pitfalls. Above all, I am appreciative of the many instances of kindness and wit which accompanied suggestions from all three advisors. Although not an advisor, Jacob Shapiro contributed substantially to my understanding of natural radiation exposure through his teaching at the School of Public Health, and I gratefully acknowledge his help.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The exposure of man to natural radiation sources in the United States has been estimated by considering the distribution of the population with respect to certain factors, principally geology and elevation, which influence exposure to terrestrial and cosmic radiation. Data obtained by aerial surveys in the United States have been used to calculate an average dose equivalent (DE) estimate of 40 mrem/yr. to the population. The results also indicate three distinct areas of terrestrial radioactivity in the United States—(1) the Coastal Plain, which consists of all or portions of States from Texas to New Jersey (23 mrem/yr.); (2) a portion of the Colorado Front Range (90 mrem/yr.); and (3) the rest of the United States, i.e., portions of the United States not included in "1" or "2" (46 mrem/yr.).

Since elevation is the primary determinant of cosmic ray DE in the United States, the population distribution with respect to elevation was determined. The average population elevation of the United States was determined to be approximately 700 feet, and the average cosmic ray DE was estimated to be 44 mrem/yr.

To arrive at an estimate of the gonadal DE, the influence of housing, biological shielding, and the DE contribution from internal emitters was also considered. The first two factors serve to attenuate man's gonadal DE due to terrestrial radiation by about the same amount that is contributed by internal emitters. The average gonadal DE to the U.S. population was calculated to be 88 mrem/yr.

NATURAL RADIATION EXPOSURE IN THE UNITED STATES [1]

Donald T. Oakley [2]

CHAPTER 1. INTRODUCTION

1.1. General

The largest source of ironizing radiation exposure to the world's population is from the natural radiation environment. This exposure is by no means uniform for all individuals, but varies because of a number of important factors: altitudes, geological features, and living habits of man himself. Variations in exposures as a result of these factors often exceed exposures from sources which have received considerably more attention. According to the existing literature, the genetically significant dose equivalent (DE) from natural radiation in the United States ranges from 80 to 200 mrem/yr. The average individual living in the United States in 1964 received an x-ray exposure DE of 55 mrem/yr. (U.S. Public Health Service, 1969). Other sources, such as nuclear reactors, fallout, etc., account for less than 5 mrem/yr. Within this perspective, the purposes of this study are to better estimate man's exposure to natural sources of radiation, to investigate the variations that occur, and to examine the parameters that influence both the levels and the variations so that the relative importance of manmade exposures may be evaluated.

It is frequently stated that man has endured and thrived in his natural environment. Thus this source of exposure has not received the attention which has been accorded to sources of less magnitude and ubiquity. However, in order to determine the significance of the effects of small manmade increments of exposure, it is necessary to determine the larger component due to natural radiation. Examples of studies which have shown no correlation of background radiation with health are Grahn and Kratchman (1963) and Segal et al. (1964). Although studies performed by Wesley (1960) and Gentry et al. (1959) show a variation in congenital malformations with background radiation, a recent review of the literature by Sagan (1971) casts doubt upon this relationship. Background radiation exposure is less well defined than smaller sources of exposure, and thus may contribute to the deleterious effects of radiation which are speculated to be associated with fallout, nuclear reactors, and x radiation.

1.2. Estimates of Natural Radiation Exposure

Measurements of natural radiation background have been performed worldwide; within the United States, measurements tend to fall into three categories. First, there are single measurements which have been made at widely varying locations. The locations may have been chosen on the basis of convenience to laboratory facilities, interest in the radioactivity of various geological formations, or interest in determining the presence of nuclear weapons fallout. The most extensive measurements of this type in the United States have been reported by the Health and

---

[1] A thesis submitted to the Faculty of the Harvard School of Public Health in partial fulfillment of the requirements for the degree of Doctor of Science in the field of Environmental Health Services.

[2] Dr. Donald T. Oakley is Deputy Director of the Surveillance and Inspection Branch, Office of Radiation Programs, Environmental Protection Agency, Rockville, Maryland.

Safety Laboratory, U.S. Atomic Energy Commission (AEC) (Beck et al., 1964ab; 1966ab). The second category of measurements has resulted from special studies, which have been conducted primarily for the purpose of estimating background radiation exposure to the population. Examples of this work include studies in New England by Segall (1963) and Lowder and Condon (1965), and measurements in 24 States by Levin et al. (1968). The third category consists of aerial surveys which have been performed by AEC and its contractors around nuclear installations within the United States.

In several other countries, surveys have been performed on a countrywide basis for the purpose of estimating the population exposure to natural radiation (table 1). The investigators have employed different techniques and instrumentation so that a direct comparison cannot be made. However, even if we consider these factors and the differing emphasis on measurements (open field vs. paved areas, indoors vs. outdoors), there is reasonable agreement among the estimates.

Measurements obtained in the United States will be presented in the following chapters, and it will be seen that they are similar to measurements obtained in other countries (table 1). It should be noted that the measurements by Hultqvist (1956), Herbst (1964), and Ohlsen (1969) were made with either ion chambers or portable scintillation detectors, and therefore the measurements include the contribution of nuclear weapons fallout to the total DE. The measurements by Herbst, which were made during 1957 to 1959 and in 1961, respectively, are probably most in error on this account, since fallout contributed as much as 30 percent to the total external DE rate during these periods.

1.3. Sources of Natural Radiation Exposure

Exposure to external natural radiation sources occurs through cosmic radiation and radioactive elements in the earth's crust and in building materials. An additional increment of external exposure, which accounts for less than 5 percent of the total, is due to the presence of radioactive decay products of radon and thoron in the atmosphere.

The natural radiation environment has been relatively constant since at least the beginning of the Neolithic Age (10,000 B.C.) and probably for much longer. The most recent reversal of the earth's magnetic field occurred 700,000 years ago, and at that time the cosmic ray intensity may have increased by 10 percent in equatorial regions of the earth for approximately 1,000 years (Black, 1967). With the exception of short-term variations in cosmic ray intensity, there is nothing in the literature to indicate the occurrence of significant changes in natural radiation sources since the most recent magnetic field reversal.

Although the intensity of natural radiation sources has remained constant in recent times, man's living habits have changed in such a way

Table 1. Estimates of dose equivalent due to terrestrial and cosmic radiation in several countries

Reference	Country	Dose equivalent (mean) (mrem/yr.)	Remarks
Hultqvist, 1956	Sweden	77 wood dwellings 130 brick 197 concrete	Measurements at centers of rooms in 986 apartments, 677 houses (all indoors); author's values of ion pairs/ cm^3-sec. converted to mrem/yr., assuming 1 ion pair/ cm^3-sec. = 1.65 μrem/hr.
Herbst, 1964	Switzerland	122	Estimate weighted by distributions of population over geological regions and indoor/outdoor occupancy
Yamagata and Iwashima, 1967	Japan	87	Soil analyses for potassium, uranium, and thorium at 230 locations; mean terrestrial DE = 47 mrem/yr.; if cosmic DE = 40 mrem/yr., total = 87 mrem/yr.
Ohlsen, 1969	E. Germany	91	1,005 measurements outdoors, 667 measurements indoors; estimate is weighted by time spent indoors and outdoors
Weng and Huang, 1970	Taiwan	112	Average of measurements at 26 outdoor locations = 72 mrem/yr. (terrestrial sources only); if cosmic ray DE is assumed to be 40 mrem/yr., total = 112 mrem/yr.

as to influence his exposure. Populations have tended to migrate from coastal to inland areas, thus increasing their elevation and exposure to cosmic radiation. At the same time, the outdoor agrarian society has largely been replaced by indoor work and life in urban centers. Man's exposure has thus been increased in some instances because of the natural radioactivity of building materials; in other instances, buildings attenuate exposure to the outdoor terrestrial sources, resulting in lower exposure.

Although this dissertation is primarily concerned with external radiation sources, it is important to note that additional increments of DE result from ingestion and inhalation of natural radionuclides. Potassium-40 is the principal contributor of internal DE; other significant internal emitters are radium-226 and -228 and their daughter products, carbon-14 and radon-222 (UNSCEAR, 1962). Gonadal exposure to external radiation is about five times greater than that from internal sources, and the ratio is similar for exposure to the bone marrow. With regard to natural internal radioactivity, Cherry et al. (1970) have recently shown that man has relatively low concentrations as compared to other mammals, fish, and birds. In fact, in a comparison of total alpha activity in the bones of 18 different mammals, only the pig ranked lower than man. From their analysis of herbivore bones and marine livers, Cherry et al. predict DE in excess of 1,000 mrem/yr. to these organs, of which 90 percent or more is due to internal alpha emitters.

The retention of inhaled radioactive daughter products of radon and thoron is the primary source of lung DE to the general population. Although the inhalation of radon daughters has been given special attention in the case of uranium miners (Federal Radiation Council, 1967), exposure to occupants of residential dwellings can also be significant. Hultqvist (1956) calculated a potential average lung dose of 205 mrem/yr. to occupants of unventilated wood dwellings and 1,780 millirem/yr. to occupants of unventilated concrete buildings. More recently, Yeates et al. (1971) have found that first-floor occupants of frame dwellings may receive a lung DE of 150 mrad/yr. from alpha emitters. If a quality factor of 10 is assumed, then the DE is 1,500 mrem/yr.

1.4. Methodology

One of the primary objectives of this study was to estimate the external natural radiation exposure to the population of the United States. To do so, existing data on terrestrial and cosmic radiation measurements were considered in light of population distribution and living habits. Many measurements made for other purposes contribute information on man's exposure to radiation from natural sources. For example, much of the existing data on cosmic radiation exposure has resulted from interest in high-energy particle reactions or from studies of cosmic ray variation.

External exposure to terrestrial radiation sources may be estimated by direct measurement or calculated from chemical assays of natural emitters in soil. Ground analyses and soil analyses, however, have not been sufficiently extensive to make an overall estimate of exposure in the United States. For this reason, the estimate of exposure due to terrestrial sources in this study relies principally on data from aerial surveys. The aerial surveys, which were previously mentioned, have been made over areas across the United States and all together cover land areas occupied by approximately 30 percent of the U.S. population.

A combined estimate of the total cosmic ray and terrestrial DE was then made in this study on the basis of what is known concerning the distribution of the population by elevation, geology, and living habits.

Units of radioactivity have perplexed practicing health physicists and those recommending units since the discovery of ionizing radiation. As a result, it is common to find units of roentgens, rads, and rems used to describe the same thing in radiation protection literature. Fortunately, the three entities are approximately equal in the case of ionizing radiation from external natural background sources, and therefore the unit of DE, the rem, is used throughout for the sake of uniformity. A full description of dosimetric terms may be found in Cember (1969) and the recommendations of the International Commission on Radiation Units and Measurements (ICRU) (1971).

CHAPTER 2. COSMIC RADIATION

2.1. Introduction

Cosmic radiation is composed primarily of galactic radiation and a varying component of solar radiation. Galactic radiation originates outside of our own solar system, and, as the name implies, solar radiation results from phenomena on the sun.

2.1.1. Galactic radiation

The primary component of galactic radiation, as it impinges on the earth's atmosphere, is estimated to be 75 to 89 percent protons, 10 to 18 percent helium nuclei, and 1 to 7 percent nuclei with $Z \geqq 3$ (UNSCEAR, 1966; Neher, 1967). The energy range is thought to extend beyond 10^{19} eV, and the average energy flux arriving at the top of the atmosphere is 2×10^3 MeV/cm²-sec. (Korff, 1964). In addition to heavy particulate radiation, electrons and x rays have also been detected in primary cosmic radiation.

Primary cosmic ray interactions with the atmosphere result in an ionizing component of cosmic radiation in the lower atmosphere, primarily muons and electrons, and a minor neutron component. The process of formation is shown schematically in figure 1. Of most significance to population exposure is the formation of muons, which are generally assumed to account for approximately 70 percent of the cosmic ray dose at sea level (Lowder and Beck, 1966).

2.1.2. Solar radiation

Particulate solar radiation is comprised almost entirely of bursts of protons and helium nuclei with energies ranging up to several GeV. The proton bursts, or flares, follow approximately 6 percent of the observed sunspots, and about 3 percent of all flares belong to class 3 (the largest) (Langham, 1967). As will be discussed later, the relatively low energy of the solar particles precludes their secondary radiations from reaching the earth's surface in all but the largest flares.

2.2. Cosmic Ray Variation

The factors which contribute to cosmic radiation variations are extensively reviewed in books by Rossi (1964), Sandstrom (1965), and Hayakawa (1969). A brief summary of the present knowledge of cosmic ray variations is presented here in order to justify the dose estimation procedures which follow. In addition, knowledge of the many variations which exist is helpful in understanding rather large differences in the reported measurements.

2.2.1. Time variations

The temporal variation of cosmic radiation has been observed for approximately 35 years, commencing with the work of Forbush (1938). At that time, Forbush reported the effect of the "seasonal wave" on cosmic ray magnitude and speculated upon the possibility of the influence of the solar cycle on cosmic ray intensity. Research thus far indicates that most variations in ground-level cosmic ray intensity are attributable to solar influence on the interplanetary magnetic field (Forbush, 1954, 1958; Kuzmin and Skripin, 1966a; Pal, 1967). In general, where variations are attributed to solar influence, the ionization intensity on earth is inversely correlated with solar activity.

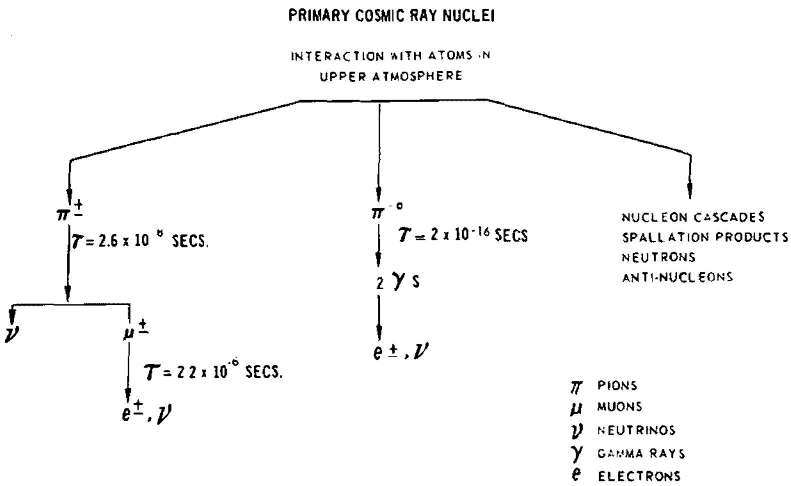

Figure 1. Formation of cosmic ray secondary products

Variations in cosmic radiation have been observed to occur in cycles of 11 years, 1 year, 27 days, and 1 day, and Neher (1971) has recently reviewed the evidence for a cycle which persists for several 11-year periods. As a result of these variations, the intensity of sea-level ionization at a given location may vary by approximately 10 percent. Based on the consideration of cosmic ray-induced radionuclides on the earth and in meteorites, Hayakawa (1969) asserts that average cosmic ray levels have remained relatively constant for at least 10^8 years. Maximum levels probably existed during the reversals of the magnetic field, the most recent of which occurred 700,000 years ago, when an increase of 10 percent may have occurred (Black, 1967).

Solar flares occur more frequently during the solar maximum period of the 11-year cycle, and therefore flares are also considered here as a temporal variation. Although the hazards to space travelers during this period are potentially great (Upton, 1966; Langham, 1967; Haffner, 1967), the magnetic field of the earth and the shielding properties of the atmosphere result in little perturbation of the sea-level intensity during a flare.

According to Haffner (1967), eleven "3+" solar flares (the largest) occurred during the 1958 to 1961 period of maximum solar activity. The ground effect of a 3+ flare is shown in figure 2. Although other flares have had a more pronounced temporary effect on neutron levels, the lack of significant influence on the ion chamber measurement is typical. Following an initial rise in neutron and muon counting rates, the levels are observed to decrease below the preflare values.

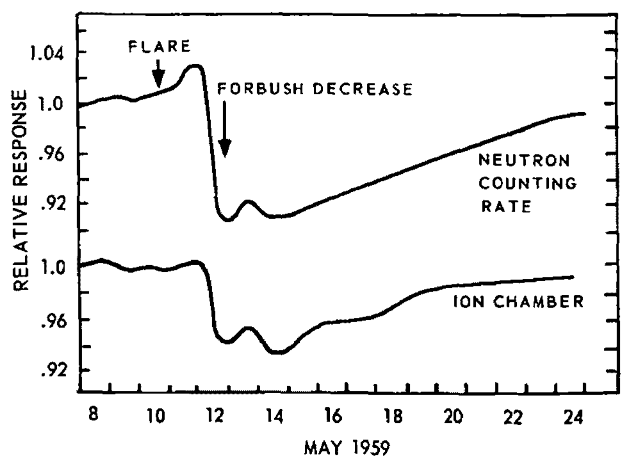

Figure 2. Cosmic ray ground level measurements during a 3+ flare, Yakutsk, U.S.S.R., 51° geomagnetic latitude (Kuzmin and Skripin, 1966b)

The phenomenon is known as the Forbush decrease, and is due to the fact that flares are followed by magnetic disturbances which reduce the low energy galactic radiation component.

2.2.2. Latitude variation

Of the factors which influence cosmic ray ionization at the earth's surface, the latitude effect was the first to be well described. This effect results from the earth's geomagnetic field, which approximates a dipole located 215 miles from the earth's center with the poles at 79° N., 69° W. (northwest Greenland) and 76° S., 121° E. (Antarctica) (UNSCEAR, 1966; Pal, 1967). The magnetic field serves to cut off incident low energy cosmic particles, and the screening effect is larger in the lower latitudes in both hemispheres.

Millikan et al. (1936a), through a worldwide survey, observed the cosmic ray variation at sea level due to the latitude effect: his results are summarized in figure 3. As shown in this figure, the ionizing component of cosmic radiation varies by about 2 percent throughout contiguous U.S. latitudes, which range from 36° to 58° N. geomagnetic. Extensive reviews of later work have been presented by Lowder and Solon (1956), Hultqvist (1956), and UNSCEAR (1962, 1966). More recent work (Raft et al., 1970; George, 1970) indicated a slight decrease in cosmic ray ionization commencing around 50° geomagnetic latitude (a line through Washington, D.C., and

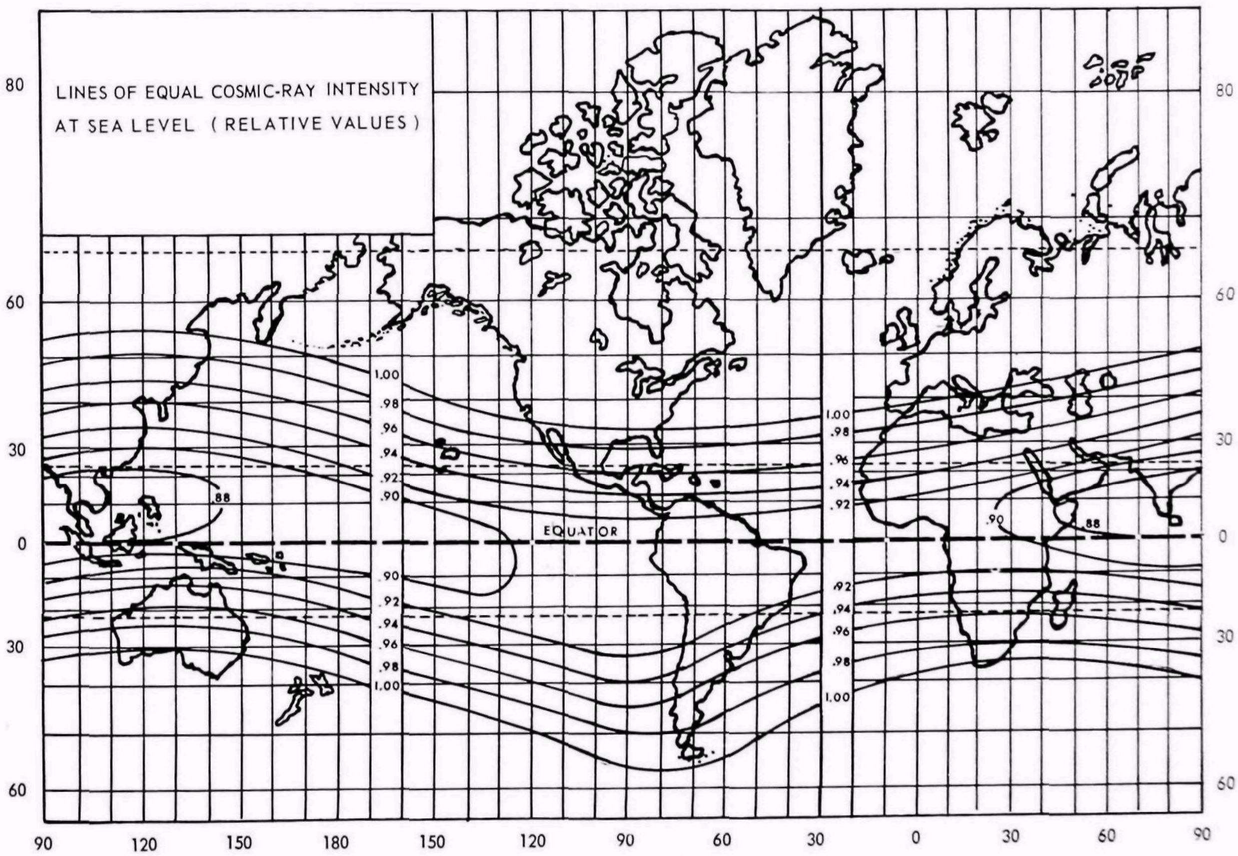

Figure 3. Variation of cosmic radiation with latitude (Millikan et al., 1936a)

central Oregon). However, it still appears that the influence of latitude on cosmic radiation exposure within the United States is negligible in terms of population exposure.

Neutron flux varies by approximately 30 percent between the poles and the equator and by 15 percent within the range of latitudes covered by United States (UNSCEAR, 1966). However, since neutrons account for a small fraction of the total cosmic ray exposure, the variation of DE with latitude in the United States is insignificant. Furthermore, in a comparison of cosmic ray measurements in section 2.3, it will be seen that uncertainties in the various measurements tend to obscure all variations except the increase of exposure with elevation, and, for purposes of dose estimation in the present study, the latitude variation in the United States will be neglected.

2.2.3. Altitude variation

The atmosphere attenuates the cosmic ray flux; the attenuation of the secondary particles is varied so the relative DE contribution from different particles changes as the atmospheric depth increases. As a general view of cosmic ray DE variation with altitude, a summary of O'Brien and McLaughlin's (1970) calculations is presented in figure 4. In their work, O'Brien and McLaughlin have shown that the calculated values agree well with measured ionization values throughout most of the atmosphere.

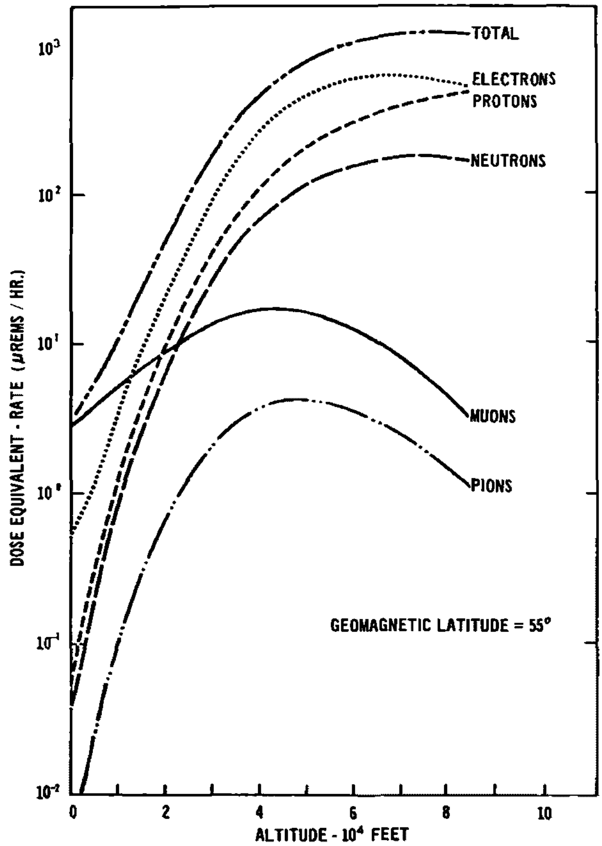

Figure 4. Cosmic ray dose equivalent rate variation with altitude (O'Brien and McLaughlin, 1970)

The ionizing component of cosmic radiation in the lower atmosphere has been measured by workers at the California Institute of Technology (Bowen et al., 1934; Millikan et al., 1936b; and George, 1970) and the AEC Health and Safety Laboratory (Solon et al., 1960; Lowder and Beck, 1966; and Raft et al., 1970). The ionization profiles (ionization vs. elevation) up to 15,000 feet as obtained by each investigator have approximately the same shape, the primary difference being in the absolute values. The profile determined by Lowder and Beck (1966) is representative of the existing information and is used to obtain the DE variation with elevation.

The neutron contribution to the cosmic radiation DE is approximately 15 percent of the total and will be discussed further in the next section. Neutron density in the atmosphere varies exponentially with pressure with an e-folding thickness of 165 g/cm^2, or a half thickness of 114 g/cm^2 (Patterson et al., 1959; Miles, 1964). The constant slope in the lower atmosphere indicates that the neutron spectrum does not change over the same range, and therefore in this report the neutron DE is assumed to vary as the neutron density.

Closely related to altitude variation is the variation of cosmic radiation with barometric pressure at a fixed elevation; Shamos and Liboff (1966), in addition to their own work, have reviewed the findings in 21 investigations concerned with this effect. The "hard component" (primarily muons) varies by about 0.17%/torr, and the "soft component" has been estimated to vary by about 0.93%/torr. The overall variation is 0.3 to 0.4%/torr. For purposes of long-term estimation, the variation is not important. However, since the barometric pressure may vary by about 3 percent from day to day, it represents a potential source of error in correcting and comparing different measurements.

2.3. Cosmic Ray Measurements

2.3.1. Ionizing component

The measurement of the ionizing component of cosmic radiation is generally expressed as ion pairs/cm³-sec. (commonly expressed as "I"), and corrected to the sea-level value at 760 torr and 0° C., although not all authors mention a temperature and pressure correction. One I corresponds to a value of 1.65 μrem/hr. This ratio has been used to convert all measurements to the same units.

Summarized in figure 5 and table 2 are measurements of the sea-level intensity that have been made by various investigators over a period of 40 years. As can be seen, there has been a considerable spread in the reported values, which is remarkable even in view of the natural variations that have been cited. Even the most recent measurements which have been reported differ by 30 to 40 percent. Shamos and Liboff (1966), Lowder and Beck (1966), and George (1970) have attempted to explain the differences through ion chamber construction, calibration, alpha contamination of the measuring chamber, and radon daughters in the atmosphere (the latter two factors may contribute up to 15 to 20 percent of the measured cosmic ray dose). However, differences still remain, and, in view of the numerous corrections which must be made to compare measurements at different locations, it appears that the

Table 2. Summary of sea-level ionization due to cosmic radiation at U.S. latitudes

Reference	Ionization (ion pairs/cm³-sec.)
Hultqvist (1956)	[a] 2.06
Solon et al. (1960)	2.52
Kastner et al. (1963)	2.78
Shamos and Liboff (1966)	2.18
Lowder and Beck (1966)	2.10
Ohlsen (1969)	2.18
George (1970)	2.60
O'Brien and McLaughlin (1970)	2.20
Yeates (1970)	2.89
Average of 20 values	2.22
Average of post-1956 values	2.44

[a] Average of 12 values from previous investigations.

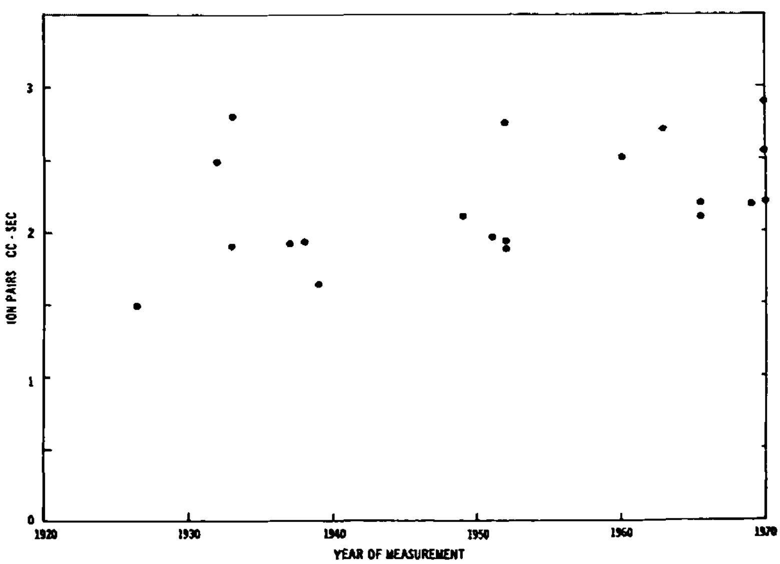

Figure 5. Summary of sea-level ionization due to cosmic radiation

differences will not be resolved soon. For the purpose of DE estimation in the present work, a value of 2.44 I has been assumed for the average cosmic ray ionization at sea level in the United States. This is the average of eight reported values since 1960 and is equivalent to 4.0 μrem/hr., or 35.3 mrem/yr. The value used in this study, 35.3 mrem/yr., compares reasonably well with the most recent reported UNSCEAR (1966) value of 28 mrem/yr.

2.3.2. Neutron component

Several factors have contributed to relatively poorer knowledge of the neutron DE rate at sea level as compared to the ionizing DE rate. First, the neutron flux in the atmosphere is more sensitive to the time, latitude, and altitude variations which have been described. Since the neutron DE rate has been measured over a relatively shorter time and by fewer investigators, the intercomparison of different work is complicated by the greater natural variations. In addition, inconsistencies exist in reporting results so that it is common to find data reported either in dose or DE units.

UNSCEAR (1966) reviewed the neutron measurements through 1965 and, based upon a reported range of 0.3 to 1.1 mrad/yr., concluded that 0.7 mrad/yr. should be taken as the typical sea-level value at middle latitudes. The International Commission on Radiological Protection (ICRP) (Upton, 1966), in reviewing cosmic radiation hazards to supersonic jet passengers and crew, has assumed a sea-level value of 4.3×10^{-2} μrad/hr. (0.38 mrad/yr.) and a quality factor of 8, which corresponds to 3.0 mrem/yr. Watt (1967) has calculated a value of 6.8 mrem/yr. O'Brien and McLaughlin (1970), in addition to reviewing the discrepancies which presently exist in the neutron data, have calculated a value of ~0.33 mrem/yr. A quality factor of 3 may also be inferred from their data. A summary of the preceding information is presented in table 3. For the purpose of dose estimation in the present study, the recommendations of UNSCEAR (1966) and Upton et al. (1966) have been followed by using the values of 0.7 mrad/yr. and QF = 8, respectively.

The cosmic radiation dose rates to be used in this study are summarized in table 4. Based upon the adopted sea-level values and ionization profile of Lowder and Beck (1966), the DE rates at altitudes up to 15,000 feet have been plotted in figure 6. Estimates of cosmic radiation DE at

Table 3. Cosmic ray neutron dose equivalent at sea level

Reference	Dose equivalent (mrem/yr.)
UNSCEAR (1966)	[a] 5.6
Upton et al. (1966)	[a] 3.0
Watt (1967)	6.8
O'Brien and McLaughlin (1970)	0.33
Hajnal et al. (1971)	3.3
This report	5.6

[a] Based on dose values presented by UNSCEAR (1966) and QF = 8.

Table 4. Cosmic radiation dose equivalent at sea level

Source	μrem/hr.	mrem/yr.
Ionizing component	4.0	35.3
Neutrons	0.64	5.6
Total	4.6	40.9

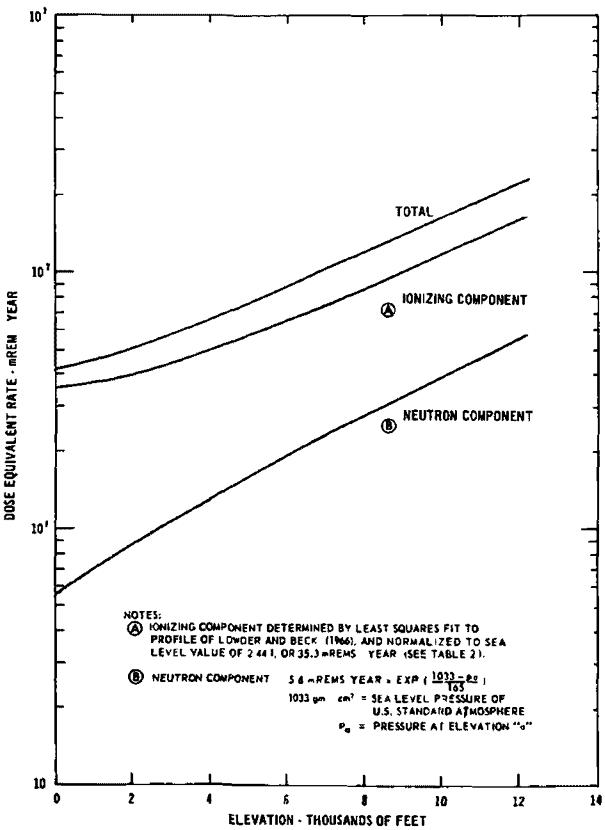

Figure 6. Cosmic ray dose equivalent vs. elevation

different elevations were made using data from this figure.

2.4. Population Distribution

The population of the United States was distributed in 1960 as shown in figure 7, which is adapted from the U.S. Census Bureau (1963). Through use of the population distribution map and a U.S. Geological Survey topographic map (Gannett, 1916), the population of the United States was found to be distributed by elevation as presented in table 5. The mean populated elevation of each State was computed by averaging the population of urbanized areas, for which an approximate elevation was available (Rand McNally, 1971; Gannett, 1906), and the population

Table 5. Distribution of the U.S. population vs. elevation (1960)

Elevation interval (10^3 feet)	Population	Cumulative percent
0–0.5	86,629,494	48.3
0.5–1	63,007,720	83.4
1–2	19,746,062	94.5
2–4	5,298,236	97.4
4–6	3,938,663	99.6
6–8	618,000	99.9
8–10	71,000	100.0
>10	14,000	100.0
Total	179,323,175	

of the nonurbanized areas. The mean elevation of the nonurbanized population was computed by weighting the population in each elevation segment by the segment midpoint. Thus, the mean populated elevation (feet) of the nonurbanized area of state =

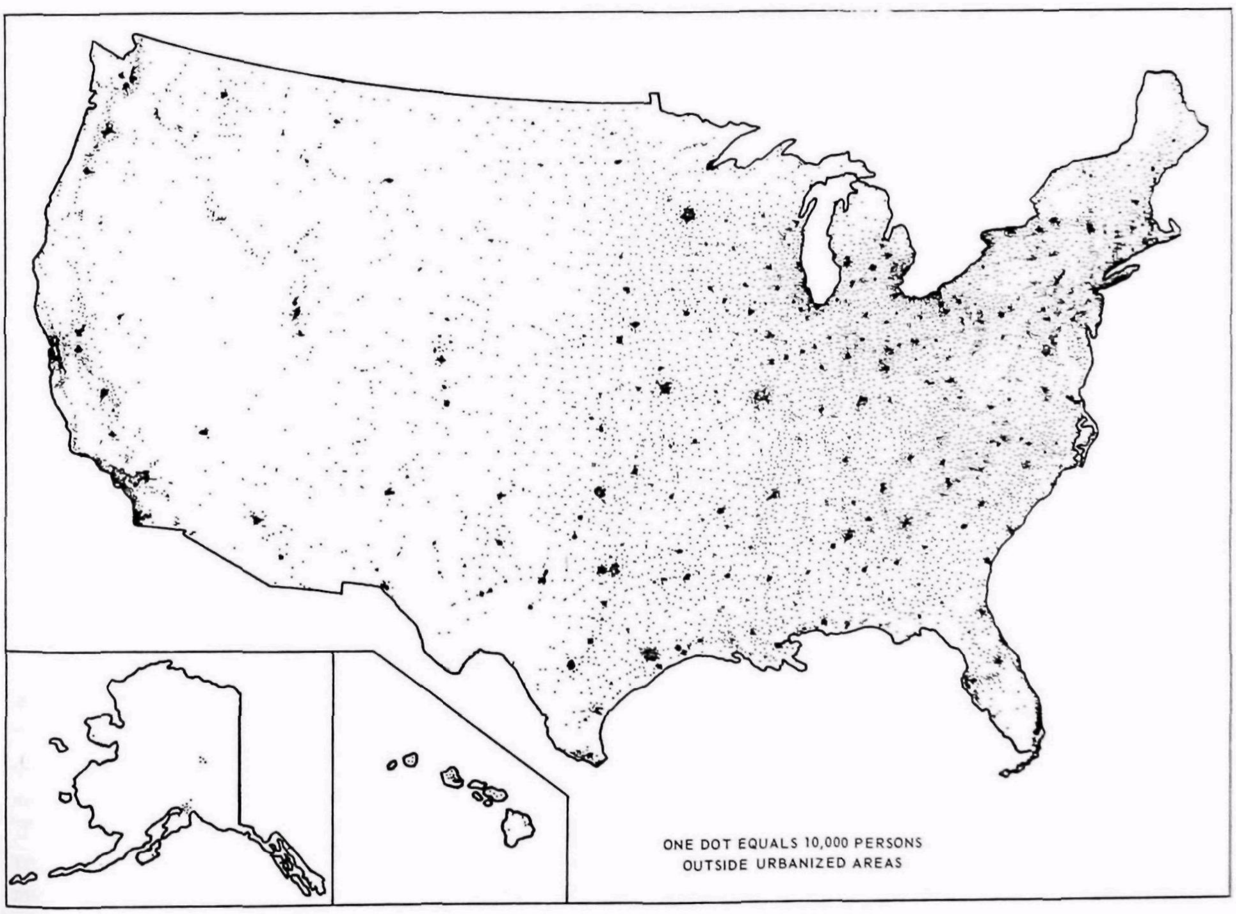

Figure 7. Population distribution, 1960

$$\frac{\begin{pmatrix}\text{No. living at}\\ \text{0 to 500 feet}\end{pmatrix}\times 250+\begin{pmatrix}\text{No. living at}\\ \text{500 to 1,000 feet}\end{pmatrix}\times 750\ldots}{\text{Nonurbanized population of State}}$$

Three exceptions to this procedure were required. First, the population of Hawaii was assumed to be distributed 95 percent in the 0 to 500-foot interval and 5 percent in the 500 to 1,000-foot interval, since the scale of the U.S. Census Bureau map did not justify a comparison with topographic data. Secondly, several low-lying States on the Atlantic and Gulf Coasts have mean elevations less than 250 feet based on geography alone. In these States, which are Delaware, Florida, Louisiana, and Rhode Island, Gannett's (1894) estimates of mean elevations were used (60, 100, 100, 200 feet, respectively) for the nonurbanized population. Thirdly, it becomes necessary later in this report to divide certain States into Coastal Plain and non-Coastal Plain regions. The Coastal Plain regions (to be specified later) are also low-lying areas and have been assigned mean elevations based on a comparison of population distribution and topographic data for the respective regions.

The estimates of mean populated elevations have been used in conjunction with values obtained from figure 6 in order to estimate the cosmic ray DE in the United States, and this information is summarized in figure 8. As can be seen, the DE is relatively uniform in the eastern half of the country but increases in areas of higher elevation in the west. The populations of Alaska and Hawaii, which are not shown, were also calculated as receiving between 40 and 50 mrem/yr.

It is interesting to note that a small area on the east side of the Rocky Mountains, in the vicinity of Leadville, Colorado, includes all of the populated communities in the United States which are at elevations greater than 10,000 feet. These communities are between 10,000 and 10,500 feet; this elevation corresponds to a cosmic ray DE of 160 mrem/yr., or approximately four times the sea-level DE. Additional calculations are presented in chapter 4, where the contribution from terrestrial and other sources will also be discussed.

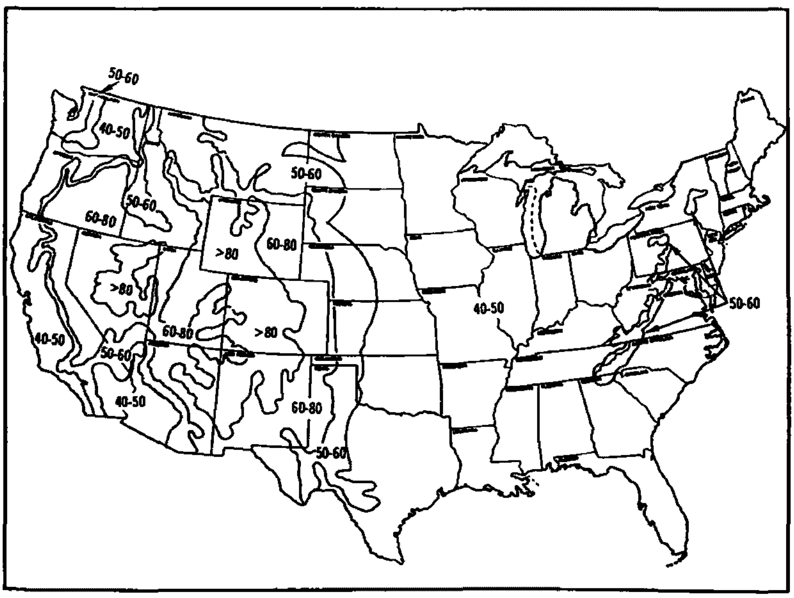

Figure 8. Dose equivalent from cosmic radiation (mrem/yr.)

CHAPTER 3. TERRESTRIAL RADIATION EXPOSURE

In the preceding chapter, the factors which affect exposure to cosmic radiation have been discussed. In this chapter, the same approach will be taken to discuss man's exposure to natural terrestrial sources of radiation.

3.1. Sources

Naturally occurring radionuclides contribute significantly to man's external exposure. In most of the United States, the magnitude of terrestrial radiation exposure is relatively uniform and is similar to that due to cosmic radiation. As far as is known, there are no terrestrial areas in the United States which yield DE rates comparable to the high radiation levels 10 to 100 times greater than "normal") which have been observed in other parts of the world, notably a few populated areas of Brazil and India (UNSCEAR, 1962).

The nuclides which contribute to man's natural exposure have been extensively reviewed elsewhere (Lowder and Solon, 1956; UNSCEAR, 1962). From the standpoint of man's exposure, only potassium-40 and the radioactive decay chains of uranium-238 and thorium-232 are significant. In addition to these nuclides, Lowder and Solon (1956) summarized physical data for 21 nuclides which exist or are hypothesized to exist; however, long half-lives and low abundances account for their insignificant DE to man. The presence of cosmic ray neutrons insures that capture reactions do occur in soil at the earth's surface and in the atmosphere, thus resulting in the probable occurrence of many additional radioactive nuclides. The production of carbon-14 and tritium are two well-known examples of this process; however, the DE due to cosmic ray-induced nuclides is insignificant.

Potassium-40 occurs as one of three potassium isotopes. The two most abundant isotopes, potassium-39 (93.1 percent) and potassium-41 (6.9 percent), are stable, whereas potassium-40 (0.0118 percent) decays with a half life of 1.25×10^9 years. A 1.46 MeV gamma ray is emitted in 11 percent of the disintegrations, and this gamma ray is the source of terrestrial DE from the nuclide.

Thorium-232 and uranium-238 decay chains are shown in tables 6a and 6b. Uranium-235 is the parent element of a third decay chain; however, as can be seen from table 7, the energy released from radioactive decay from this chain is insignificant in comparison to the uranium-238 and thorium-232 chains. Although the nuclide composition of the rock in table 7 differs slightly from estimates which will be presented later, it is clear that uranium-238, thorium-232, and potassium-40 may be assumed to account for practically all of man's terrestrial radiation exposure.

As in the case of cosmic radiation, terrestrial sources have been studied primarily for purposes other than interest in population exposure to background radiation. For example, measurements made early in this century were concerned with geologic dating and heat generation due to radioactive decay. Since the 1940's, however, most of the literature concerning uranium and thorium has resulted from an economic interest in the two elements. Within the past 15 years, additional data have been reported which relate directly to man's exposure to terrestrial sources.

Table 6a. Uranium-238 decay chain—uranium series (4n + 2)*
(Courtesy Radiological Health Handbook, Revised January 1970)

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities† α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^9y	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}Th$	Uranium X_1	24.1d	---	0.103 (21%) 0.193 (79%)	0.063c‡ (3.5%) 0.093c (4%)
$^{234}_{91}Pa^m$ 99.87% / 0.13%	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
$^{234}_{91}Pa$	Uranium Z	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}U$	Uranium II	2.47×10^5y	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^4y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}Po$ 99.98% / 0.02%	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
$^{214}_{82}Pb$	Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$	Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{83}Bi$ 99.98% / 0.02%	Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{84}Po$	Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
$^{210}_{81}Tl$	Radium C"	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21y	3.72 (.0000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$ ~100% / .00013%	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
$^{210}_{84}Po$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E"	4.19m	---	1.571 (100%)	---
$^{206}_{82}Pb$	Radium G	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{206}_{82}Pb$ (4n + 2)......4(51) + 2 = 206
†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.
‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.
Data taken from: Table of Isotopes and USNRDL-TR-802.

Table 6b. Thorium-232 decay chain—thorium series (4n)*
(Courtesy Radiological Health Handbook, Revised January 1970)

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{232}_{90}Th$	Thorium	1.41×10^{10}y	3.95 (24%) 4.01 (76%)	---	---
$^{228}_{88}Ra$	Mesothorium I	6.7y	---	0.055 (100%)	---
$^{228}_{89}Ac$	Mesothorium II	6.13h	---	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34c‡ (15%) 0.908 (25%) 0.96c (20%)
$^{228}_{90}Th$	Radiothorium	1.910y	5.34 (28%) 5.43 (71%)	---	0.084 (1.6%) 0.214 (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64d	5.45 (6%) 5.68 (94%)	---	0.241 (3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55s	6.29 (100%)	---	0.55 (0.07%)
$^{216}_{84}Po$	Thorium A	0.15s	6.78 (100%)	---	---
$^{212}_{82}Pb$	Thorium B	10.64h	---	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
$^{212}_{83}Bi$ (64.0% → $^{212}_{84}Po$; 36.0% → $^{208}_{81}Tl$)	Thorium C	60.6m	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
$^{212}_{84}Po$	Thorium C'	304ns	8.78 (100%)	---	---
$^{208}_{81}Tl$	Thorium C"	3.10m	---	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
$^{208}_{82}Pb$	Thorium D	Stable	---	---	---

*This expression describes the mass number of any member in this series, where n is an integer.
Example: $^{232}_{90}Th$ (4n)......4(58) = 232

†Intensities refer to percentage of disintegrations of the nuclide itself, not to original parent of series.

‡Complex energy peak which would be incompletely resolved by instruments of moderately low resolving power such as scintillators.

Data taken from: Lederer, C. M., Hollander, J. M., and Perlman, I., Table of Isotopes (6th ed.; New York: John Wiley & Sons, Inc., 1967) and Hogan, O. H., Zigman, P. E., and Mackin, J. L., Beta Spectra (USNRDL-TR-802 [Washington, D.C.: U.S. Atomic Energy Commission, 1964]).

Table 7. Gamma-ray energy released by 1 gram of rock (lithosphere) Kogan et al. (1971)

Isotope	Average concentration, percent	Energy (MeV/ sec.×10^{-3})
Uranium-238 (in equilibrium with decay products)	2.98×10^{-4}	6.82
Uranium-235 (in equilibrium with decay products)	0.02×10^{-4}	0.153
Thorium-232 (in equilibrium with decay products)	11.4×10^{-4}	8.78
Potassium-40	3.0	11.4
Other elements	–	.27

Gentry et al. (1959) and Grahn and Kratchman (1963), in investigations of fetal malformation, estimated population exposure from data on local geology and uranium reserves, but made no measurements. Segall (1963) conducted a later study concerned with health effects of background radiation, and, in support of the study, Billings (1961) prepared a radioactivity map ("isorad map") of Vermont, New Hampshire, and Maine, based upon chemical analysis of bedrock. At about this time, portable multichannel gamma-ray spectrometers were developed, and these instruments allowed field determinations of the amounts of potassium-40, uranium-238, and thorium-232 present in the soil. Data reported by Beck et al. (1964a, 1964b, 1966a) are representative of this technique.

Extensive literature reviews exist concerning the distribution and abundance of the naturally occurring radioactive elements in the earth's crust (Adams et al., 1959; Peterman, 1963; Clark et al., 1966; Finch, 1967; Overstreet, 1967; Wedepohl, 1969). The purpose of the following text is not to duplicate this information, but rather to present sufficient data from these sources to permit an understanding of variations which exist in measurements of background radiation.

The earth's crust is composed of igneous, metamorphic, and sedimentary rocks; the first two classifications account for approximately 90 percent of the mass of the crust. Sedimentary rocks accumulate at the top of the crust, however, and thus Jackson (1964) estimates that sedimentary rocks cover about 75 percent of the earth's land area.

Based on an analysis of the geology map, U.S. Geological Survey (1971), sedimentary rocks cover approximately 85 percent of the contiguous U.S. land area, and are distributed by geologic age as shown in table 8. Sedimentary rocks may be classified as shale, sandstone, or limestone, which have a relative abundance in the ratio of 3:1:1. Since the metamorphic and igneous rocks of table 8 are concentrated in sparsely inhabited mountainous areas, it can be assumed that the U.S. population lives almost entirely over rocks of sedimentary origin.

Table 8. Types of bedrock in the contiguous United States

Geologic period	Type	Percent of land area	
Quaternary		6.5	
Upper Tertiary		13.8	
Lower Tertiary		9.6	
Cretaceous		17.9	
Jurassic and Triassic	Sedimentary	3.4	85.1
Upper Paleozoic		19.3	
Mid Paleozoic		5.4	
Lower Paleozoic		5.9	
Younger Precambrian		3.3	
Old Precambrian	Metamorphic and igneous	4.4	
Quarternary and Tertiary	Volcanic—igneous	7.7	
Lower Tertiary, Mesozoic, Paleozoic	Intrusive—igneous	2.8	
Total		100.0	

Table 9 presents the average amounts of uranium, thorium, and potassium-40 in common rocks, soil, and the earth's upper crust. It can be seen from the crustal average that potassium-40 and the thorium-232 decay chain each contribute approximately 40 percent of the dose rate at three feet above the ground, and the uranium-238 decay chain contributes approximately 20 percent of the total. The uranium-238 decay chain includes the gas radon-222, which can diffuse through the soil and into the atmosphere. The diffusion reduces the equilibrium concentration of radon-222 daughters in the soil, thereby reducing the DE contribution from the uranium-238 series by as much as 50 percent (Beck and de Planque, 1968). The thorium-232 decay chain also includes a gas,

Table 9. Radionuclide content and dose equivalent rates from common rocks and soil

Rock	ppm	Uranium (mrem/yr.) [a]	ppm	Thorium (mrem/yr.) [a]	ppm	Potassium-40 (mrem/yr.) [a]	Total (mrem/yr.) [a]
Igneous [b]							
Basic	0.9	5.2	2.7	7.3	1.2	14.7	27.2
Silicic (granite)	4.7	26.9	20.0	53.8	5.0	61.3	142.0
Sedimentary [b]							
Shale	3.7	21.2	12.0	32.3	3.2	39.2	92.7
Sandstone	.45	2.6	1.7	4.6	1.1	13.5	20.7
Limestone	2.2	12.6	1.7	4.6	0.32	3.9	21.1
Upper crustal average [c]	2.8	16.0	10	26.9	2.4	29.4	72.3
U.S. surficial average [d]	1.8	10.3	9.0	24.2	1.8	21.8	56.3

[a] mrem/yr./ppm.: uranium, 5.73; thorium, 2.69; potassium-40, 12.3; Beck and de Planque (1968).
[b] Clark et al. (1966).
[c] Uranium and thorium averages from Phair and Gottfried (1964); potassium from Heier and Billings (1969).
[d] Lowder et al. (1964).

radon-220; however, the short half-life of radon-220 (54.5 sec.) prevents a significant loss of gas (and daughter products) to the atmosphere.

In addition to the gamma rays from terrestrial sources, which are the basis for the DE values in table 9, alpha and beta particle emissions also occur. The alpha particles may be assumed to be absorbed in the soil, and it is generally assumed that the beta rays may also be neglected. Beck et al. (1966a) have completed the most recent and thorough study of terrestrial beta-ray sources. In measurements conducted 40 to 180 cm above the ground surface, they found beta rays were attenuated with a half thickness of 150 mg/cm^2. At one meter above the ground, gamma rays and cosmic rays produced 7 ion $pair/cm^3$-sec. (I) in air and beta rays produced 13 I. Although these authors concluded that the gonads and bone marrow received a small and negligible DE from beta rays, it is conceivable that this source could present a significant exposure for persons in special circumstances, e.g., individuals who live on earthen floors. In summary, present evidence suggests that the beta-ray DE due to terrestrial sources may be neglected; however, extensive supporting evidence is lacking.

Table 9 is intended to present a general idea of the DE rate from various rocks, but practical limitations prevent the use of these data for estimating population exposure. Phair and Gottfried (1964) have outlined some of the pitfalls in estimating average elemental contents of various rocks. For example, they recommend that the number of analyses of a rock type should be proportional to the abundance of the rock in nature. In practice, however, rare rocks tend to be overanalyzed in relation to the common types and thereby contribute a disproportionate share to the overall mean. In addition, surficial events, such as mixing of rocks with organic matter, glaciation, and the simultaneous occurrence of several rock types, make population exposure from a single rock type or rock derivative unlikely. For these reasons, elemental analyses of rocks are not adequate for making estimates of population exposure, but are helpful in understanding variations which exist in DE rate measurements.

Table 9 shows that the averages for surficial measurements are slightly less than for the upper crust. This is as expected, since the surficial data are based upon *in situ* spectrometric measurements and reflect the factors which have already been discussed. Mixing and weathering processes at the soil/atmosphere interface serve to reduce the amount of variation that one would expect based upon bedrock analyses. Lowder and Condon (1965), for example, found that although bedrock radioactivity and above-ground DE rates could be correlated, the DE rate above ground increased only slightly for a several-fold increase in bedrock radioactivity.

3.2. Variations in Terrestrial Radiation

As one might expect from section 3.1, the primary determinant of the terrestrial radiation level in a given location is the soil concentration of natural radionuclides. However, the radiation level above the ground will vary because of the presence of soil moisture and the amount of radon daughters present in the atmosphere. The two factors are related but will be discussed separately. The resulting variations in terrestrial radiation exposure will be cyclical and can markedly affect the observations from day to day. As with the variations in cosmic radiation, an understanding of the sources of variation in terrestrial sources is helpful in explaining differences in reported measurements.

3.2.1. Radon daughter products

Radon-222, $T_{1/2} = 3.8$ days, occurs in the uranium-238 decay chain, and radon-220, $T_{1/2} = 54.5$ sec., in the thorium-232 decay chain. Because of the shorter half-life of radon-220, there is less opportunity for diffusion from the ground, and thus airborne concentrations of radon-222 are generally two orders of magnitude greater than those of radon-220 (Gold et al., 1964).

Under most conditions radon daughters in the atmosphere contribute a few tenths of a μrem/hr. to the DE rate (Beck et al., 1964b). Low barometric pressure, atmospheric temperature inversions, little wind, and low soil moisture result in increased radon emanation from the ground and high air concentrations of radon daughters (Gold et al., 1964; Kraner et al., 1964). Gold et al.

(1964), in a 5-year study of atmospheric radon levels, reported an average radon-222 concentration of 0.26 pCi/liter, with maximum concentrations (0.8 pCi/liter) occurring during the fall months. These concentrations correspond to 0.4 and 1.3 μrem/hr., assuming the conversion factor of Hultqvist (1956).[3] In developing this factor, Hultqvist assumed the radon-222 was in equilibrium with its daughters. In fact, however, the daughter concentrations are generally 50 to 100 percent of the values that could be estimated from the radon-222 concentration (Gold et al., 1964; Harley, 1953), so that a value of 0.3 μrem/hr. is probably a reasonable estimate of the average external DE due to radon daughters. This estimate is supported by the spectrometric measurements by Beck et al. (1966a), who reported gamma DE rates at several locations to be between 0.1 to 0.5 μrem/hr. due to radon daughters. There are other reports of outdoor radon levels averaging 10 percent of the estimate cited here (see Lowder and Solon, 1956; and Hultqvist, 1956), but the estimate by Gold et al. (1964) is assumed to be more correct because of the longer period of observation.

George (1970) has provided what may be an example of a relatively high DE rate due to radon and its daughters. In an effort to isolate his cosmic ray detection instruments from terrestrial sources, he moved to an offshore drilling platform 3.6 km west of Los Angeles. By so doing, he was able to observe increases in the ionization which coincided with the offshore winds (figure 9). The difference in high and low readings was approximately 0.6 ion pairs/cm³-sec., or 1.0 μrem/hr. Since the usual temperature inversion of the Los Angeles basin results in little vertical mixing, this value is probably close to the upper limit of the external DE from radon and its daughters. It should be noted that radon levels over oceans are approximately one one-hundredth of land values (Hess and Parkinson, 1953), and thus there was probably an insignificant radon contribution from the ocean to the measurement.

The probable range of external DE due to radon daughters, therefore, is 0 to 1 μrem/hr., and

[3] Ion pairs/cm³-sec. = 0.97 × radon-222 concentration pCi/liter; 1 ion pair/cm³-sec. = 1.65 μrem/hr.

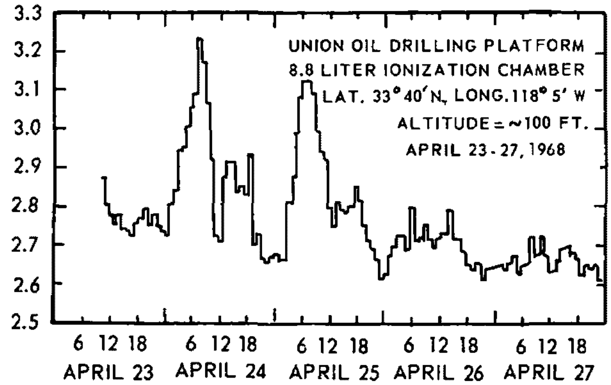

Figure 9. Ionization vs. date and local time (PST) on offshore drilling platform near Huntington Beach, Calif., (George, 1970)

the average is about 0.3 μrem/hr. Under these circumstances, the contribution of radon daughters to the total terrestrial plus cosmic DE rate at most locations will be less than 10 percent, and usually less than 5 percent of the total.

3.2.2. Moisture and snow cover

It has already been mentioned that soil moisture retards the diffusion of radon into the atmosphere and thus reduces exposure to the airborne daughter products; in most soils, the amount of water varies from 5 to 25 percent on a weight basis (Jackson, 1964). Beck et al. (1966a) found that the potassium-40 DE rate decreases by about 30 percent when the soil water content increases from 0 to 30 percent, because of the increased shielding provided by the water; however, soil moisture acts in two conflicting ways on the terrestrial DE rate. The first has already been mentioned, e.g., the gamma-ray attenuation of the natural emitters. Conflicting with this is the reduced radon migration to the surface and accumulation of radon daughters in the ground. The daughters of radon account for more than 95 percent of the gamma ray energy from the uranium-238 series (Kogan et al., 1971), so that their presence in the ground increases the exposure from this series. The net effect is for soil moisture to decrease the potassium-40 and thorium-232 rates and to increase or leave unchanged the uranium-238 series DE rate (Beck et al., 1966a).

In a comparison of spectrometeric measurements obtained in Denver, Beck et al. (1966a) observed that the measurements obtained in dry years (1962 and 1963) were 15 to 25 percent less than in a wet year (1965). This indicates that the gamma ray attenuation by the soil water was more than offset by accompanying soil retention of radon daughter products. Therefore, one would expect variations of this magnitude throughout the country where periodic drought and rainy periods occur. Once again, this emphasizes the difficulty in interpreting spot measurements and using such measurements for long-term exposure estimates.

The effect of snow cover on the dose rate from terrestrial sources was calculated by Sievert and Hultqvist (1952) (figure 10). The calculated values agree well with measurements reported in the same reference and with more recent measurements by Magi et al. (1970). Concurrently obtained snow cover and background radiation measurements are virtually nonexistent. This fact illustrates a bias which might exist in practically all measurements of background radiation. They are obtained in fair weather when personnel and equipment stress is at a minimum, and therefore the measurements may not reflect the seasonal variations of background due to ground moisture and snow cover.

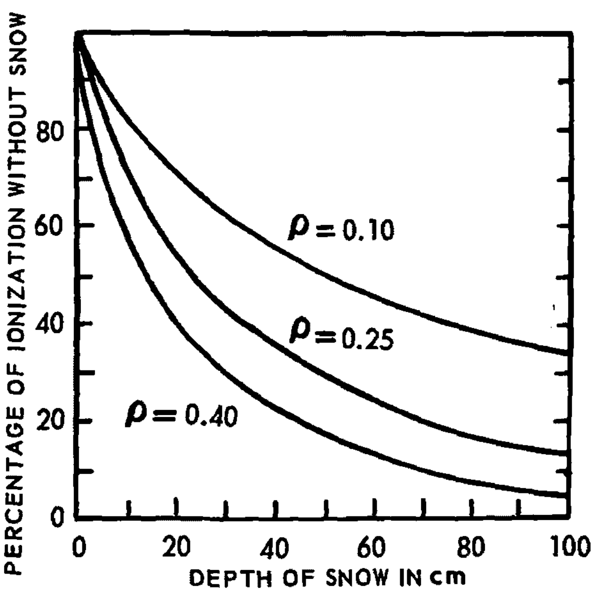

Figure 10. Decrease in gamma radiation with depth of snow cover at three different densities (Sievert and Hultqvist, 1952)

It is possible, however, to estimate the importance of snow cover on long-term exposure from the data of Magi et al. (1970). Based on summer measurements alone, they estimated the yearly DE from natural radiation to be 78 mrem/yr. at Idre, Sweden, whereas year-round measurements resulted in a 10 percent lower estimate, 70 mrem/yr. They attributed this difference to the attenuation of terrestrial sources by snow cover. The average snow cover at this location is 15 inches and persists for approximately 180 days/yr. (Pershagen, 1969). Natural radiation measurements in three other Swedish cities, located in regions of less snowfall, showed no variation from summer to winter.

Although the effect of snow cover on measurements can be substantial, the overall influence on population exposure is assumed to be negligible in the United States. In most populated areas, there is relatively little snowfall, and it does not remain for long periods of time. In addition to these factors, the propensity for indoor urban living, and rapid removal of snow in most populated areas in the United States, tend to reduce the significance of snow buildup as an attenuator of terrestrial gamma sources.

In addition to the variation in the source term (terrestrial gamma-ray sources), there are also other factors which affect the exposure of man to natural radiation. Examples of such factors are man's choice of home—elevation, geology, and building material. In addition, shielding provided by the body attenuates the dose to internal organs. These factors will be discussed in chapter 4.

3.3. Measurements

3.3.1. Ground surveys

A summary of ground surveys of natural terrestrial radiation in the United States is presented in table 10. Lowder and Solon (1956) reviewed several isolated background measurements made prior to that time, but the more extensive measurements have been reported since 1956. The

Table 10. Ground surveys of background radiation in the United States

Reference	Location	Instrumentation	Value (mrem/yr.)	Remarks
Solon, 1960	38 U.S. towns and cities	Ion chamber	ᵃ 73–197	125 measurements
Stephens et al., 1961	30 locations near San Francisco	Portable scintillator	ᵃ 39–108	
Beck et al., 1964a, 1964b, 1966a, 1966b	Approx. 210 locations in 25 States	Spectrometer and ion chamber	4–180 (From 1966b ref.)	2–3 measurements/location, some taken in different years
Segall and Reed, 1964	New Hampshire, Vermont	Personal dosimeters (ion chambers)	ᵃ 119–171	400 people; performed concurrently with Lowder and Condon (1965)
Lowder and Condon, 1965	New Hampshire, Vermont	Spectrometer Portable scintillator	45–95 0.7 × outdoor values	Outdoors Indoors—160 homes and apartments
Wollenberg et al., 1969	30 locations near San Francisco (same as Stephens et al., 1961)	Portable scintillator	ᵃ 35–102	
Levin et al., 1968	1102 towns in 24 States	Portable scintillator	ᵃ 59–116	9026 measurements; all States were east of the Mississippi River except Iowa, Minnesota, and Colorado
Golden, J., 1968	Florida—vicinity of phosphate beds	Portable scintillator	ᵃ 59–115	1,161 measurements, majority in southwestern Polk County
Yeates et al., 1970	Boston, Mass.	Ion chamber	ᵃ 83–121 ᵃ 61–105 ᵃ 81–114 ᵃ 73–118	6 measurements outdoors 15 measurements/6 frame dwellings 3 measurements/3 apts. 16 measurements/4 office bldgs.
Lindeken et al., 1971	Livermore, Calif., inside 110 homes	Thermoluminescent dosimeters	ᵃ 32–75	All frame homes except 4

ᵃ Values include response to terrestrial and cosmic radiation, those not footnoted, the values are terrestrial component only.

authors cited in table 10 have frequently reported their results in more than one article; an attempt has been made to cite the most comprehensive reference for each set of measurements.

The usefulness of the various measurements in table 10 for estimating population exposure varies considerably, and the reported measurements will be used to illustrate several limitations on making such estimates. Ideally, an estimate of exposure to people should rely upon measurements as close as possible to the receptor, i.e., personal dosimeters. The measurement of background radiation strains the detection capability of most dosimeters, however, and this difficulty is compounded by the exposure which is received by the dosimeter while it is not being worn—at night or en route from user to reader. Therefore, unless relatively small differences of exposure in a population are being studied and good control over the experiment exists, as in an epidemiological study (Segall and Reed, 1964), it is simpler and perhaps more accurate to take environmental measurements and estimate population exposure.

In order for population exposure estimates to be made from environmental measurements, it would be desirable for the measurements to be distributed according to population density—large cities having the most measurements and rural areas having the least. The data in table 10 generally do not satisfy this criterion, but in fairness to the investigators it should be noted that no one had as his primary goal the estimation of population exposure for the entire United States. The measurements by Beck et al. (1964ab, 1966ab), Solon (1960), Stephens et al. (1961), and Wollenberg et al. (1969) resulted from an initial interest in the impact of nuclear weapons fallout on man's radiation exposure. In contrast to this, the data of Lowder and Condon (1965) and Yeates et al. (1970) were obtained because of the authors' interest in natural background radiation. These latter data are useful in estimating population exposure, but only for a relatively small proportion of the total U.S. population.

The choice of instrumentation in environmental surveys of background radiation has also influenced the utility of the data. As one would expect, the most comprehensive data would be obtained by using more than one instrument at each measurement site. This technique is exemplified by the data of Beck et al. (1964ab, 1966ab), who generally obtained spectral data and an ion chamber reading at each location. The spectral data were especially important for interpreting measurements obtained in the first half of the 1960's, when work by Beck et al. was accomplished. In addition to allowing for an estimation of the contribution of potassium-40, thorium-232, and uranium-238 to the total terrestrial DE, the contribution of nuclear weapons fallout to the total DE could be estimated with the spectrometer data. The significance of fallout will be discussed later in this section.

Several investigators have used portable scintillation detectors for measuring natural background. These small, hand-held instruments allow the user to make several measurements in the time it would take to obtain ion chamber and spectrum measurements at one location. Unfortunately sodium iodide (NaI) detectors, the scintillating medium, do not detect cosmic radiation as efficiently as gamma radiation. In using a 3- by 5-inch detector with a high energy cutoff of 3.4 MeV, Beck et al. (1964b) found that the sea-level cosmic ray contribution to the energy spectrum was equivalent to a gamma-ray DE of 0.2 μrem/hr. instead of the expected value of approximately 3.7 μrem/hr. In a similar study using several energy bands with a 4- by 4-inch detector, Beck et al. (1966a) observed a gamma-ray response of less than 0.5 μrem/hr. up to 6,000 feet. This figure is based on the response of several energy bands of less than 3.4 MeV, but it is also indicative of the lack of detector response to cosmic rays. Another limitation on the use of portable scintillators is the strong directional dependence of the detector (see Ohlsen, 1969). However, this limitation can be overcome by maintaining the same detector orientation during calibration and measurements.

Notwithstanding the limitations which have been discussed, it seems desirable to report in more detail the scintillometer measurements by Levin et al. (1968), since they greatly outnumber all other U.S. measurements combined. Levin does not report the averages for the states in which measurements were obtained, ostensibly because of the fact that measured sites were not necessarily representative of the entire State. However, the averages have been computed from his reported data and are presented in table 11. As can be seen from table 11. the means vary by as much as a factor of two—from 6.76 μrem/hr. (59 mrem/yr.) in Florida to 13.32 μrem/hr. (117 mrem/yr.) in Colorado.

Table 11. Dose equivalent measurements in 21 States, adapted from Levin et al. (1968)

State	Number of measurements	Towns	mrem/yr
Colorado	760	11	117
Michigan	2,354	24	68
Minnesota	1,514	18	76
Connecticut	223	56	88
Delaware	41	10	81
Florida	879	239	59
Georgia	319	91	80
Illinois	494	67	78
Iowa	488	63	77
Kentucky	62	30	82
Maine	301	87	87
Maryland	81	22	73
Massachusetts	326	58	87
North Carolina	228	67	72
New Hampshire	63	11	90
New Jersey	192	66	68
New York	196	48	79
Ohio	4	4	89
Pennsylvania	53	10	93
Rhode Island	51	4	85
South Carolina	197	50	71
Tennessee	34	20	84
Vermont	15	3	80
Virginia	151	43	76
Total	9,026	1,102	[a] 77

[a] Mean.
Extreme values: East of Facil, Fla., 50 mrem/yr., Ft Morgan, Colo., 128 mrem/yr.

The response to cosmic rays of the detector used by Levin et al. (1968) is unknown. Since these authors reported that frequent intercomparisons of measurements with an ion chamber (see Kastner et al., 1963) were made in the field. it is likely that the reported values are representative of the terrestrial, fallout, and cosmic radiation. Levin's observation was that "the readings were within 4 percent of the ionization chamber readings 95 percent of the time."

3.3.2. Dose equivalent rate due to fallout

The presence of fission products on the ground from nuclear weapons testing complicates the interpretation of terrestrial DE rate measurements obtained during the late 1950's and the early and middle 1960's. Unless spectrometric measurements are made, the DE contribution from fallout cannot be accurately assessed. This could be a source of varying error, since fallout contributed a DE of a magnitude similar to that from terrestrial sources in 1962 to 1963, whereas more recent measurements show the DE rate from fallout to be approximately 5 to 15 percent of the natural terrestrial DE rate (McLaughlin, 1970).

An estimate of the external DE rate due to fallout is presented in figure 11. The figure is based upon estimates and measurements in the United States; the two solid lines define a range in which most measurements would be expected to fall, and the dashed line represents the best estimate for making a fallout correction to nonspectrometric dose measurements.

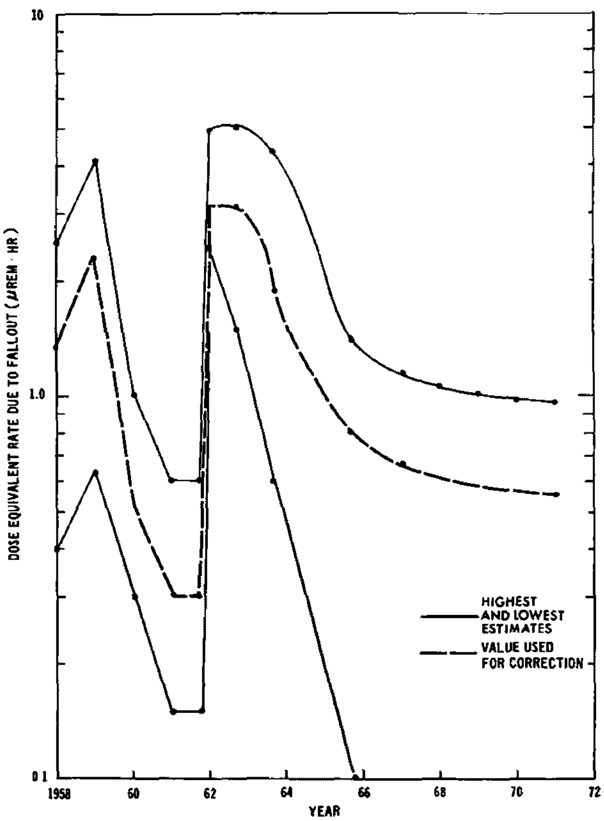

Figure 11. Dose equivalent rate due to fallout in the United States, 1958-1971

For purposes of making corrections, it would be desirable to know the local and countrywide variations in fallout dose rate. It has been shown, for example, that variations in fallout deposition are closely related to precipitation and, as a result, wet areas (i.e., areas of higher precipitation) receive more fallout than dry areas (Straub et al., 1964). Unfortunately, existing data are not sufficiently detailed to justify making more than one estimate of the DE rate contributed by fallout at a given time in the United States.

Fallout measurements by Beck (1966a) suggest more uniformity in fallout DE rates across the United States than would be expected from rainfall patterns. For example, measurements in relatively "dry" States (Wyoming, Nevada, Utah) varied between 0.6 to 1.5 μrem/hr. in 1965, and at approximately the same time measurements in "wet" States (Louisiana, South Carolina, North Carolina) varied between 0.7 and 1.3 μrem/hr. However, too few measurements are reported to allow a conclusion as to how the fallout DE rate varied across the country.

Three different procedures were used in developing figure 11. These are as follows:

1958 to 1962: The range of values was obtained from UNSCEAR (1964), figure 32. The correction values are 54 percent of the maximum value. This correction is based on a composite of 67 measurements in the United States between 1962 to 1965 (Beck et al., 1964a, 1966a).

1962 to 1965: The range of values and the averages are based on the same measurements by Beck et al. (1964a, 1966a).

1966 to present: The 1965 values of Beck et al. (1966a) show that 25 percent of the fallout dose rate was due to ruthenium-106 and manganese-54 and 75 percent was due to cesium-137. The post-1965 values are based on the assumption that the 25 percent portion decayed with the half-life of 1 year and the 75 percent portion decayed with a half-life of 28 years. The resulting range of values is consistent with fallout measurements in the northern hemisphere (UNSCEAR, 1966), in San Francisco (Wollenberg et al., 1969), and in the eastern United States (McLaughlin, 1970) during this time. Some fresh fission products have been added in this interval as a result of French and Chinese weapons tests, but their contribution to the total is negligible.

3.3.3. Aerial surveys

The U.S. Atomic Energy Commission has sponsored nationwide aerial surveys of radioactivity in the vicinity of nuclear facilities. During 1958 to 1963, Aerial Radiological Measurement Surveys (ARMS) were conducted (by the U.S.

Geological Survey and E.G.&G., Inc.) over approximately 25 areas which are shown in figure 12. A few additional areas have been surveyed but are not included in this analysis because of their relatively small size and sparse population.

In the course of reviewing available sources of information on natural radiation sources, it was found that none of the published ARMS data had been used for estimating population exposure. As a first step in determining if the data would be useful for this purpose, the population of each survey area (table 12) was estimated from U.S. Census Bureau Map G.E. 50, No. 1, 1963. It was found that approximately 30 percent of the U.S. population (1960 census) resided in the survey areas, and thus it was concluded that the ARMS data would be potentially useful for making exposure estimates.

Details of the purpose and procedures of the ARMS surveys are presented in the reports listed in table 12 (or see Guillou, 1964); however, a brief description is presented here in order to introduce the measurements. The standard ARMS survey covered an area of 10,000 square miles encompassing a nuclear facility, although there is some variation in areas covered depending on the site location in relation to mountains and oceans. The surveys were intended to provide information on radiation levels in the vicinity of nuclear installations, so that future releases of radioactive material to the environment from the facilities could be detected. This naturally raises

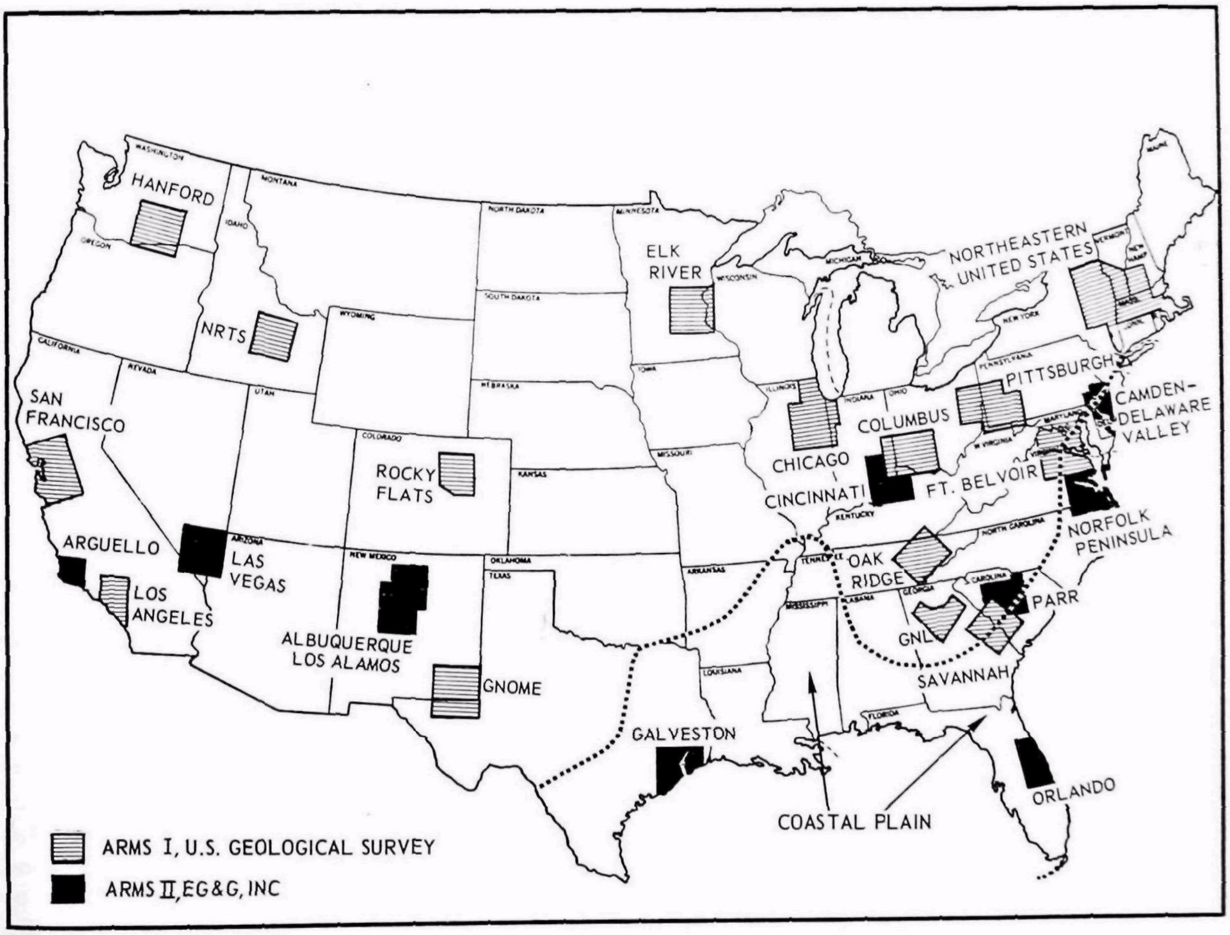

Figure 12. Aerial radiological measuring surveys

Table 12. Population in ARMS areas

Reference	Area (figure 10)	Population (est. 1960)
Bates (1962)	Oak Ridge, Tenn.	922,734
Bates (1965)	Idaho Falls, Idaho (NRTS)	130,000
Bates (1966a)	Pittsburgh, Pa.	3,853,622
Bates (1966b)	Columbus, Ohio	2,108,564
Books (1962)	Los Angeles, Calif.	6,768,791
Books (1966)	San Francisco, Calif.	4,386,992
Flint and Pitkin (1970)	Chicago, Ill.	6,881,320
Guillou (1963a)	Camden, N.J.–Philadelphia, Pa.	4,741,296
Guillou (1963b)	Norfolk, Va.	1,096,699
Guillou (1963c)	Galveston, Tex.	1,508,160
Guillou et al. (1963)	Las Vegas, Nev.	129,427
Guillou (1965)	Santa Barbara, Calif. (Arguello)	202,740
Guillou (1966a)	Parr, S.C.	602,601
Guillou (1966b)	Orlando, Fla.	540,995
Guillou (1966c)	Cincinnati, Ohio	3,721,910
Guillou (1966d)	Albuquerque, N.Mex.	361,216
MacKallor (1962)	Atlanta, Ga. (GNL)	1,458,125
MacKallor (1965)	Gnome–Carlsbad, N.Mex.	110,000
Neuschel (1966)	Washington, D.C. (Ft. Belvoir)	3,777,371
Neuschel (1970)	Minneapolis, Minn. (Elk River)	2,027,143
Popenoe (1964)	New England (North)	2,082,976
Popenoe (1966a)	New England (South)	5,354,722
Popenoe (1966b)	Denver, Colo. (Rocky Flats)	1,073,624
Schmidt (1962a)	Augusta, Ga. (Savannah)	423,698
Schmidt (1962b)	Richland, Wash. (Hanford)	350,000
Total		54,614,726

the question as to the influence of the facilities on their environs prior to the initial aerial survey. In general, the facilities occupy considerably less than 1 percent of the surveyed areas, and there were no reported or obvious patterns of radionuclide deposition around the facilities. In some instances measurements directly over plant facilities were affected, and in these cases the natural radioactivity was inferred from local geology. For example, the aerial effluent from an operating reactor at the AEC's Brookhaven Laboratory was detected (Popenoe, 1966a), but the author corrected for this effect on the radioactivity map.

Sodium iodide (NaI) scintillation detectors were mounted in the bottom of the survey aircraft, which were flown at 500 feet over the surveyed terrain on traverses spaced 1 mile apart. Although different aircraft and detectors were flown by the U.S. Geological Survey and E.G.&G., Inc., the results from the two systems are compatible (Guillou, 1964). Count rate data were corrected for the influence of cosmic radiation and then were used to plot contour maps of the gamma-ray count rate resulting from terrestrial sources: the maps accompany the respective ARMS reports. Several weeks were required to survey most of the areas, although longer times were occasionally reported.

In this study, histograms of terrestrial DE rates for each ARMS area were developed from the contour maps in the following manner. Each area map contained up to several hundred distinct radioactivity segments, which were traced onto Keuffel and Esser Albanene tracing paper (thickness = 0.0025 in., 37.92 mg/in.^{2}, S.D. = 1.15 mg/in.^{2}). Contour segments were then cut and weighed, the weight being proportional to the portion of the area in each radioactivity contour. Radioactivity data obtained over lakes, reservoirs, and swamps were deleted, since these areas will not ordinarily contribute to population exposure.

Conversion from cps detected at 500 feet in the aircraft to DE rate at 3 feet above ground was not performed in the ARMS reports. A conversion factor of 1 μrem/hr. at 3 feet from 25 cps at 500 feet (for cesium-137, 0.662 MeV gamma ray) is reported in many of the ARMS reports and is based on the work of Davis and Reinhardt (1962). It should be noted that the monoenergetic emission of cesium-137 is probably not representative of the wide spectrum of energies observed in radiation from natural radionuclides. A low energy component from scattered radiation is especially prominent with these nuclides. In addition, the conversion factor obtained by Davis and Reinhardt is based on flights over distributed point sources on the surface of the ground rather than over a uniform volume source such as natural terrestrial radioactivity. Thus, it does not appear valid to use this conversion (25 cps = 1 μrem/hr.) for terrestrial DE rates due to natural background radiation. In addition, unpublished experimental work by K. Larsen (University of California at Los Angeles) is quoted in the ARMS reports in relation to the contribution from fallout. Larsen is quoted by Popenoe (1966a) as stating that ". . . a count rate of approximately 77,000 cps measured at 500 feet above the ground by Geological Survey equipment over an infinite fallout source is equivalent to 1 mR/hr. measured at three feet above the ground . . ." or 77 cps = 1 μrem/hr. This value was used in conjunction with figure 11 in order to correct the ARMS data for fallout contribution. Fourteen areas had fallout corrections of less than 1 μrem/hr., whereas the fallout DE rate in 11 areas was greater than 1 μrem/hr.

Ground measurements were compared with aerial data from several locations in order to arrive at a conversion for natural emitters. There are four separate determinations of this conversion:

1. MacKallor (1962), based on a comparison of ground survey and aerial measurements, found a conversion of 47 cps (500 feet) = 1 μrem/hr. at 3 feet. However, the ground and air measurements were taken 1½ years apart, during which time the dose contribution to fallout changed by 1.6 μrem/hr. When this difference is accounted for, the conversion is 76 cps = 1 μrem/hr.
2. Levin et al. (1968) reported an average DE rate of 8.5 μrem/hr. in Little Falls, Minn. (76 measurements); the ARMS data map (Neuschel, 1970) for this location presents an average of 275 cps. To compare the two, 0.9 μrem/hr. (fallout in summer of 1965 from figure 11) and 4.3 μrem/hr. (ionizing component of cosmic radiation) were subtracted from the ground value; the fallout value from figure 11 in the summer of 1961 was 0.3 μrem/hr. or 0.3 × 77 = 23 cps. Thus,

$$\frac{275-23}{8.5-(0.9+4.3)}=\frac{76\ \text{cps}}{1\ \mu\text{rem/hr.}}$$

3. A similar comparison was made from Levin et al. (1968) and Neuschel (1970) for Falcon Heights, Minn. In this case, the conversion was

$$\frac{325-23}{8.6-(0.9+4.3)}=\frac{90\ \text{cps}}{1\ \mu\text{rem/hr.}}$$

4. A total of 16 terrestrial measurements, corrected for fallout (Beck et al., 1964a, 1966a), were obtained in Denver, Colo., in 1962, 1963, and 1965. The average DE rate was 11.6 μrem/hr. The ARMS map for this area gives a value of 850 cps in the vicinity of Denver, and the fallout contribution during the ARMS study was 0.37 μrem/hr., or 28 cps. The conversion value is thus

$$\frac{850-28}{11.6}=\frac{71\ \text{cps}}{1\ \mu\text{rem/hr.}}$$

Based on the comparison of aerial and ground data, a factor of 78 cps at 500 feet = 1 μrem/hr. at 3 feet was assumed for converting the aerial data to dose values at the 3-foot level. In applying this factor to the data of all ARMS areas, it is assumed that the source spectra do not change significantly across the United States, i.e., the relative contributions of potassium-40, uranium-238, and thorium-232 do not change drastically. This assumption is supported by the countrywide spectrometric surveys of Beck et al. (1964ab, 1966a). In addition, the utility of aerial survey data has been enhanced by the demonstration that the DE rates from potassium-40, uranium-238, and thorium-232 show almost exactly the same variation with height (Beck and La Planque, 1968).

The procedure in analyzing the aerial data may then be summarized as follows:

$$\frac{\text{counts/sec. at 500 ft. minus fallout correction}}{78\ \text{cps}/\mu\text{rem/hr.}}=\mu\text{rem/hr. at 3 ft.}$$

The data were then grouped in 2 μrem/hr. intervals in order to arrive at figures 13, which present the percent of each ARMS area vs. DE rate. The average DE rates of the ARMS areas varied from 1.51 μrem/hr. in the Orlando, Fla. area to 10.23 μrem/hr. in the Rocky Flats-Denver, Colo., area.

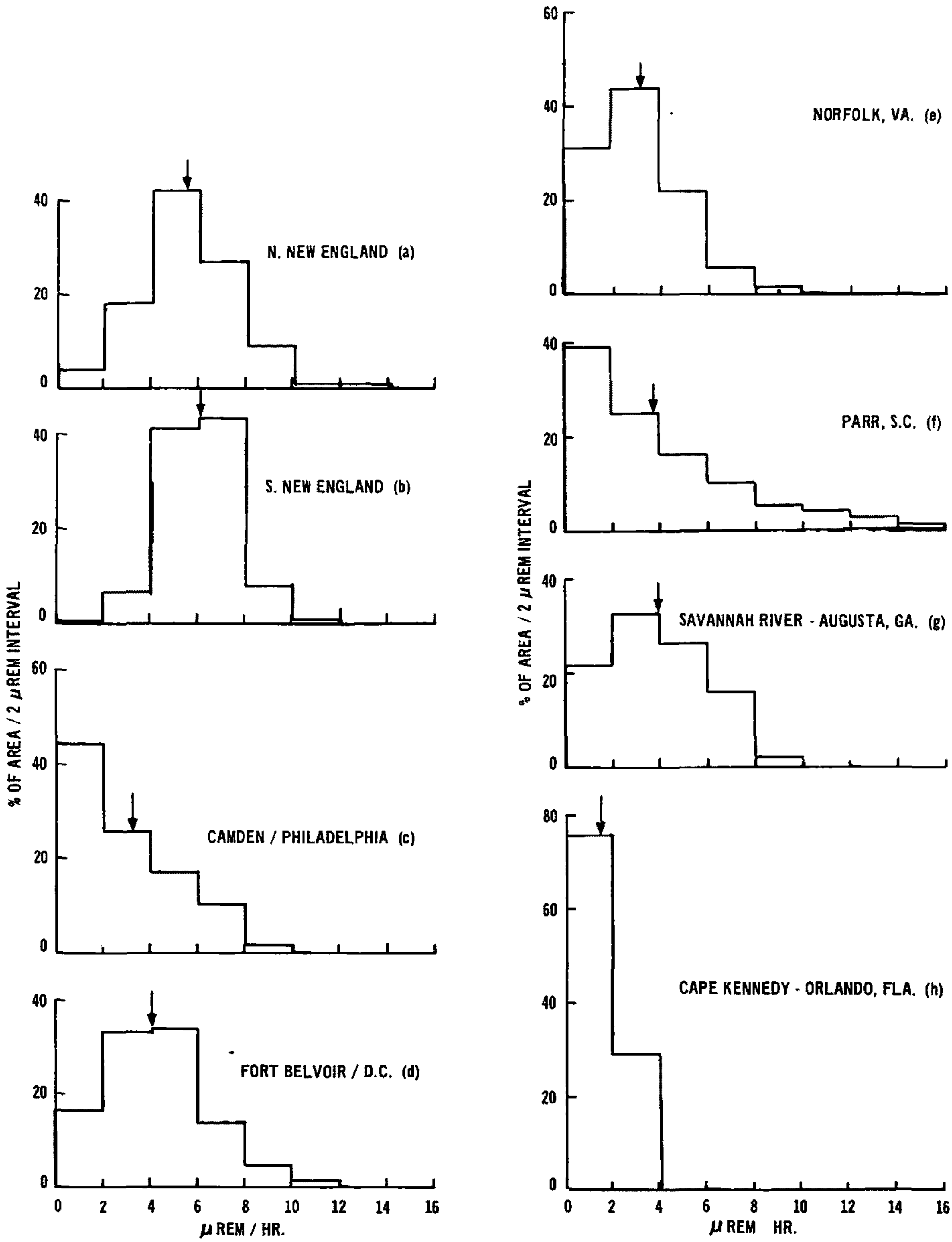

Figure 13. Dose equivalent rates in ARMS areas

(mean denoted by arrow)

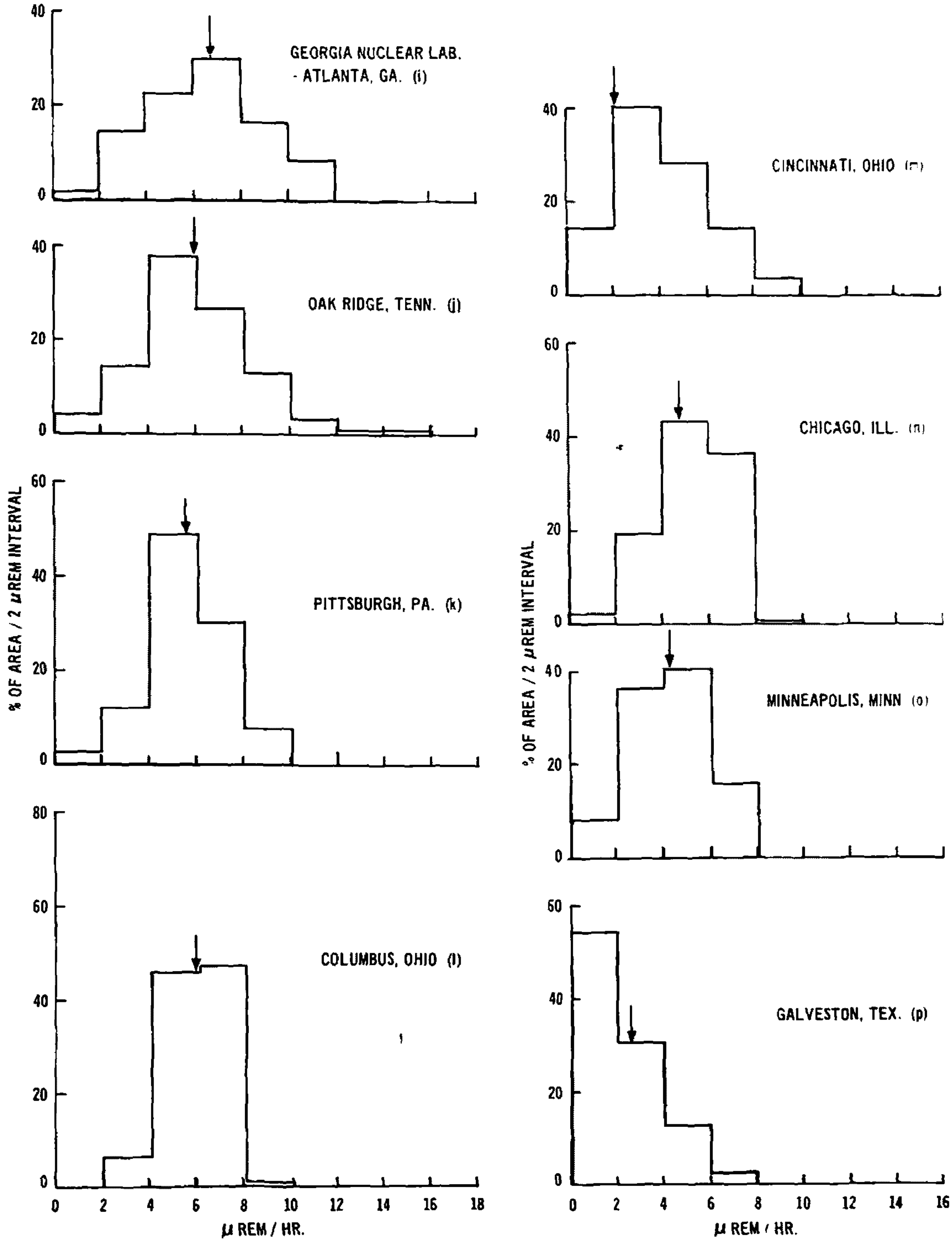

Figure 13. Dose equivalent rates in ARMS areas—Continued

(mean denoted by arrow)

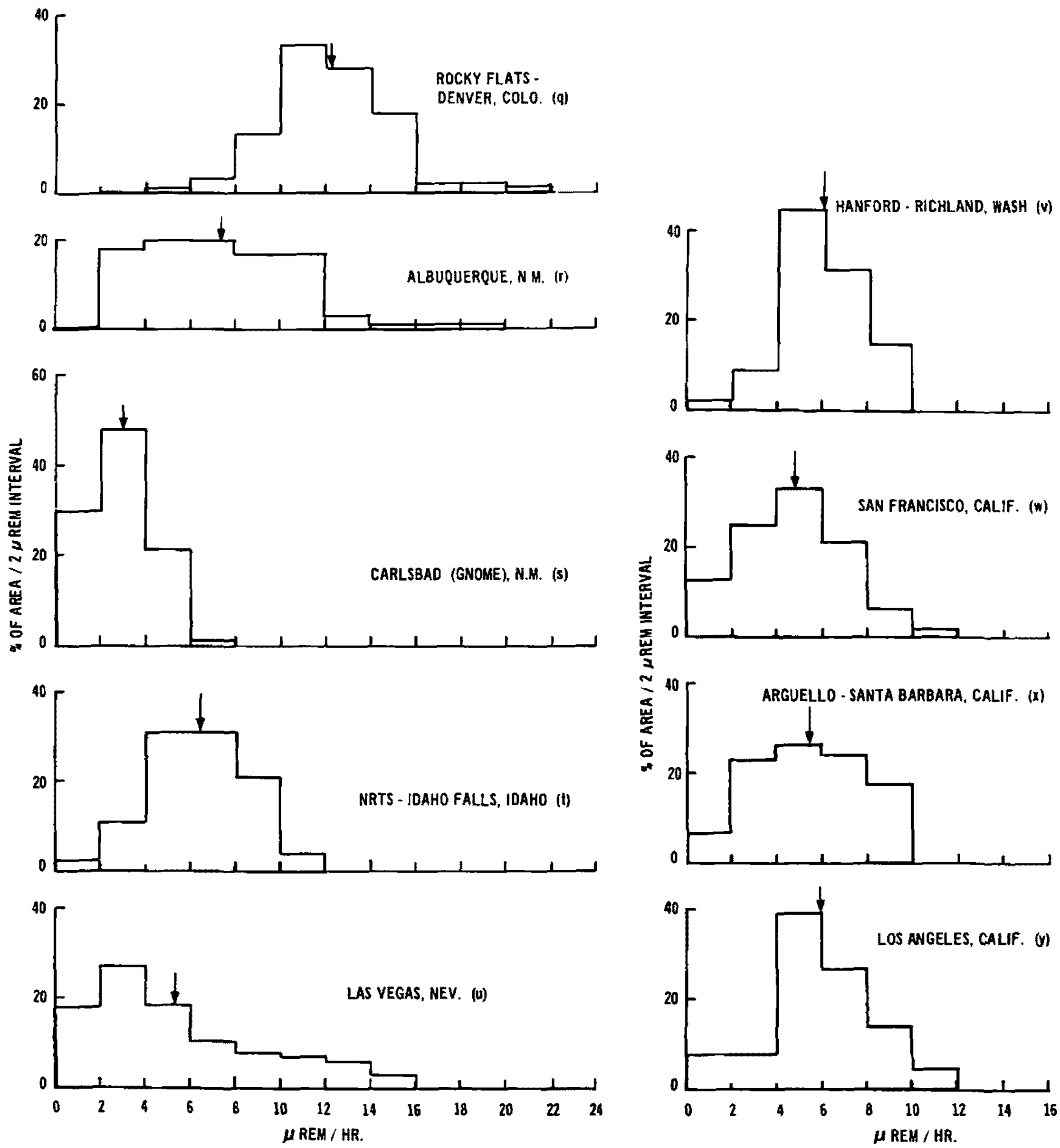

Figure 13. Dose equivalent rates in ARMS areas—Continued

(mean denoted by arrow)

Each histogram covers between 98 to 100 percent of the respective ARMS area with the exception of Las Vegas, which covers 95.2 percent of the area. The totals do not add up to 100 percent in each case since the count rate data for 1 to 2 percent of some areas were presented in very broad contours (i.e., 1,200 to 4,000 cps) relative to the rest of the map data. In general, the omitted portions covered unpopulated areas such as mountainous terrain. The highest count rate found in the ARMS data occurred in the Las Vegas area (Guillou et al., 1963) and the Albuquerque area (Guillou, 1966d), where a maximum of 4,000 cps was observed (50 μrem/hr.). In both cases the locations were unpopulated; the Albuquerque area maximum occurred in the vicinity of a uranium mine.

The original ARMS data are grouped in count intervals which commence at zero cps, and this is reflected in the histograms, which in most instances commence at a zero DE rate. Therefore, it should be noted that the zero DE rate represents the lower limit of the ARMS reporting method rather than an actual estimate of DE rate. The mean DE of each area was computed by assuming that the midpoint of each DE interval (1, 3, 5, etc.) was representative of the DE for the respective interval, and the means are designated by arrows on figure 13.

By weighting the individual distributions of figure 13 by the population of each area, a summary histogram was obtained (figure 14), of which the mean is 5.0 μrem/hr., or 44 mrem/yr. As shown in table 11, the overall mean of 9,026 measurements by Levin et al. (1968) is 77 mrem/yr. If the ionizing component of cosmic radiation is assumed to account for 36 mrem/yr., then the terrestrial DE is 41 mrem/yr., which compares well with the mean obtained from the ARMS data. A summary of 210 ground survey measurements (Beck, 1966b) also is presented in figure 14, and, as can be seen, the mean is approximately 40 percent higher than the value derived from the ARMS data. The locations of Beck's (1966b) measurements are not given; however, the measurements are a summary of data reported in Beck et al. (1964ab, 1966a). The latter references include 16 measurements (ranging from 7.1 to 15.2 μrem/hr.) in the relatively high background area of Denver and measurements over unpopulated granitic outcrops in North Carolina; this could explain the higher overall mean.

Three distinct areas of terrestrial radiation are evident from an analysis of the ARMS data. First, the Coastal Plain, bordering the Atlantic Ocean and the Gulf of Mexico, has a terrestrial radiation level of approximately half the U.S. average. This is partially evident from the mean exposure of three areas lying entirely on the plain: Norfolk (3.09 μrem/hr.), Orlando (1.51 μrem/hr.) and Galveston (2.26 μrem/hr.). The Coastal Plain includes marine deposits of Quaternary, Tertiary and Late Cretaceous age (Neuschel, 1966; Schmidt, 1967a) and is shown in figure 12.

Neuschel and Schmidt observed in their respective reports of ARMS surveys (Washington, D.C., and the AEC's Savannah River plant) that the portion of the area on the Coastal Plain was considerably less radioactive than the rest of the area. In order to quantitate this observation, the radiation levels of four areas which straddle the Coastal Plain were studied in more detail. Table 13 summarizes the DE rates of the total and partial Coastal Plain area. It is interesting to note that the average radiation level in the non-Coastal Plain portion of the mixed areas is similar to the U.S. average.

Table 13. Dose equivalent rates in areas on or straddling the Coastal Plain

Area	Mean dose equivalent rates (μrem/hr.)		
	Coastal Plain	Non-Coastal Plain	Entire area
Camden–Philadelphia	1.9	4.9	2.7
Washington, D.C.–Fort Belvoir	3.2	5.0	4.1
Norfolk	3.1		3.1
Parr	2.9	4.0	3.6
Savannah River	3.5	5.3	3.9
Orlando	1.5		1.5
Galveston	2.3		2.3
Average	2.6	4.9	3.1

In order to compare the Coastal Plain and non-Coastal Plain regions graphically (excluding the Denver ARMS data), the ARMS data for each region were population-weighted in the same

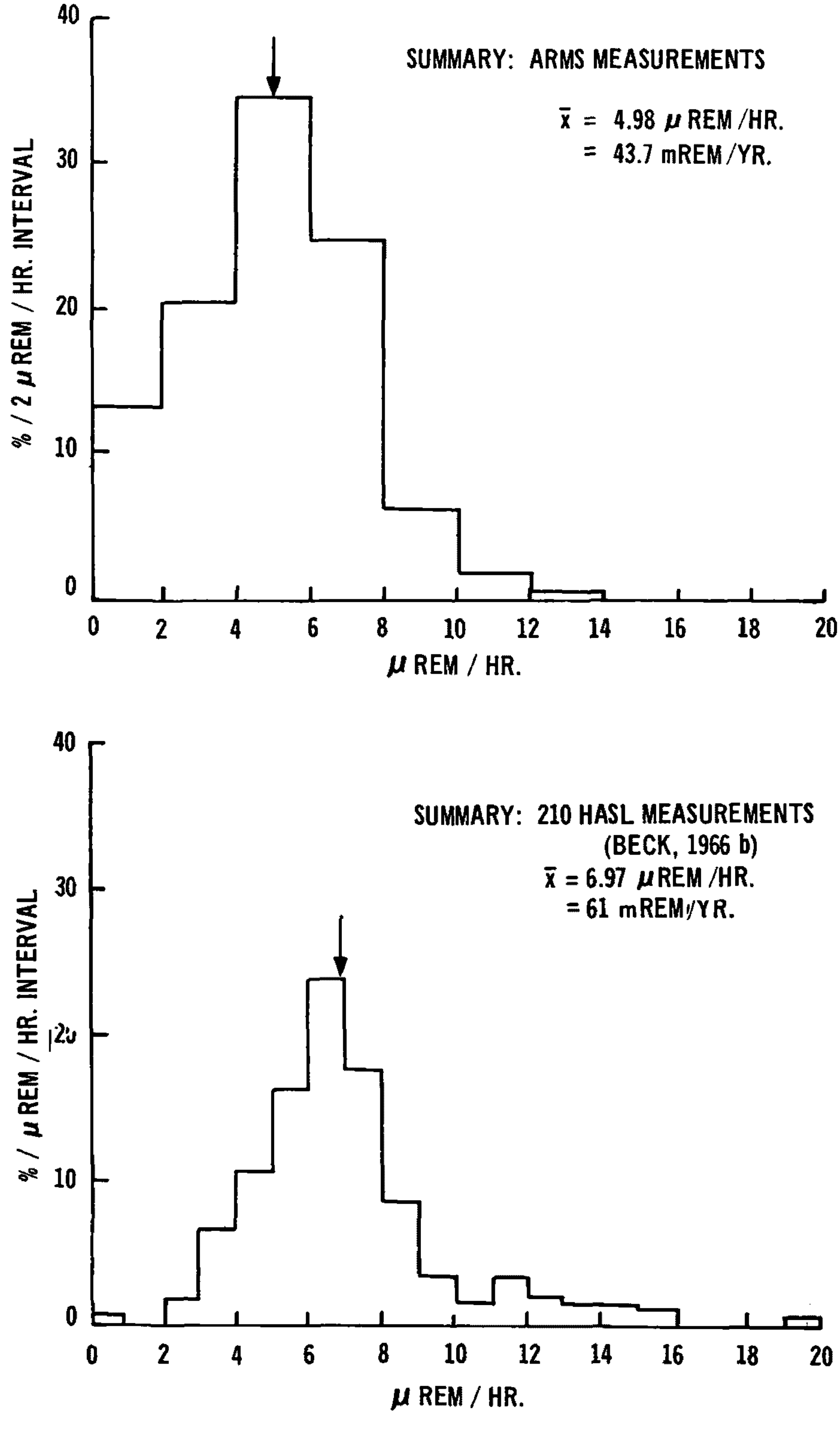

Figure 14. Dose equivalent from terrestrial sources based on population-weighted ARMS data

manner that was used to obtain figure 14, and the resulting distributions are presented in figure 15. As can be seen, the DE in approximately 80 percent of the Coastal Plain area is less than 4 μrem/hr. (35 mrem/yr.), whereas most of the non-Coastal Plain (64 percent) lies in the range 4 to 8 μrem/hr. (35 to 70 mrem/yr.).

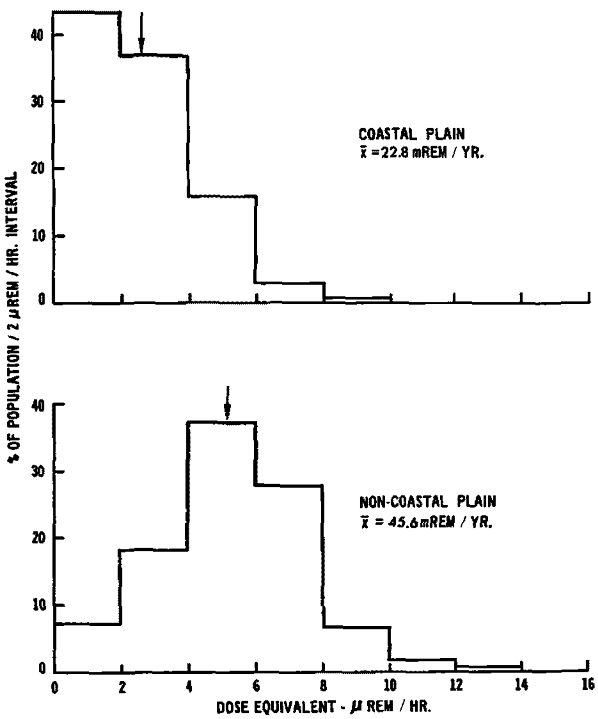

Figure 15. Dose equivalent from terrestrial sources in Coastal and non-Coastal Plain regions

The areas of table 13 are all on the Atlantic Coastal Plain except Galveston, and therefore it is assumed with less certainty that the Gulf Coastal Plain follows the pattern of lower radioactivity that was observed in the Atlantic Coastal Plain. The natural radioactivity of Gulf and Atlantic beach sands has been shown to be relatively uniform (Mahdavi, 1964); yet this fact can probably not be related to the radioactivity of the entire Coastal Plain since Mahdavi's samples were taken on and near the beaches. Significant uranium ore deposits exist in the Tertiary portion of the Coastal Plain of south Texas (Finch, 1967), and the deposits may be reflected in increased radiation levels over the region of the deposits. There are no reported measurements in the region, which is sparsely populated, and there are no other significant deposits in the entire Coastal Plain. Recognizing the limitations on data from the Gulf Coastal Plain, it will be assumed that the Gulf and Atlantic Coastal Plains follow the same pattern of producing low terrestrial radiation exposures. This assumption is based primarily upon the fact that both areas have similar geology, i.e., marine sediments deposited since the late Cretaceous age.

The second region of the United States, which stands apart from the rest, is the Denver region of Colorado. Based on the ARMS data analysis, the mean terrestrial DE rate for the Denver area is 10.2 μrem/hr. This is approximately 40 percent higher than the next highest value of 7.3 μrem/hr. (Albuquerque area) and twice the average of all the ARMS areas. Phair and Gottfried (1964) found that levels of uranium and thorium were twice the normal crustal concentrations over a 7,000 square mile area along the Colorado Front Range. Furthermore, they observed that the Front Range was the only large area in the United States in which the uranium and thorium concentrations in bedrock were consistently above average. Much of the Denver survey area is over alluvia derived from the Front Range, and the aerial data and the previously mentioned ground data (Beck et al., 1964a, 1966a) corroborate the measurements of Phair and Gottfried (1964). There is no evidence to suggest that other areas of higher terrestrial radiation and comparable size to the Front Range exist in the United States.

Levin et al. (1968) obtained ground readings in 11 Colorado towns, none of which were in the Denver ARMS area. They found terrestrial + cosmic + fallout DE rates of 11.6 to 14.6 μrem/hr.; the average of all Colorado measurements was 13.3 μrem/hr. If cosmic radiation and fallout (1966) are assumed to result in 7.3 μrem/hr., then the average terrestrial DE in Colorado outside the ARMS area is about 6.0 μrem/hr., which is similar to the values obtained in many of the ARMS areas. It is not suggested that natural background levels vary according to political units. The fact is, however, that New Mexico, Colorado, Utah, and Wyoming are the principal uranium ore-bearing States (Finch, 1967), and it is not surprising that areas on alluvia derived from ore-rich regions would have higher background radiation levels.

If the Coastal Plain and Colorado may be considered as the location of low and high values of terrestrial radiation, than the balance of the United States represents a vast Middle America, radiologically speaking. A summary of ARMS-derived DE rates due to terrestrial sources is presented in table 14, and these estimates will be used in chapter 4 to compute the total DE due to natural radiation.

Table 14. Dose equivalent rate from terrestrial sources based on population-weighted ARMS data

Area	Population covered by ARMS (1960)	Dose equivalent (mrem/yr.)
Coastal Plain	6,759,772	22.8
Non-Coastal Plain (excluding Denver)	46,781,330	45.6
Denver	1,073,624	89.7
Average		43.7

CHAPTER 4. NATURAL RADIATION EXPOSURE OF THE U.S. POPULATION

In the preceding chapters, two major natural contributors to population DE have been considered. These are (a) cosmic radiation and (b) terrestrial radiation. In order to calculate an average and range of external DE in the United States, it is necessary to consider the influence of population distribution on exposure from each of these two sources. Initial calculations are directed to the determination of external radiation DE from these two sources outdoors, and these estimates will then be modified in this chapter to consider the influence of housing construction and man's biological shielding on DE to the gonads and bone marrow.

4.1. External Sources

The calculation of DE from external sources has been performed by considering the population to be located in either urbanized or nonurbanized areas; an urbanized area, as described by the U.S. Census Bureau, is a city (including suburbs) which has a total population of more than 50,000. As of the 1960 census, there were 213 urbanized areas in the United States, some of which overlap adjoining States. The nonurbanized areas of the 50 States are treated as additional segments. Thirteen of the 50 States lie partially on the Coastal Plain as shown in figure 12. Each of these States contains two nonurbanized segments corresponding to the Coastal Plain and non-Coastal Plain portions, and thus there are 50 + 13 = 63 nonurbanized segments. The total number of areas is 310, 247 of which are urbanized and 63 of which are nonurbanized.

Urbanized and nonurbanized areas were selected as the basis for the model because they provide the potential for updating exposure estimates in the future as new census data become available. As a secondary reason, manmade sources of radiation are concentrated around urban areas (hospital use of x rays and radionuclides and nuclear power reactors), and this model may facilitate the computation of total natural and manmade radiation exposure.

For each population segment, the cosmic ray (ionizing and neutron components), terrestrial, and total external radiation DE rates have been calculated. The cosmic ray DE rates due to ionizing and neutron radiation were calculated based on the elevation of each segment and the data presented in figure 6. The terrestrial DE rates for each population segment were assigned on the basis of general estimates from table 14, except in the case of those urbanized areas (49) which lie within the boundaries of ARMS areas. These areas have been assigned a DE which was obtained by converting the measured count rate in the same manner as discussed in Chapter 3.

The results of the computations for each area are shown in appendix A, tables A–1 and A–2, and a summary of DE estimates is presented in table 15. The data in the table are presented in two different ways, urbanized vs. nonurbanized areas and Coastal Plain vs. non-Coastal Plain. First, the mean and ranges of data for urbanized areas and nonurbanized areas are given. The most significant difference in the two groups is the average and range of elevations; urbanized areas range in elevation from 5 feet (New Orleans, La.) to 5,980 feet (Colorado Springs, Colo.), whereas the nonurbanized population lives in areas ranging up to 10,500 feet (Leadville, Colo., and vicinity). The terrestrial DE ranges from

Table 15. Dose equivalent outdoors from terrestrial and cosmic radiation (1960 census)

	Population	Populated elevation (feet)		Cosmic ray DE (mrem/yr.)		Terrestrial DE [a] (mrem/yr.)		Total external DE [b] (mrem/yr.)		Integrated DE (10^6 man-rem)
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	
Urbanized areas	95,848,487	481	5–5,980	43	40–83	41	0–120	83	40–200	8.0
Nonurbanized areas	83,474,688	965	0–10,500	45	40–160	40	0–120	85	40–300	7.1
Coastal Plain	32,140,217	170	0–400	41	40–42	24	0–90	65	40–130	2.1
Non-Coastal Plain	147,182,958	824	0–10,500	44	40–160	44	0–120	88	40–300	13.0
U.S. summary	179,323,715	707	0–10,500	44	40–160	40	0–120	84	40–300	15.1

[a] Lower and upper limits correspond to values presented in figure 15.
[b] Totals are based upon the combination of cosmic ray and terrestrial DE. The DE's for the nonurbanized and non-Coastal Plain areas, and the total United States, have been rounded off to 300 mrem/yr.

approximately 10 mrem/yr. (12 mrem/yr. in Orlando, Fla.) to 92 mrem/yr. (Denver, Colo.). At present, there is no reason to indicate that the populations of urbanized and nonurbanized areas have different exposures to terrestrial sources. A similar conclusion was reported by Segall and Reed (1964), who found no difference in DE to residents of urban and rural regions in New Hampshire and Vermont. The total DE due to external sources is also practically the same for both areas, and the difference in integrated exposure (man-rem) is due to the difference in population of each group.

It is interesting to note from table A–1 that the lowest cosmic and terrestrial DE estimates both occur in areas on the Coastal Plain, and the highest values of each occur in Colorado. For this reason the results have also been divided into the Coastal Plain and non-Coastal Plain regions; Denver has been placed in the latter category in this classification. As can be seen, there is a large difference in the ranges of cosmic and terrestrial DE in both regions. Although the mean of cosmic radiation DE is approximately the same in both regions, it can be seen that the range of DE in the non-Coastal Plain (40 to 160 mrem/yr.) is much greater than the range in the Coastal Plain (40 to 42 mrem/yr.). In contrast to this, the mean terrestrial DE of the non-Coastal Plain region is nearly twice that of the Coastal Plain. This is as expected, since the terrestrial DE estimates are based on the results of the ARMS surveys which were summarized in the previous chapter. As a result of the difference in terrestrial DE, there is considerable difference in the total DE of the two regions. The differences in total DE, in addition to the fact that the Coastal Plain holds only 18 percent of the population, are reflected in the larger integrated DE (man-rem) of the non-Coastal Plain population.

Summary data for the entire United States are presented in the last line of table 15. As can be seen, the average DE of the population due to terrestrial and cosmic ray sources is 84 mrem/yr.; this value will be used to calculate the gonadal DE in section 4.4. The distribution of the population vs. external radiation levels is presented in figure 16. In order to determine the overall distribution of population DE in figure 16, the terrestrial DE in each population segment was assumed to be distributed as shown in figure 15, except for those segments in ARMS areas for which the terrestrial DE could be directly estimated. In other words, those population segments in table A–1 for which a general estimate of terrestrial DE is given (22.8 or 45.6 mrem/yr.)

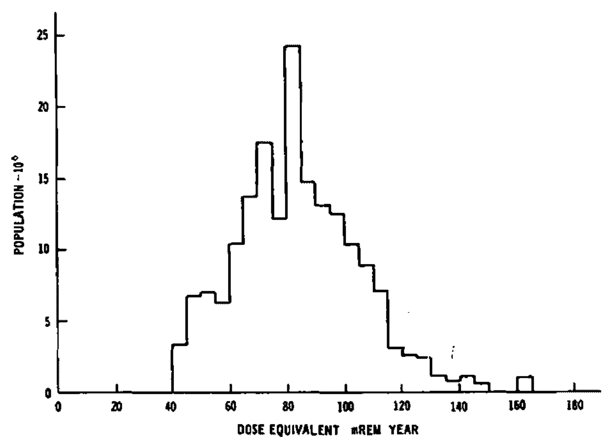

Figure 16. Population distribution vs. dose equivalent from terrestrial and cosmic radiation

were assumed to have a variation in terrestrial DE as shown in figure 15. A cumulative distribution of population vs. DE is presented in figure 17. As can be seen, virtually the entire population receives less than 170 mrem/yr.

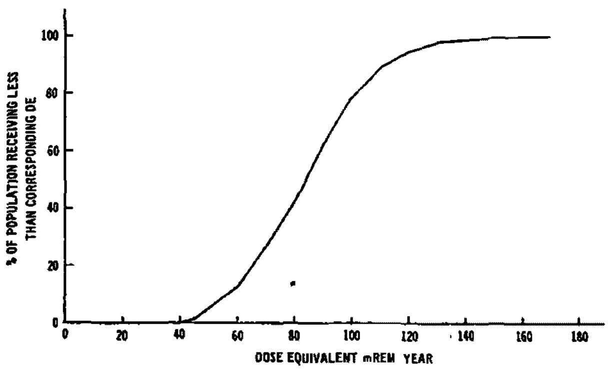

Figure 17. Cumulative distribution of population vs. dose equivalent from terrestrial and cosmic rediation

The distribution in figure 16 should be regarded as an approximation of the population distribution vs. external DE since the distribution is based upon aerial surveys of terrestrial DE rather than on estimates of population DE within the survey areas. It should also be noted that the distribution is based on the two quite different distributions of terrestrial DE in the Coastal and non-Coastal Plain regions, as shown in figure 15. The contribution of the Coastal Plain distribution of terrestrial DE, which is skewed strongly to the right, is muted in figure 16 since only 18 percent of the population resides in the Coastal Plain.

4.2. Attenuation of External Sources

The estimate of man's DE which was presented in section 4.1 is that due to natural external radiation sources and is based on outdoor measurements. In this section, the effect on the DE of housing construction materials, biological shielding and the contribution of internal emitters, principally potassium-40, will be discussed.

4.2.1. Housing

Inasmuch as man spends most of his time indoors, the nature of construction materials will influence his exposure to natural sources. In general, the interiors of stone houses have the highest exposure rates; brick and frame houses have the next highest. The amount of time spent indoors will, of course, determine the importance of construction materials as a source. Estimates of both factors, time and the amount of natural radioactivity in building materials, are based on relatively little data, and probably represent the greatest uncertainty in estimating man's exposure to natural sources.

A summary of indoor measurements is presented in table 16. As can be seen, exposures in

Table 16. Ratio of indoor to outdoor dose equivalent

Country and reference	Building material (outer walls)	Ratio of indoor/outdoor DE (%)	Remarks
United States: Solon et al. (1960)	Frame, brick, and stone apartments and houses	Approx. 80–100	17 dwellings
United States: Lowder and Condon (1965)	Mostly wood frame	70	160 single homes
East Germany: Ohlsen (1969)	Pre-1945 half-frame	78	667 indoor measurements
	Pre-1945 stone	106	
	Pre-1945 brick	81	
	Post-1945 brick	72	Single homes and apartments
	Post-1945 prefabricated	68	
	Post-1945 mixed	66	
	All buildings	82	
Poland: Pensko et al. (1969)	Concrete and brick	102	732 measurements in 97 new apartments
United States: Yeates et al. (1970)	Frame	82	5 single homes. 1st floor
	Brick	96	1 apartment. 2nd floor
	Steel and concrete	87–106	4 office buildings
United States: Lindeken et al. (1971)	Mostly wood frame (96%)	75	110 single homes

frame dwellings are 70 to 80 percent of outdoor values. In masonry buildings the percentage is somewhat higher (80 to 106 percent), which indicates that the DE from nuclides in the building material partially offsets the attenuation of outdoor terrestrial sources. It is interesting to note that the second-floor measurements by Yeates et al. (1970) in single family frame houses averaged 84 percent of the first-floor measurements. In a multistory building of masonry construction, however, there is no apparent variation of the DE with height in the building (Ohlsen, 1970; Pensko et al., 1969). The comprehensive measurements by Ohlsen indicate that buildings of more recent construction (since 1945) tend to have lower indoor DE rates than older buildings, at least in the German Democratic Republic (DDR). Although buildings of "mixed" construction materials may include a number of variations, the low inside DE ratio for this type of construction possibly reflects the increased use of glass, plastics, steel, aluminum, and other materials containing relatively little natural radioactivity.

In order to determine what effect building construction might have on natural exposures, it is necessary to make assumptions on how people spend their time in various activities. A basic approach to this problem has been taken in appendix B, in which it is estimated that indoor living habits of the United States result in the population receiving 80 percent of the outdoor DE.

4.2.2. Biological shielding

The estimates of DE in section 4.1 are for tissue with no self-shielding. Since the gonadal DE and bone marrow DE are often used for dose-risk assessment, it is necessary to determine the effect of buildup and attenuation of radiation in the overlying tissue. The most widely quoted reference on this subject, UNSCEAR (1962), recommends a screening factor of 0.6 for gonadal and bone marrow dose rates from terrestrial radiation. This factor was partly based on the work of Spiers (1956), who found that terrestrial gamma radiation was reduced by factors of 0.52 to 0.59 depending on the body orientation. In males, the screening factor varied from 0.67 to 0.72. In both sexes, the least attenuation (i.e., highest screening factor) occurred in the standing position, the greatest attenuation was provided in a horizontal position, and intermediate attenuation occurred in a sitting position.

More recent work by Bennett (1970) indicates that the gonadal screening factor, averaged over both sexes, is 0.82, and a personal communication from Bennett indicated that he believes the bone marrow screening factor also to be closer to 0.8. In addition to discussing limitations of earlier work, Bennett also has inferred similar screening factors from work by Jones (1966) and Clifford and Facey (1970). Based on these data, it is assumed that in the present work a screening factor of 0.8 describes the biological shielding of the gonads and bone marrow by overlying tissue. The shielding factor is assumed to apply to the terrestrial component of background radiation and not to cosmic radiation, which is more penetrating. This is the same approach used by UNSCEAR (1962, 1966).

4.3. Internal Sources

This study is devoted primarily to natural external sources of radiation, which have been discussed in the preceding sections; however, in order to arrive at an overall estimate of whole body exposure, the contribution of internal natural emitters also must be considered.

The average potassium content of the body is about 0.2 percent. On the basis of g K/kg body weight, males show higher values past the age of puberty, but this is related to the difference in fat content of the body since fat contains relatively little potassium (Anderson and Langham, 1958). Females have more fatty tissue than males and therefore have a lower ratio of g K/kg body weight. Ninety percent of the tissue DE from potassium-40 is due to β particles (range = 2 mm in tissue); the remaining 10 percent is due to gamma rays (Rundo, 1960). Therefore, the tissue DE is largely determined by the potassium-40 concentrations within the tissue in question.

Gonadal concentrations of potassium in the U.S. population are 0.2 percent and 0.14 percent for males and females, respectively (Tipton and Cook, 1963); these concentrations correspond to

DE rates of 19 and 13 mrem/yr., assuming the conversion factor calculated by Rundo (1960). For the purpose of estimating gonadal DE, an average of these two values, 16 mrem/yr., will be assumed. Other internally deposited natural nuclides, principally rubidium-87, carbon-14, radium-226, radium-228, polonium-216, and radon-222, are assumed to result in DE rates to the gonads and bone marrow of 2 mrem/yr. (UNSCEAR, 1966). These estimates will be presented in section 4.4, in which the overall estimate of population DE is made.

4.4. Dose Equivalent to the Gonads and Bone Marrow

Table 17 presents a summary of gonadal DE to the U.S. population. The estimates for cosmic and terrestrial exposure are based upon the results of section 4.1, and the terrestrial DE contribution has been reduced by the housing and gonadal screening factors of section 4.2. As can be seen, the estimate of DE to the gonads from natural radiation sources is 88 mrem/yr. Since all members of the population are exposed to background radiation, the gonadal DE is also equivalent to the genetically significant DE. It should be noted that the reduction of terrestrial radiation contribution to gonadal DE is 14 mrem/yr. due to biological and housing attenuation. However, this reduction is offset by the contribution of internal emitters (18 mrem/yr.). With this in mind, it can be seen that figures 16 and 17 are also reasonable approximations of the population distribution vs. gonadal DE.

Table 17. Gonadal dose equivalent to the U.S. population from natural radiation

Source	Dose equivalent (mrem/yr.)
External	
Terrestrial	26
Housing factor = 0.80 (section 4.2.1)	
Screening factor = 0.80 (section 4.2.2)	
Cosmic	44
Internal	
Potassium-40	16
Other nuclides	2
Total	88

Estimates of DE to the bone marrow from internally deposited nuclides are 15 mrem/yr. because of potassium-40 and 2 mrem/yr. because of the other nuclides mentioned in section 4.4.3 (UNSCEAR, 1966). As has been discussed, the same biological screening factor is assumed for bone marrow as for gonads, so that the bone marrow DE from terrestrial and cosmic sources is the same as that presented in table 17, or 70 mrem/yr. Thus, the total bone marrow DE from natural sources is 87 mrem/yr.

The estimate of gonadal DE in table 17 is considerably lower than the UNSCEAR (1962) worldwide estimate of 125 mrem/yr., which is often cited in the United States as the "baseline" radiation level against which manmade radiation sources are compared. If the relative importance of manmade sources is evaluated by comparing the magnitude of manmade and natural radiation DE, as is often done, then it follows that manmade radiation sources must be considered as a more significant portion of man's total exposure to ionizing radiation.

4.5. Discussion

The estimates of DE in the present work are based upon measurements and census and housing data from many different sources. For this reason it is not possible to calculate the variance of the end result in the conventional manner. It is possible, however, to discuss the uncertainties which affect the separate components of the overall totals and, based on the uncertainties, to estimate the accuracy of the several important factors. These contributing errors are taken to represent in each case a sample at the 95 percent probability level drawn from a normal population of observations.

Cosmic radiation accounts for approximately 40 to 70 percent of the external radiation DE to the U.S. population. The ionizing and neutron components contribute about 85 and 15 percent, respectively, of the cosmic ray DE. The estimate of the sea-level ionization values, from which the DE estimates are derived, is probably within 10 percent of the true value; however, the sea-level neutron value may be in error by as much as 50 percent. As a result, the cosmic ray DE at a specified elevation is probably within 12 percent of the true value.

At this point it is appropriate to discuss the uncertainties present in the determination of the terrestrial DE, which is based upon the aerial data conversion values discussed in section 3.3.3. In this regard, there are three observations to be made on the conversion determination. First, three of the four individual conversion determinations (1., 2., and 3.) in section 3.3.3. required a cosmic ray correction. The relationship is such that, for example, a 10 percent decrease in the cosmic ray DE will result in approximately a 7 percent increase in the terrestrial DE estimate, so that the net effect of a change in the cosmic ray DE on the overall DE estimate is small.

Secondly, it should be noted that the fallout correction value does not have a significant influence on the final conversion factor. For example, if the fallout correction in conversions "1, 2, and 3" in section 3.3.3. were increased by 100 percent (3.2, 1.8, 1.8, respectively) the average terrestrial DE decreases by 20 percent (from 40 to 32 mrem/yr.), and the overall DE decreases by approximately 10 percent (from 84 to 76 mrem/yr.). It should be noted that a 100 percent *decrease* in the present fallout estimates will have a smaller effect—approximately a 10 percent increase in the terrestrial DE and 5 percent increase in the overall DE.

Thirdly, since the terrestrial and cosmic ray DE are approximately the same, an arbitrary change in the conversion value (with no change in cosmic ray DE) will have a smaller impact on the combined estimate. For example, a 10 percent change in the conversion value (and terrestrial DE) will result in a 5 percent change in the overall DE.

The average terrestrial DE estimated for the entire United States is probably within 20 percent of the true value. Support for this belief rests primarily on the similarity in ARMS estimates of ground DE rates and the spectrometric data-DE estimates by Beck (1966b). The accuracy of DE estimates for individual ARMS areas and urbanized areas within ARMS areas is strongly influenced by the accuracy of the weapons fallout DE during the time of each survey. During much of the 1961 to 1963 period, for example, the DE from weapons-testing fallout was 50 percent or more of the natural terrestrial DE. As a result the DE estimates for the ARMS areas are probably within 30 percent of the true value. Most of the locations in appendix A were assigned terrestrial DE values based on location —either Coastal Plain or non-Coastal Plain. These estimates may be in error by 50 percent.

The estimate of the contribution of internal emitters to gonadal and bone marrow DE is probably within 30 percent of the true value. The estimate in this work is slightly lower than the commonly quoted UNSCEAR (1962) estimate of 25 mrem/yr., and this is due to the use of more recent and complete data for the potassium-40 contribution to the total.

The biological shielding factor used in this work is believed to be within 10 percent of the true value, based upon the similarity of recent estimates (Bennett, 1970). As has already been mentioned, the other major modifying influence on the natural radiation source term is the contribution and attenuation by housing. Even with the uncertainties present in the development of the housing factor, it seems unlikely that this factor is in error by more than 20 percent. The amount of time spent outdoors is based on little more than a guess; however, if this proportion were 0.25 instead of 0.05, the housing factor would only increase to 0.84, or by 5 percent.

A summary of the error estimates is presented in table 18, and as can be seen the gonadal DE is 88 ± 11 mrem/yr. The error of the bone marrow DE also may be assumed to be the same. The error calculation tends to impart an unintended sense of precision to the overall estimate. Therefore, one may wish to say that the estimate

Table 18. Estimate of errors in determining the gonadal dose equivalent (appendix C)

Parameter	Value	2σ estimate
Terrestrial DE [a]	40	8
Housing factor	0.8	0.16
Tissue screening factor	.8	.08
Cosmic DE	44	5
Internal emitters	18	5
Gonadal DE	88	11

[a] Note that the contribution of terrestrial DE to gonadal DE is 0.8 × 0.8 × 40 mrem/yr., or 26 mrem/yr. Thus, the total gonadal DE is 26 + 44 + 18 = 88 mrem/yr.

of the average gonadal and bone marrow DE is approximately 90 mrem/yr.

In summary, the average DE from terrestrial radiation (unattenuated by housing or biological shielding) and cosmic radiation to the U.S. population is 84 mrem/yr. There are three distinct areas of different population DE—the Coastal Plain, non-Coastal Plain (excluding Denver), and Denver vicinity. Eighteen percent of the population lives in the Coastal Plain, where the mean DE is 65 mrem/yr., and 82 percent lives in non-Coastal Plain regions where the mean DE is 88 mrem/yr. The Denver area, which has approximately 0.5 percent of the population, receives 165 mrem/yr. Population DE in the United States probably varies by a factor of 7.5, from approximately 40 to 300 mrem/yr.

In view of the uncertainties which affect the development of natural radiation exposure estimates, one may question the improvement of the results over earlier estimates and the usefulness of the results. The use of the ARMS data has provided a basis for directly estimating the natural exposure of approximately 30 percent of the U.S. population, which is a considerably larger sample than can be associated with previous ground surveys. In addition, the same data indicate the existence of three distinct areas of terrestrial radiation in the United States. Through the determination of the U.S. population distribution vs. elevation, it is now possible to cite State-to-State differences in cosmic ray DE.

The present data may be used as a guide to the average U.S. background radiation exposure and as reasonable estimates of background exposure in the areas for which ARMS data exist. Caution is advised when using the total DE estimates for locations in which general terrestrial DE values have been assigned, although the total DE estimates for these locations are of value in assessing the relative contribution of cosmic ray DE. The DE estimation procedure outlined in appendix A may be refined as more specific data become available on natural radiation DE rates in various sections of the country. Similarly, information concerning living habits may easily be factored into the computation, and the author would be grateful for any information which could be used for updating and improving the present DE estimates.

SUMMARY

Natural background constitutes the greatest source of ionizing radiation to the world's population today. This exposure is by no means uniform for all individuals, but varies because of a number of influencing factors. Such factors include altitude, geological features, and living habits. The resulting variations in exposures often exceed those from manmade sources which generally receive considerably more attention. For example, although no detailed overall study of the subject has been made, published data indicate that the genetically significant dose equivalent (DE) from natural background in the United States ranges from 80 to 200 mrem/yr. A survey conducted by the U.S. Public Health Service in 1964 indicated that the comparable dose from medical x radiation was only 55 mrem/yr. Other sources, such as nuclear reactors, fallout from atmospheric weapons tests, etc., account for a DE less than 5 mrem/yr.

The purposes of this study of natural radiation exposure in the United States were to better estimate population dose from radiation of natural origin, to investigate the DE variations that occur, and to examine the parameters that influence both the levels and the variations so that the relative importance of manmade exposures can be better evaluated. In undertaking these tasks, it was recognized that external exposure to terrestrial radiation sources, a primary component of natural background exposure, can be estimated by direct measurements or calculated on the basis of knowledge of chemical assays of natural emitters in the soil. Direct measurements and soil analyses, however, have not been sufficiently extensive to provide adequate data to make an overall estimate of the population DE in the United States. For these reasons, alternate methods were sought and an answer was found in the series of ARMS conducted over major areas of the United States under sponsorship of the AEC

A second major component of natural background exposure to the population is cosmic radiation. The DE from this source was computed on the basis of knowledge of the distribution of population with elevation. The third, and last, major component of population dose from natural background, that is, exposure from naturally occurring radionuclides deposited within the body, was calculated on the basis of published information. Once data were available for the DE from each of the three major components of natural background, a combined estimate of the total cosmic and terrestrial DE was made taking into account what is known concerning the distribution of population by elevation, geology, and living habits. These data were then combined with those for internal exposure to yield a final estimate of total population dose from natural sources.

The primary problem in using the information resulting from the ARMS surveys was in converting the count rate data taken at altitude into DE rate data at ground level. In addition, there was the necessity in certain cases of subtracting the contribution of weapons testing fallout from the ARMS readings. Suitable corrections for this latter factor were made, and a conversion factor for the ARMS data was determined by correlating the measurements at a number of points with readings made at 3 feet above ground level. The mean terrestrial DE, obtained on the basis of 25 areas surveyed under the ARMS program and weighted for the population of each area, was computed to be 44 mrem/yr. This value compared well with results from limited ground surveys

within the United States, which are summarized in the text.

On the basis of an analysis of the ARMS data, it appears that the United States can be divided into three distinct terrestrial radiation zones, or areas. One is the Atlantic and Gulf Coastal Plain, which includes all or portions of all States bordering the Atlantic Ocean and Gulf of Mexico from Texas to New Jersey. For this area, the mean terrestrial DE was 22.8 mrem/yr. The second area is a portion of the Colorado Front Range, on the eastern slope of the Rocky Mountains, which yielded a mean terrestrial DE rate of 89.7 mrem/yr. This is somewhat as expected since this area (approximately 7,000 square miles) has crustal concentrations of natural radionuclides which have been shown to be approximately twice the U.S. average. The DE in the rest of the United States, that is, excluding the Coastal Plain and the Colorado Range, was calculated to be 45.6 mrem/yr. When the distribution of the population in the three zones was considered, the mean terrestrial DE in the United States was calculated to be 40 mrem/yr.

A detailed analysis of the distribution of population with elevation showed that 83 percent of the people in the United States live in areas with an elevation of less than 1,000 feet. Populated areas, however, occur up to 10,500 feet. At sea level, the ionizing and neutron components of cosmic radiation result in DE of 35 and 6 mrem/yr. for a total of 41 mrem/yr. The DE increases to 44 mrem/yr. at 1,000 feet and ranges up to 162 mrem/yr. at 10,500 feet. On this basis, the DE from cosmic radiation for various population groups in the United States varies by a factor of 4. Overall, the calculations revealed that the average DE from this source in the United States was 44 mrem/yr.

Combining the DE from terrestrial and cosmic radiation, the average DE to the U.S. population from natural external radiation was computed to be 84 mrem/yr. per person. Based on the 1960 census, this results in an integrated DE of 15.1 million man-rem/yr. The range in DE in the United States is 40 to 300 mrem/yr.; however, almost the entire population receives less than 170 mrem/yr.

For the purpose of determining the DE to the gonads and bone marrow, the influence of housing, biological shielding, and internal emitters was also considered. A "housing factor" was computed to take into account the attenuation of terrestrial radiation due to building materials. This factor included allowances for the major types of building materials in use in the United States and for the percentage of total time spent indoors by the population. Also included in the calculations was the attenuation of terrestrial radiation by body tissues. On the basis of these considerations, the ratio of indoor to outdoor DE from terrestrial sources was calculated to be 0.8; coincidentally the biological "screening factor" was estimated to be 0.8. Allowing for these factors and a DE from internally deposited radionuclides of 18 mrem/yr. to the gonads and 17 mrem/yr. to the bone marrow, the total gonadal and bone marrow DE for the U.S. population were calculated to be 88 and 87 mrem/yr., respectively.

It is to be noted that the gonadal DE as calculated in this study is considerably lower than the UNSCEAR worldwide estimate of 125 mrem/yr., which is often cited in the United States as the "baseline" radiation level against which manmade radiation sources are compared. If the results of this study are true, it is quite probable that certain manmade sources, particularly medical x radiation, will now be given greater importance in terms of their overall contribution to the population's total dose.

REFERENCES

Adams, J. A. S., Osmond, J. K., and Rogers, J. J. W. (1959): The geochemistry of thorium and uranium. In Physics and Chemistry of the Earth, Volume III. Pergammon Press, New York, N.Y., pp. 298–348.

Anderson, E. C. and Langham, W. H. (1958): Average potassium concentration of the human body as a function of age. Science 130:713–714.

Bates, R. G. (1962): Aeroradioactivity survey and areal geology of the Oak Ridge National Laboratory area, Tennessee and Kentucky (ARMS–I), USAEC Document CEX–59.4.15.

Bates, R. G. (1965): Aeroradioactivity survey and areal geology of the National Reactor Testing Station area, Idaho (ARMS–I), USAEC Document CEX–59.4.10.

Bates, R. G. (1966a): Aeroradioactivity survey and areal geology of the Pittsburgh area, Pennsylvania, Ohio, West Virginia and Maryland (ARMS–I), USAEC Document CEX–59.4.12.

Bates, R. G. (1966b): Aeroradioactivity survey and areal geology of parts of Ohio and Indiana (ARMS–I), USAEC Document CEX–59.4.23.

Beck, H. L., Condon, W. J., and Lowder, W. M. (1964a): Environmental radiation measurements in the southeastern, central and western United States, 1962–63, USAEC Document HASL–145.

Beck, H. L., Condon, W. J., and Lowder, W. M. (1964b): Spectrometric techniques for measuring environmental gamma radiation, USAEC Document HASL–150.

Beck, H. L., Lowder, W. M., Bennett, B. G., and Condon, W. J. (1966a): Further studies of external environmental radiation, USAEC Document HASL–170.

Beck, H. L. (1966b): Environmental gamma radiation from deposited fission products. Health Phys 12:313–322.

Beck, H. and de Planque, G. (1968): The radiation field in air due to distributed gamma-ray sources in the ground, USAEC Document HASL–195.

Bennett, B. G. (1970): Estimation of gonadal absorbed dose due to environmental gamma radiation. Health Phys 19:757–767.

Billings, M. P. (1961): Areal distribution of natural radioactivity from rocks in northern New England. Geology Department, Harvard University, Cambridge, Mass. (Unpublished manuscript).

Black, D. I. (1967): Cosmic ray effects and faunal extinctions at geomagnetic field reversals. Earth Planet Sci Letters 3:225–236.

Books, K. G. (1962): Aeroradioactivity survey and related surface geology of parts of the Los Angeles region, California (ARMS–I), USAEC Document CEX–59.4.16.

Books, K. G. (1966): Aeroradioactivity survey and related surface geology of parts of the San Francisco region, California (ARMS–I), USAEC Document CEX–58.4.5.

Bowen, I. S., Millikan, R. A., and Neher, H. (1934): A very high altitude survey of the effect of latitude upon cosmic-ray intensities and an attempt at a general interpolation of cosmic-ray phenomena. Phys. Rev. 46:641–652.

Cember, H. (1969): Introduction to health physics. Pergammon Press, New York, N.Y.

Cherry, R. D., Shay, M. M., and Shannon, L. V. (1970): Natural alpha-radioactivity concentrations in bone and liver from various animal species. Nature 228:1002–1003.

Clark, Jr., S. P., Peterman, Z. E., and Heier, K. S. (1966): Abundances of uranium, thorium and potassium. In Handbook of Physical Constants (Revised edition). Geological Society of America, Inc., New York, N.Y., pp. 521–541.

Clifford, C. E. and Facey, R. A. (1970): Changes in acute radiation hazards associated with changes in exposure geometry. Health Phys 18:217–225.

Davis, F. J. and Reinhardt, P. W. (1962): Radiation measurements over simulated plane sources. Health Phys 8:233–243.

Federal Radiation Council (1967): Guidance for the control of radiation hazards in uranium mining. Report No. 8 (Revised). Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Finch, W. I. (1967): Geology of epigenetic uranium deposits in sandstone in the United States. Professional Paper 538, U.S. Geological Survey. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Flint, Jr., G. M. and Pitkin, J. A. (1970): Aeroradioactivity survey and related surface geology of the Chicago area, Illinois and Indiana (ARMS–I), USAEC Document CEX–59.4.13.

Forbush, S. E. (1938): On worldwide changes in cosmic-ray intensity, Phys Rev 54:975–988.

Forbush, S. E. (1954): World-wide cosmic ray variations, 1937–1952. J Geophys Res 59:525–542.

Forbush, S. E. (1958): Cosmic ray intensity variations during two solar cycles. J Geophys Res 63:651–669.

Gannett, H. (1894): The average elevation of the United States. In The Thirteenth Annual Report of the Director, 1891–1892. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. pp. 284–289.

Gannett, H. (1906): A dictionary of altitudes in the United States (Fourth edition). U.S. Geological Survey, Bulletin 274. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Gannett, H. (1916): United States contour map. U.S. Geological Survey, Washington, D.C.

Gentry, J. T., Parkhurst, E., and Bulin, Jr., G. V. (1959): An epidemiological study of congenital malformations in New York State. Amer J Public Health 49:497–513.

George, M. J. (1970): New data on the absolute cosmic ray ionization in the lower atmosphere. J Geophys Res 75:3693–3705.
Gold, S., Barkhau, H. W., Shleien, B., and Kahn, B. (1964): Measurement of naturally occurring radionuclides in air. In The Natural Radiation Environment. University of Chicago Press, Chicago, Ill. pp. 369–382.
Golden, Jr., J. C. (1968): Natural background radiation levels in Florida. Sandia Corporation Document SC-RR-68-196.
Grahn, D. and Kratchman, J. (1963): Variation in neonatal death rate and birth weight in the U.S. and possible relations to environmental radiation, geology and altitude. Amer J Hum Genet 15:329–352.
Guillou, R. B. (1963a): Camden-Delaware Valley area (ARMS-II), USAEC Document CEX-61.6.3.
Guillou, R. B. (1963b): Norfolk-Peninsula area (ARMS-II), USAEC Document CEX-61.6.4.
Guillou, R. B. (1963c): Galveston area (ARMS-I), USAEC Document CEX-62.6.1.
Guillou, R. B., Hands, J. E., and Borella, H. M. (1963): Las Vegas area (ARMS-II), USAEC Document CEX-61.6.1.
Guillou, R. B. (1964): The aerial radiological measuring surveys (ARMS) program. In The Natural Radiation Environment. University of Chicago Press, Chicago, Ill. pp. 705–721.
Guillou, R. B. (1965): Arguello area (ARMS-II), USAEC Document CEX-62.6.3.
Guillou, R. B. (1966a): Parr area (ARMS-II), USAEC Document CEX-63.6.2.
Guillou, R. B. (1966b): Orlando area (ARMS-II), USAEC Document CEX-63.6.1.
Guillou, R. B. (1966c): Cincinnati area (ARMS-II), USAEC Document CEX-62.6.5.
Guillou, R. B. (1966d): Albuquerque-Los Alamos area (ARMS-II), USAEC Document CEX-61.6.2.
Haffner, J. W. (1967): Radiation and shielding in space. Academic Press, New York, N.Y.
Hajnal, F., McLaughlin, J. E., Weinstein, M. S., and O'Brien, K. (1971): 1970 sea level cosmic ray neutron measurements, USAEC Document HASL-241.
Harley, J. H. (1953): Sampling and measurement of airborne daughter products of radon. Nucleonics 11:12–15.
Hayakawa, S. (1969): Cosmic ray physics. John Wiley and Sons, New York, N.Y.
Heier, K. S. and Billings, G. K. (1969): Potassium. In the Handbook of Geochemistry (Chapter 19). Springer-Verlag, Berlin.
Herbst, W. (1964): Investigations of environmental radiation and its variability. In The Natural Radiation Environment. University of Chicago Press, Chicago, Ill. pp. 781–796.
Hess, V. F. and Parkinson, W. D. (1953): Small ion balance over the ocean. Fordham University, Department of Physics, Scientific Report No. 2.
Hultqvist, B. (1956): Studies on naturally occurring ionizing radiations. Kgl Svenska Vetenkapsakad Handl 6. No. 3.
ICRU (1971): Radiation quantities and units, Report No. 19. International Commission on Radiation Units and Measurements, Washington, D.C.
Jackson, M. L. (1964): Chemical composition of soils. In Chemistry of the Soil (Second edition, chapter 2). Reinhold Publishing Corporation, New York, N.Y. pp. 71–141.
Jones, A. R. (1966): Proposed calibration factors for various dosimeters at different energies. Health Phys 12:663–671.
Kastner, J., Rose, J. E., and Shonka, F. R. (1963): Muscle equivalent environmental radiation meter of extreme sensitivity. Science 140:1100–1101.
Kline, S. J. and McClintock, F. A. (1953): Describing uncertainties in single-sample experiments. Mechanical Engineering 75:3–8.
Kogan, R. M., Nazarov, I. M., and Fridman, S. D. (1971): Gamma spectrometry of natural environments and formations. Translated from Russian by Israel Program for Scientific Translations, Ltd., Document No. TT 70-50092. National Technical Information Service, Springfield, Va. 22151.
Korff, S. A. (1964): Production of neutrons by cosmic radiation. In The Natural Radiation Environment, University of Chicago Press, Chicago, Ill. pp. 427–440.
Kraner, H. W., Schroeder, G. L., and Evans, R. D. (1964): Measurements of the effects of atmospheric variables on radon-222 flux and soil-gas concentrations. In The Natural Radiation Environment, University of Chicago Press, Chicago, Ill. pp. 191–215.
Kuzmin, A. I. and Skripin, G. V. (1966a): Underground variations in the intensity of cosmic rays in 1957–1959. In Intensity Variations of Cosmic Rays, NASA Document TT F-183, pp. 84–105.
Kuzmin, A. I. and Skripin, G. V. (1966b): Electromagnetic conditions in the earth's neighborhood on May 10–24, 1959. In Intensity Variations of Cosmic Rays, NASA Document TT F-183, pp. 148–158.
Langham, W. H. (1967): Radiobiological factors in manned space flight. National Research Council Publication 1487, National Academy of Sciences.
Levin, S. G., Stoms, R. K., Kuerze, E., and Huskisson, W. (1968): Summary of natural enviromental gamma radiation using a calibrated portable scintillation counter. Radiol. Health Data Rep. 9:679–695.
Lindeken, C. L., Jones, D. E., and McMillen, R. E. (1971): Natural terrestrial background variations between residencies, University of California Document UCRL-72964.
Lowder, W. M. and Solon, L. R. (1956): Background radiation, a literature search, USAEC Document NYO-4712.
Lowder, W. M. and Condon, W. J. (1965): Measurement of the exposure of human populations to environmental radiation. Nature 206:658–662.
Lowder, W. M., Condon, W. J., and Beck, H. L. (1964): Field spectrometric investigations of environmental radiation in the U.S.A. In The Natural Radiation Environment, University of Chicago Press, Chicago, Ill. pp. 597–616.
Lowder, W. M. and Beck, H. L. (1966): Cosmic-ray ionization in the lower atmosphere. J Geophys Res 71:4661–4668.
MacKallor, J. A. (1962): Aeroradioactivity survey and areal geology of the Georgia Nuclear Laboratory area, northern Georgia (ARMS-I), USAEC Document CEX-58.4.8.
MacKallor, J. A. (1965): Aeroradioactivity survey and areal geology of the Gnome (Carlsbad) area, New Mexico and Texas (ARMS-I), USAEC Document CEX-59.4.24.
Magi, A., Snihs, J. O., and Swedjemark, G. A. (1970): Some measurements on radioactivity in Sweden caused by nuclear test explosions. Radiol. Health Data Rep. 11:487–509.
Mahdavi, A. (1964): The thorium, uranium, and potassium contents of Atlantic and Gulf Coast beach sands. In The Natural Radiation Environment. University of Chicago Press, Chicago, Ill. pp. 87–114.
McLaughlin, J. E. (1970): Application of gamma ray spectrometry to environmental radioactive contamination, USAEC Document HASL TM-70-8 (Unpublished data).

Miles, R. F. (1964): Density of cosmic ray neutrons in the atmosphere. J Geophys Res 69:1277–1284.

Millikan, R. A. and Neher, H. V. (1936a): A precision world survey of sea-level cosmic-ray intensities. J Geophys Res 50:15–24.

Millikan, R. A., Neher, H. V., and Haynes, S. K. (1936b): Precision cosmic-ray measurements up to within a percent or two of the top of the atmosphere. Phys Rev 50:992–998.

Neher, H. V. (1967): Cosmic ray particles that changed from 1954 to 1958 to 1965. J Geophys Res 72:1527–1539.

Neher, H. V. (1971): Cosmic rays at high latitudes and altitudes covering four solar maxima. J Geophys Res 76:1637–1651.

Neuschel, S. K. (1966): Aeroradioactivity survey and areal geology of the District of Columbia and parts of Maryland, Virginia and West Virginia (ARMS–I), USAEC Document CEX–59.4.17.

Neuschel, S. K. (1970): Aeroradioactivity survey and areal geology of the Minneapolis-Saint Paul area, Minnesota-Wisconsin (ARMS–I), USAEC Document CEX–61.7.1.

O'Brien, K. and McLaughlin, J. E. (1970): Calculation of dose and dose-equivalent rates to man in the atmosphere from galactic cosmic rays. USAEC Document HASL–228.

Ohlsen, H. (1969): Bestimmung der mittleren Bevolkerungsbelastung durch naturliche aussere stralung auf dem gebiet der DDR. Staatliche Zentrale fur Strahlenschutz, Report No. SZS–14/69.

Overstreet, W. C. (1967): The geologic occurrence of monazite. Professional Paper 530, U.S. Geological Survey. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Pal, Y. (1967): Cosmic rays and their interactions. (Second edition, chapter 11, part 9) In Handbook of Physics. McGraw-Hill Book Co., New York, N.Y.

Patterson, H. W., Hess, W. N., Moyer, B. J., and Wallace, R. W. (1959): The flux and spectrum of cosmic-ray produced neutrons as a function of altitude. Health Phys 2:69–72.

Pensko, J., Mamont, K., and Wardaszko, T. (1969): Measurements of ionizing radiation doses in dwellings in Poland. Nukleonika 14:415–424.

Pershagen, A. H. (1969): Snow cover in Sweden 1931–1960. Sveriges Meteorologiska och Hydrologiska Institut, Communication Series A. No. 5.

Peterman, Z. E. (1963): Geochemistry of uranium and thorium. (Unpublished data). U.S. Geological Survey, Washington, D.C.

Phair, G. and Gottfried, D. (1964): The Colorado Front Range, Colorado, U.S.A. as a uranium and thorium province. In The Natural Radiation Environment, University of Chicago Press, Chicago, Ill. pp. 7–38.

Popenoe, P. (1964): Aeroradioactivity survey and areal geology of parts of east-central New York and west-central New England (ARMS–I), USAEC Document CEX–59.4.14.

Popenoe, P. (1966a): Aeroradioactivity survey and areal geology of parts of southeastern New York and southern New England (ARMS–I), USAEC Document CEX–58.4.6.

Popenoe, P. (1966b): Aeroradioactivity survey and areal geology of the Denver area, Colorado (ARMS–I), USAEC Document CEX–59.4.26.

Raft, P. D., Lowder, W. M., and Beck, H. L. (1970): Measurements of cosmic ray ionization in the atmosphere, 1968–1970. USAEC Document HASL–234.

Rand McNally (1971): 1971 Commercial Atlas and Marketing Guide. Rand McNally and Co., Chicago, Ill.

Robinson, J. P. and Converse, P. E. (1966): Summary of United States time use survey. Institute for Social Research, University of Michigan, Ann Arbor, Mich.

Rossi, B. (1964): Cosmic rays. McGraw-Hill Book Co., New York, N.Y.

Rundo, J. (1960): Radiocesium in human beings. Nature 188:703–706.

Sagan, L. A. (1971): Human radiation effect: an overview. Health Phys 21:827–833.

Sandstrom, A. E. (1965): Cosmic ray physics. North-Holland Pub. Co. Amsterdam.

Schmidt, R. G. (1962a): Aeroradioactivity survey and areal geology of the Savannah River Plant area, South Carolina and Georgia (ARMS–I), USAEC Document CEX–58.4.2.

Schmidt, R. G. (1962b): Aeroradioactivity survey and areal geology of the Hanford Plant area, Washington and Oregon (ARMS–I), USAEC Document CEX–59.4.11.

Segall, A. (1963): Radiogeology and population exposure to background radiation in northern New England. Science 140:1337–1339.

Segall, A., MacMahon, B., and Hannigan, M. (1964): Congenital malformations and background radiation in northern New England. J Chron Dis 17:915–932.

Segall, A. and Reed, R. (1964): Human exposure to external background radiation. Arch Env Health 9:492–499.

Shamos, M. H. and Liboff, A. R. (1966): A new measurement of the intensity of cosmic ray ionization at sea level. J Geophys Res 71:4651–4659.

Sievert, R. M. and Hultqvist, B. (1952): Variations in natural gamma radiation in Sweden. Acta Radiol 37:388–398.

Solon, L. R. (1960): Dosimetry of natural ionizing radiation. (Ph.D. Thesis) New York University, New York, N.Y.

Solon, L. R., Lowder, W. M., Shambon, A. and Blatz, H. (1960): Investigations of natural environmental radiation. Science 131:903–906.

Spiers, F. W. (1956): Radioactivity in man and his environment. Brit J Rad 29:409–417.

Stephens, L. D., Patterson, H. W. and Smith, A. R. (1961): Fallout and natural background in the San Francisco Bay area. Health Phys 4:267–274.

Straub, C. P., Carter, M. W., and Moeller, D. W. (1964): Environmental behavior of nuclear debris. J Sanitary Engineering Division, ASCE, 90, No. SA6, Proceedings Paper 4159, December, 1964, pp. 25–40.

Tipton, I. H. and Cook, M. J. (1963): Trace elements in human tissue. Part II. Adult subjects from the United States. Health Phys 9:103–145.

U.S. Census Bureau (1960): 1960 Census of Housing. Volume I. States and small areas, Part 1—U.S. summary. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

U.S. Census Bureau (1963): Population distribution, urban and rural, in the United States: 1960. Map G.E. 50, No. 1. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

U.S. Census Bureau (1969): Statistical Abstract of the United States. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

U.S. Department of Housing and Urban Development (1969): Annual statistical summary—1968. Department of Housing and Urban Development, Washington, D.C.

U.S. Geological Survey (1970): Geology, a map in the U.S. National Atlas. U.S. Geological Survey, Washington, D.C.

U.S. Public Health Service (1969): Population dose from

X rays, U.S. 1964, Publication No. 2001. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

U.S. Public Health Service (1970): Radiological Health Handbook (Revised edition). Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

UNSCEAR (1962): Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. Seventeenth session. Supplement No. 16 (A/5216). United Nations, New York, N.Y.

UNSCEAR (1964): Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. Nineteenth session. Supplement No. 14 (A/5814). United Nations, New York, N.Y.

UNSCEAR (1966): Report of the United Nations Scientific Committee on the Effects of Atomic Radiation. Twenty-first session, Supplement No. 14 (A/6314). United Nations, New York, N.Y.

Upton, A. C. (1966): Radiobiological aspects of the supersonic transport. A report of the ICRP task group on the biological effects of high-energy radiations. Health Phys 12:209–226.

Watt, D. E. (1967): Dose equivalent rate from cosmic ray neutrons. Health Phys 13:501–507.

Wedepohl, K. H., Exec. Ed. (1969): Handbook of geochemistry. Springer-Verlag. Berlin.

Weng, P. S. and Huang, C. Y. (1970): Background activity of Taiwan. Presentation at fifteenth annual meeting of the Health Physics Society, Chicago, Illinois, June 28–July 2, 1970.

Wesley, J. P. (1960): Background radiation as the cause of fatal congenital malformation. Int J Rad Biol 2:97–118.

Wollenberg, H. A., Patterson, H. W., Smith, A. R., and Stephens, L. D. (1969): Natural and fallout radioactivity in the San Francisco Bay area. Health Phys 17:313–321.

Yamagata, N. and Iwashima, K. (1967): Terrestrial background radiation in Japan. Health Phys 13:1145–1148.

Yeates, D. B., Goldin, A. S., and Moeller, D. W. (1970): Radiation from natural sources in the urban environment, Report No. HSPH/EHS-70-2. Dept. of Environmental Health Sciences, Harvard School of Public Health.

Yeates, D. B., Goldin, A. S., and Moeller, D. W. (1972): Radiation from natural sources in the urban environment (to be published in Nuclear Safety).

APPENDICES

APPENDIX A

Calculation of Average Dose Equivalents due to Terrestrial and Cosmic Radiation [4]

Table A–1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and unurbanized areas

Table A–2. Total calculation of average dose equivalents due to terrestrial and cosmic radiation by States

Table A–3. Program to calculate average dose equivalents from terrestrial and cosmic radiation

[4] Some of the values in the following tables are presented in tenths of mrem/yr. This was done in order to avoid rounding off errors, and one should not assume that the data are known to the accuracy indicated by the numbers.

Table A-1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and nonurbanized areas

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	 6 ION	 7=5+6 TOTAL	8 TERR DOSE EQ MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
BIRMINGHAM AL	521330	600	44	6.4	36.4	42.8	45.6	88.4	46025
COLUMBUS AL-GA	27630	265	43	5.9	35.7	41.7	22.8	64.5	1781
GADSDEN AL	68944	555	44	5.3	36.3	42.7	45.6	88.3	6084
HUNTSVILLE AL	74970	636	45	6.5	36.5	43.0	45.6	88.6	6639
MOBILE AL	268139	15	41	5.6	35.3	40.9	22.8	63.7	17090
MONTGOMERY AL	142893	160	43	5.8	35.5	41.3	22.8	64.1	9166
TUSCALOOSA AL	76815	225	43	5.9	35.6	41.5	22.8	64.3	4942
ALABAMA NU-CP	1020000	250	42	5.9	35.7	41.6	22.8	64.4	65705
ALABAMA NU-NCP	1066019	966	44	6.8	37.1	43.9	45.6	89.5	95372
ALABAMA	3266740	498	43	6.3	36.2	42.5	34.9	77.4	252874
ALASKA NU	226167	250	61	5.9	35.7	41.6	45.6	87.2	19725
ALASKA	226167	250	61	5.9	35.7	41.6	45.6	97.2	19726
PHOENIX AZ	552043	1090	41	7.1	37.7	44.8	45.6	90.4	49921
TUCSON AZ	227433	2390	40	9.5	42.3	51.7	45.6	97.3	22136
ARIZONA NU	522685	3268	42	11.4	46.2	57.5	45.6	103.1	53913
ARIZONA	1302161	2191	42	9.2	41.9	51.1	45.6	96.7	125970
FORT SMITH AR	59778	450	45	6.2	36.1	42.3	45.6	87.9	5253
LITTLE ROCK AR	185017	330	44	6.0	35.8	41.9	22.8	64.7	11966
TEXARKANA AR-TX	20371	336	43	6.0	35.8	41.9	22.8	64.7	1318
ARKANSAS NU-CP	1010000	200	43	5.9	35.6	41.5	22.8	64.3	64906
ARKANSAS NU-NCP	511106	1698	45	8.1	39.6	47.7	45.6	93.3	47709
ARKANSAS	1786272	649	44	6.5	36.8	43.3	30.1	73.4	131151
BAKERSFIELD CA	141763	406	42	6.1	36.0	42.1	45.6	87.7	12436
FRESNO CA	213444	294	43	6.0	35.8	41.8	45.6	87.4	18646
LOS ANGELES CA	6488791	287	41	6.0	35.8	41.7	31.9	73.6	477795
POMONA CA	186547	850	41	6.8	37.0	43.8	45.6	89.4	16677
SACRAMENTO CA	451920	25	45	5.6	35.3	41.0	45.6	86.6	39120
S BERNARDINO CA	377531	1049	41	7.1	37.6	44.6	45.6	90.2	34071
SAN DIEGO CA	836175	42	40	5.7	35.4	41.0	45.6	86.6	72420
S FRANCISCO CA	2430663	63	44	5.7	35.4	41.1	27.6	68.7	166905
SAN JOSE CA	602805	65	44	5.7	35.4	41.1	27.6	68.7	41396
STA BARBARA CA	72740	42	41	5.7	35.4	41.0	35.9	76.9	5594
STOCKTON CA	141604	13	44	5.6	35.3	40.9	45.6	86.5	12253
CALIFORNIA NU	3773221	893	43	6.8	37.1	44.0	45.6	89.6	337996
CALIFORNIA	15717204	391	43	6.1	36.0	42.2	36.4	78.6	1235310
COLORADO SPG CO	100220	5980	48	19.5	63.1	82.6	45.6	128.2	12844
DENVER CO	803624	5280	48	17.0	57.9	74.9	89.7	164.6	132245
PUEBLO CO	103336	4690	47	15.1	54.0	69.1	45.6	114.7	11854
COLORADO NU	746767	5555	48	17.9	59.8	77.8	45.6	123.4	92123
COLORADO	1753947	5402	48	17.4	58.8	76.2	65.8	142.0	249066

1	2	3	4	COSMIC RADIATION DE MREMS/YR			8	9=7+8	10=(2X9)X.001
LOCATION	1960 POPULATION	ELEVATION FEET	MAGLAT DEG NO	5 NEUT	6 ION	7=5+6 TOTAL	TERR DOSE EQ MREMS/YR	TOTAL EXT DE MREMS/YR	MAN-REM
BRIDGEPORT CT	356654	10	53	5.6	35.3	40.9	58.8	99.7	36564
HARTFORD CT	391619	40	53	5.7	35.3	41.0	41.9	82.9	31638
MERIDEN CT	51950	150	53	5.8	35.5	41.3	53.2	94.5	4901
NEW BRITAIN CT	99894	200	53	5.9	35.6	41.5	61.6	103.1	10295
NEW HAVEN CT	278794	40	53	5.7	35.3	41.0	50.3	91.3	25455
NORWALK CT	82270	40	53	5.7	35.3	41.0	70.0	111.0	9132
SPRFIELD CT-MA	31464	85	54	5.7	35.4	41.1	40.0	81.1	2553
STAMFORD CT	166990	35	53	5.6	35.3	41.0	64.4	105.4	17599
WATERBURY CT	141626	260	53	5.9	35.7	41.6	61.6	103.2	14573
CONN NU	934073	344	53	6.1	35.9	41.9	45.6	87.5	81749
CONN	2535234	169	53	5.9	35.6	41.4	51.1	92.5	234509
WILMINGTON DE	266339	135	52	5.8	35.5	41.3	36.2	77.5	20633
DELAWARE NU-CP	179954	60	51	5.7	35.4	41.1	22.8	63.9	11492
DELAWARE	446292	105	51	5.7	35.4	41.2	30.8	72.0	32125
WASH DC	763955	150	50	5.8	35.5	41.3	35.4	76.7	58636
WASH DC	763955	150	50	5.8	35.5	41.3	35.4	76.7	58596
FT LAUD FL	319951	10	37	5.6	35.3	40.9	22.8	63.7	20388
JACKSONVILLE FL	372569	20	41	5.6	35.3	40.9	22.8	63.7	23751
MIAMI FL	852705	10	37	5.6	35.3	40.9	22.8	63.7	54337
ORLANDO FL	200995	70	39	5.7	35.4	41.1	11.6	52.7	10590
PENSACOLA FL	128049	15	41	5.6	35.3	40.9	22.8	63.7	8151
ST PETERSBRG FL	324842	20	38	5.6	35.3	40.9	22.8	63.7	20709
TAMPA FL	301790	15	38	5.6	35.3	40.9	22.8	63.7	19235
W PALM BEACH FL	172935	15	38	5.6	35.3	40.9	22.8	63.7	11016
FLORIDA NU-CP	2277824	100	38	5.7	35.4	41.2	22.8	64.0	145713
FLORIDA	4951560	56	38	5.7	35.4	41.0	22.3	63.4	313899
ALBANY GA	58353	190	42	5.8	35.6	41.4	22.8	64.2	3749
ATLANTA GA	768125	1050	44	7.1	37.6	44.7	57.2	101.9	78235
AUGUSTA GA-SC	113970	143	44	5.8	35.5	41.3	42.8	94.1	9323
CHATTA GA-TN	20290	675	45	6.5	36.6	43.1	45.6	88.7	1801
COLUMBUS GA-AL	130752	265	43	5.9	35.7	41.7	22.8	64.5	8429
MACON GA	114161	335	43	6.0	35.9	41.9	22.8	64.7	7385
SAVANNAH GA	169997	20	43	5.6	35.3	40.9	22.8	63.7	10830
GEORGIA NU-CP	1060000	250	42	5.9	35.7	41.6	22.8	64.4	68292
GEORGIA NU-NCP	1510669	1013	44	7.0	37.5	44.5	45.6	90.1	136096
GEORGIA	3943116	689	43	6.6	36.7	43.3	38.9	92.2	324130
HONOLULU HI	351336	19	21	5.6	35.3	40.9	45.6	86.5	30406
HAWAII NU	281436	307	21	6.0	35.8	41.8	45.6	87.4	24597
HAWAII	632772	147	21	5.9	35.5	41.3	45.6	86.9	55003

Table A-1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and nonurbanized areas—Continued

1	2	3	4	COSMIC RADIATION DE			8	9=7+8	10=(2X9)X.001
LOCATION	1960 POPULATION	ELEVATION FEET	MAGLAT DEG NO	MREMS/YR 5 NEUT	6 ION	7=5+6 TOTAL	TERR DOSE EQ MREMS/YR	TOTAL EXT DE MREMS/YR	MAN-REM
IDAHO NU	667191	3659	51	12.3	48.1	60.4	45.6	106.0	70751
IDAHO	667191	3659	51	12.3	48.1	60.4	45.6	106.0	70751
AURORA IL	85522	636	52	6.5	36.5	43.0	38.6	81.6	6975
CHAMPAIGN IL	78014	740	50	6.6	36.7	43.4	45.6	89.0	6940
CHICAGO IL	5480267	595	52	6.4	36.4	42.8	38.6	81.4	446089
DAVENPORT IL-IA	126158	590	51	6.4	36.4	42.8	45.6	88.4	11150
DECATUR IL	89516	682	50	6.5	36.6	43.1	45.6	88.7	7943
DUBUQUE IL-IA	2082	645	52	6.5	36.5	43.0	45.6	88.6	184
JOLIET IL	116585	545	50	6.3	36.3	42.6	44.3	86.9	10133
PEORIA IL	181432	470	51	6.2	36.1	42.3	45.6	87.9	15956
ROCKFORD IL	171681	715	52	6.6	36.7	43.3	45.6	88.9	15255
ST LOUIS IL-MO	276295	470	48	6.2	36.1	42.3	45.6	87.9	24299
SPRINGFIELD IL	111403	610	50	6.4	36.4	42.9	45.6	88.5	9854
ILLINOIS NU	3362203	738	52	6.6	36.7	43.3	45.6	88.9	299059
ILLINOIS	10081159	641	52	6.5	36.5	43.0	41.7	84.7	853836
CHICAGO IN-IL	478946	595	52	6.4	36.4	42.8	38.6	81.4	38986
EVANSVILLE IN	143650	385	48	6.1	35.9	42.1	45.6	87.7	12593
FT WAYNE IN	179571	790	52	6.7	36.9	43.6	45.6	89.2	16010
INDIANAPOLIS IN	639340	710	50	6.6	36.7	43.2	45.6	88.8	56797
LOUISV'LE IN-KY	72396	450	49	6.2	36.1	42.3	45.6	87.9	6362
MUNCIE IN	77504	950	51	6.9	37.3	44.2	45.6	89.8	6961
SO BEND IN -MI	198514	710	52	6.6	36.7	43.2	45.6	88.8	17635
TERRA HAUTE IN	81415	495	50	6.3	36.2	42.4	45.6	88.0	7167
INDIANA NU	2791152	779	50	6.7	36.8	43.5	45.6	89.1	248721
INDIANA	4662498	729	50	6.6	36.7	43.3	44.9	88.2	411232
CEDAR RAPIDS IA	105118	730	52	6.6	36.7	43.3	45.6	88.9	9347
DAVENPORT IA-IL	101018	590	51	6.4	36.4	42.8	45.6	88.4	8928
DES MOINES IA	241115	805	51	6.7	36.9	43.6	45.6	89.2	21511
DUBUQUE IA-IL	57365	645	52	6.5	36.5	43.0	45.6	88.6	5082
OMAHA IA-NE	60547	1040	51	7.1	37.5	44.6	45.6	90.2	5462
SOUIX CTY IA-NE	89990	1110	52	7.2	37.7	44.9	45.6	90.5	8146
WATERLOO IA	102827	850	52	6.8	37.0	43.8	45.6	89.4	9193
IOWA NU	1999557	1125	52	7.2	37.8	45.0	45.6	90.6	181135
IOWA	2757537	1040	52	7.1	37.6	44.6	45.6	90.2	248803
KANSAS CY KS-MO	272095	750	48	6.6	36.8	43.4	45.6	89.0	24215
ST JOSEPH KS-MO	1191	850	49	6.8	37.0	43.8	45.6	89.4	106
TOPEKA KS	119500	930	48	6.9	37.2	44.1	45.6	89.7	10723
WICHITA KS	292138	1290	47	7.5	38.3	45.8	45.6	91.4	26687
KANSAS NU	1493687	1570	48	7.9	39.2	47.1	45.6	92.7	138512
KANSAS	2178611	1395	48	7.6	38.7	46.3	45.6	91.9	200244

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	6 ION	7=5+6 TOTAL	8 TERR DOSE EQ MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
CINTI KY-OH	179489	550	50	6.3	36.3	42.6	30.2	72.8	13073
HUNT KY-WV-OH	48091	565	49	6.4	36.3	42.7	45.6	88.3	4246
LEXINGTON KY	111940	955	48	6.9	37.3	44.2	45.6	89.8	10057
LOUISV'LE KY-IN	534263	450	49	6.2	36.1	42.3	45.6	87.9	46950
KENTUCKY NU-CP	170000	340	47	6.0	35.9	41.9	22.8	64.7	11000
KENTUCKY NU-NCP	1994373	934	48	6.9	37.2	44.2	45.6	89.8	179996
KENTUCKY	3038156	788	48	6.7	36.9	43.6	43.4	87.0	264320
BATON ROUGE LA	193485	57	40	5.7	35.4	41.1	22.8	63.9	12354
LAKE CHARLES LA	89115	20	40	5.6	35.3	40.9	22.8	63.7	5681
MONROE LA	80546	82	42	5.7	35.4	41.1	22.8	63.9	5148
NEW ORLEANS LA	845237	5	40	5.6	35.3	40.9	22.8	63.7	53850
SHREVEPORT LA	208583	204	42	5.9	35.6	41.5	22.8	64.3	13407
LOUISIANA NU-CP	1840056	100	41	5.7	35.4	41.2	22.8	64.0	117709
LOUISIANA	3257022	77	41	5.7	35.4	41.1	22.8	63.9	208149
LEWISTON ME	65253	200	56	5.9	35.6	41.5	45.6	87.1	5681
PORTLAND ME	111701	25	55	5.6	35.3	41.0	45.6	86.6	9669
MAINE NU	792311	395	56	6.1	36.0	42.1	45.6	87.7	69477
MAINE	969265	339	56	6.0	35.9	41.9	45.6	87.5	84827
BALTIMORE MD	1418948	20	51	5.6	35.3	40.9	27.4	68.3	96985
WASH DC(MD)	578980	150	50	5.8	35.5	41.3	35.4	76.7	44416
MARYLAND NU-CP	470000	100	50	5.7	35.4	41.2	22.8	64.0	30066
MARYLAND NU-NCP	632761	558	51	6.3	36.3	42.7	45.6	88.3	55849
MARYLAND	3100689	166	51	5.8	35.6	41.4	31.9	73.3	227316
BOSTON MA	2413236	27	54	5.6	35.3	41.0	45.6	86.6	208910
BROCKTON MA	111315	130	54	5.8	35.5	41.3	45.6	86.9	9668
FALL RIV MA-RI	117787	40	53	5.7	35.3	41.0	45.6	86.6	10201
FITCH-LEO MA	72347	440	54	6.2	36.1	42.2	45.6	87.8	6355
LAW-HAVER MA-NH	165233	65	54	5.7	35.4	41.1	45.6	86.7	14321
LOWELL MA	118547	100	54	5.7	35.4	41.2	45.6	86.8	10286
NEW BEDFORD MA	126657	15	53	5.6	35.3	40.9	45.6	86.5	10960
PITTSFIELD MA	62306	1015	54	7.0	37.5	44.5	27.9	72.4	4511
PRO'DENCE MA-RI	43381	80	53	5.7	35.4	41.1	41.9	83.0	3601
SPRNGFLD MA-CT	418313	85	54	5.7	35.4	41.1	40.0	81.1	33937
WORCESTER MA	225446	475	54	6.2	36.1	42.4	53.1	95.5	21522
MASS NU	1274010	492	54	6.3	36.2	42.4	45.6	88.0	112144
MASS	5148578	190	54	5.9	35.6	41.5	45.2	86.7	446418
ANN ARBOR MI	115282	880	53	6.8	37.1	43.9	45.6	89.5	10320
BAY CITY MI	72763	595	54	6.4	36.4	42.8	45.6	88.4	6432
DETROIT MI	3537709	600	53	6.4	36.4	42.8	45.6	88.4	312796
FLINT MI	277786	715	53	6.6	36.7	43.3	45.6	88.9	24683

Table A-1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and nonurbanized areas—Continued

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	 6 ION	 7=5+6 TOTAL	8 TERR DOSE EQ MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
GRD RAPIDS MI	294230	610	53	6.4	36.4	42.9	45.6	88.5	26026
JACKSON MI	71412	940	53	6.9	37.3	44.2	45.6	89.8	6411
KALAMAZOO MI	115659	755	53	6.6	36.8	43.4	45.6	89.0	10295
LANSING MI	169325	830	53	6.7	37.0	43.7	45.6	89.3	15124
MUSKEGON MI	95350	625	53	6.4	36.5	42.9	45.6	88.5	8440
SAGINAW MI	129215	595	54	6.4	36.4	42.8	45.6	88.4	11422
SO BEND MI-IN	20419	710	52	6.6	36.7	43.2	45.6	88.8	1814
MICHIGAN NU	2924044	817	54	6.7	36.9	43.7	45.6	89.3	261012
MICHIGAN	7823194	701	54	6.6	36.7	43.2	45.6	88.8	694776
DULUTH MN-WI	110826	610	56	6.4	36.4	42.9	45.6	88.5	9803
FARG MOOR MN-ND	25054	900	56	6.8	37.2	44.0	45.6	89.6	2245
MINN-ST PAUL MN	1377143	815	55	6.7	36.9	43.7	31.2	74.9	103087
MINNESOTA NU	1900841	1403	54	7.6	38.6	46.3	45.6	91.9	174680
MINNESOTA	3413864	1136	54	7.2	37.9	45.1	39.8	84.9	289815
JACKSON MS	147480	294	42	6.0	35.8	41.8	22.8	64.6	9521
MISS'IPPI NU-CP	2030661	267	43	6.0	35.7	41.7	22.8	64.5	130918
MISSISSIPPI	2178141	269	43	6.0	35.7	41.7	22.8	64.5	140438
KANSAS CY MO-KS	649026	750	48	6.6	36.8	43.4	45.6	89.0	57760
ST JOSEPH MO-KS	79996	850	49	6.8	37.0	43.8	45.6	89.4	7152
ST LOUIS MO-IL	1391398	470	48	6.2	36.1	42.3	45.6	87.9	122369
SPRINGFIELD MO	97224	1300	47	7.5	38.3	45.8	45.6	91.4	8886
MISSOURI NU-CP	150000	350	47	6.1	35.9	41.9	22.8	64.7	9711
MISSOURI NU-NCP	1952169	881	48	6.8	37.1	43.9	45.6	89.5	174773
MISSOURI	4319813	719	48	6.6	36.7	43.3	44.8	88.1	380651
BILLINGS MT	60712	3120	54	11.0	45.5	56.5	45.6	102.1	6199
GREAT FALLS MT	57629	3330	55	11.5	46.5	58.0	45.6	103.6	5970
MONTANA NU	556426	3521	54	12.0	47.4	59.4	45.6	105.0	58423
MONTANA	674767	3469	54	11.8	47.2	59.0	45.6	104.6	70592
LINCOLN NE	136220	1150	50	7.2	37.9	45.1	45.6	90.7	12355
OMAHA NE-IA	329334	1040	51	7.1	37.5	44.6	45.6	90.2	29709
SIOUX CY NE-IA	7200	1110	52	7.2	37.7	44.9	45.6	90.5	652
NEBRASKA NU	938576	1604	50	8.0	39.3	47.3	45.6	92.9	87199
NEBRASKA	1411330	1426	50	7.7	38.8	46.5	45.6	92.1	129915
LAS VEGAS NV	89427	2030	43	8.8	40.9	49.6	19.9	69.5	6216
RENO NV	70189	4498	46	14.6	52.8	67.4	45.6	113.0	7930
NEVADA NU	125662	4565	45	14.8	53.2	68.0	45.6	113.6	14272
NEVADA	285278	3754	45	12.8	49.2	62.1	37.5	99.6	28418

1	2	3	4	COSMIC RADIATION DE MREMS/YR			8	9=7+8	10=(2X9)X.001
LOCATION	1960 POPULATION	ELEVATION FEET	MAGLAT DEG NO	5 NEUT	6 ION	7=5+6 TOTAL	TERR DOSE EQ MREMS/YR	TOTAL EXT DE MREMS/YR	MAN-REM
LAW HAVER NH-MA	892	65	54	5.7	35.4	41.1	45.6	86.7	77
MANCHESTER NH	91698	175	54	5.8	35.6	41.4	45.6	87.0	7977
NEW HAMP NU	514331	712	55	6.6	36.7	43.2	45.6	88.8	45696
N HAMPSHIRE	606921	630	55	6.5	36.5	43.0	45.6	88.6	53750
ATLANTIC CY NJ	124902	10	51	5.6	35.3	40.9	22.8	63.7	7959
NEW YORK NJ-NY	3878897	30	52	5.6	35.3	41.0	45.6	86.6	335821
PHILADEL NJ-PA	521995	45	52	5.7	35.4	41.0	47.5	88.5	46206
TRENTON NJ-PA	226563	35	52	5.6	35.3	41.0	41.9	82.9	18780
WILMINGTN NJ-DE	17329	135	52	5.8	35.5	41.3	36.2	77.5	1342
N JERSEY NU-CP	440000	200	52	5.9	35.6	41.5	22.8	64.3	28276
N JERSEY NU-NCP	857096	295	52	6.0	35.8	41.8	45.6	87.4	74875
NEW JERSEY	6066782	81	52	5.7	35.4	41.1	43.5	84.6	513259
ALBUQUERQUE NM	241216	4958	43	16.0	55.7	71.6	69.5	141.1	34047
NEW MEXICO NU	709807	5254	43	16.9	57.7	74.6	45.6	120.2	85315
NEW MEXICO	951023	5179	43	16.7	57.2	73.8	51.7	125.5	119362
ALBANY NY	455447	20	54	5.6	35.3	40.9	25.1	66.0	30082
BINGHAMPTON NY	158141	865	53	6.8	37.1	43.9	45.6	89.5	14147
BUFFALO NY	1054370	585	54	6.4	36.4	42.8	45.6	88.4	93166
NEW YORK NY	10236030	30	52	5.6	35.3	41.0	45.6	86.6	886199
ROCHESTER NY	493402	515	54	6.3	36.2	42.5	45.6	88.1	43472
SYRACUSE NY	333286	400	54	6.1	36.0	42.1	45.6	87.7	29231
UTICA ROME NY	187779	415	54	6.2	36.0	42.2	45.6	87.8	16479
NEW YORK NU	3863849	544	53	6.3	36.3	42.6	45.6	88.2	340836
NEW YORK	16782304	217	53	5.9	35.7	41.6	45.0	86.6	1453613
ASHEVILLE NC	68592	2216	46	9.1	41.6	50.7	45.6	96.3	6605
CHARLOTTE NC	209551	721	46	6.6	36.7	43.3	45.6	88.9	18625
DURHAM NC	84642	414	47	6.1	36.0	42.2	45.6	87.8	7428
HIGH POINT NC	66543	940	47	6.9	37.3	44.2	45.6	89.8	5974
GREENSBORO NC	123334	841	47	6.8	37.0	43.8	45.6	89.4	11021
RALEIGH NC	93931	363	47	6.1	35.9	42.0	45.6	87.6	8227
WINSTON SAL NC	128176	860	47	6.9	37.1	43.8	45.6	89.4	11464
N CAROL NU-CP	1410000	100	47	5.7	35.4	41.2	22.8	64.0	90198
N CAROL NU-NCP	2371386	1204	47	7.3	38.0	45.3	45.6	90.9	215674
N CAROLINA	4556155	800	47	6.7	37.1	43.8	38.5	82.4	375216
FARG MOOR ND-MN	47676	900	56	6.8	37.2	44.0	45.6	89.6	4272
N DAKOTA NU	584770	1687	56	8.1	39.6	47.7	45.6	93.3	54581
N DAKOTA	632446	1628	56	8.0	39.4	47.5	45.6	93.1	58853

Table A-1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and nonurbanized areas—Continued

1	2	3	4	COSMIC RADIATION DE MREMS/YR			8	9=7+8	10=(2X9)X.001
LOCATION	1960 POPULATION	ELEVATION FEET	MAGLAT DEG NO	5 NEUT	6 ION	7=5+6 TOTAL	TERR DOSE EQ MREMS/YR	TOTAL EXT DE MREMS/YR	MAN-REM
AKRON OH	458253	1027	52	7.0	37.5	44.6	45.6	90.2	41312
CANTON OH	213574	1060	52	7.1	37.6	44.7	45.6	90.3	19285
CINCINNATI OH	914079	550	50	6.3	36.3	42.6	30.2	72.8	59292
CLEVELAND OH	1784991	680	52	6.5	36.6	43.1	45.6	88.7	158366
COLUMBUS OH	616743	780	51	6.7	36.8	43.5	41.9	85.4	52679
DAYTON OH	501664	757	50	6.6	36.9	43.4	41.9	85.3	42803
HAMILTON OH	99778	605	50	6.4	36.4	42.8	45.6	88.4	7940
HUNT OH-KY-WV	24897	565	49	6.4	36.3	42.7	45.6	88.3	2198
LIMA OH	62963	880	51	6.8	37.1	43.9	47.5	91.4	5756
LOR-ELYRIA OH	142860	608	52	6.4	36.4	42.8	45.6	88.4	12636
SPRINGFIELD OH	90157	980	51	7.0	37.4	44.4	45.6	89.9	8109
STEUBENVL OH-WV	47315	715	51	6.6	36.7	43.3	60.5	103.8	4909
TOLEDO OH	438293	587	52	6.4	36.4	42.8	45.6	88.4	38731
WHEELING OH-WV	33471	650	51	6.5	36.5	43.0	68.9	111.9	3746
YOUNGSTOWN OH	372748	840	52	6.8	37.0	43.8	40.8	84.6	31519
OHIO NU	4014671	799	52	6.7	36.9	43.6	45.6	89.2	358068
OHIO	9706397	757	52	6.6	36.8	43.4	43.9	87.3	847349
FT SMITH OK-AR	1862	450	45	6.2	36.1	42.3	45.6	87.9	164
LAWTON OK	61941	1109	43	7.2	37.7	44.9	45.6	90.5	5607
OKLAHOMA CY OK	429188	1207	45	7.3	38.0	45.4	45.6	91.0	39040
TULSA OK	298922	744	45	6.6	36.8	43.4	45.6	89.0	26595
OKLAHOMA NU-CP	70003	450	44	6.2	36.1	42.3	22.8	65.1	4555
OKLAHOMA NU-NCP	1466371	1512	45	7.8	39.0	46.8	45.6	92.4	135547
OKLAHOMA	2329284	1314	45	7.5	38.4	45.9	44.9	90.8	211508
EUGENE OR	95686	422	51	6.2	36.0	42.2	45.6	87.8	8399
PORTLAND OR-WA	604729	77	52	5.7	35.4	41.1	45.6	86.7	52433
OREGON NU	1068272	1063	51	7.1	37.6	44.7	45.6	90.3	96476
OREGON	1768687	691	51	6.6	36.8	43.3	45.6	88.9	157308
ALLEN-BETH PA	256016	255	52	5.9	35.7	41.6	45.6	87.2	22333
ALTOONA PA	83058	1180	52	7.3	38.0	45.2	45.6	90.8	7545
ERIE PA	177433	685	53	6.5	36.6	43.1	45.6	88.7	15745
HARRISBURG PA	209501	365	52	6.1	35.9	42.0	45.6	87.6	18350
JOHNSTOWN PA	96474	1185	52	7.3	38.0	45.3	45.6	90.9	8766
LANCASTER PA	93855	355	52	6.1	35.9	42.0	45.6	87.6	8217
PHILADEL PA-NJ	3113233	45	52	5.7	35.4	41.0	42.5	83.5	260008
PITTSBURG PA	1804400	760	52	6.6	36.8	43.4	52.0	95.4	172202
READING PA	160297	265	52	5.9	35.7	41.7	45.6	87.3	13988
SCRANTON PA	210676	725	53	6.6	36.7	43.3	45.6	88.9	18728
TRENTON PA-NJ	15838	35	52	5.6	35.3	41.0	41.9	82.9	1313
WILKES BARRE PA	233932	640	53	6.5	36.5	43.0	45.6	88.6	20719
YORK PA	100872	370	51	6.1	35.9	42.0	45.6	87.6	8837
PENN NU	4763781	750	52	6.6	36.8	43.4	22.8	66.2	315337
PENN	11319366	528	52	6.3	36.3	42.6	36.2	78.8	892089

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	6 ION	7=5+6 TOTAL	8 TERR DOSE EQ MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
FALL RIV RI-MA	6164	40	53	5.7	35.3	41.0	45.6	86.6	534
PROVIDENCE RI-MA	616161	80	53	5.7	35.4	41.1	41.9	83.0	51150
RHODE ID NU	237163	200	53	5.9	35.6	41.5	45.6	87.1	20648
RHODE ID	959488	113	53	5.7	35.5	41.2	42.9	84.2	72332
AUGUSTA SC-GA	12828	143	44	5.8	35.5	41.3	42.8	84.1	1079
CHARLESTON SC	160113	9	44	5.6	35.3	40.9	22.8	63.7	10202
COLUMBIA SC	162601	259	45	5.9	35.7	41.6	68.3	109.9	17877
GREENVILLE SC	126987	966	45	6.9	37.3	44.3	22.8	67.1	8512
S CAROL NU-CP	810000	100	44	5.7	35.4	41.2	22.8	64.0	51816
S CAROL NU-NCP	1110165	686	45	6.5	36.6	43.1	45.6	88.7	98521
S CAROLINA	2382594	424	45	6.2	36.1	42.3	36.6	78.9	188007
SIOUX CY SD-IA	736	1110	52	7.2	37.7	44.9	45.6	90.5	67
SIOUX FALLS SD	66582	1395	53	7.6	38.6	46.3	45.6	91.9	6116
S DAKCTA NU	613196	1977	53	8.7	40.7	49.3	45.6	94.9	58201
S DAKOTA	680514	1919	53	8.6	40.5	49.0	45.6	94.6	64383
CHATTA TN-GA	184844	675	45	6.5	36.6	43.1	45.6	88.7	16396
KNOXVILLE TN	172734	890	46	6.8	37.1	44.0	60.0	104.0	17958
MEMPHIS TN	544505	275	45	6.0	35.7	41.7	22.8	64.5	35118
NASHVILLE TN	346729	450	46	6.2	36.1	42.3	45.6	87.9	30470
TENN NU-CP	530000	300	46	6.0	35.8	41.8	22.8	64.6	34225
TENN NU-NCP	1788277	1026	46	7.0	37.5	44.5	45.6	90.1	161208
TENNESSEE	3567089	723	46	6.6	36.8	43.4	39.4	82.8	295375
ABILENE TX	91566	1738	42	8.2	39.8	48.0	45.6	93.6	8571
AMARILLO TX	137969	3676	44	12.3	48.2	60.6	45.6	106.2	14649
AUSTIN TX	187157	550	39	6.3	36.3	42.6	22.8	65.4	12246
BEAUMCNT TX	119178	24	40	5.6	35.3	41.0	22.8	63.8	7599
CORPUS CHRIS TX	177380	35	37	5.6	35.3	41.0	22.8	63.8	11315
DALLAS TX	932349	512	42	6.3	36.2	42.5	22.8	65.3	60879
EL PASO TX	277128	3762	40	12.6	48.7	61.2	45.6	106.8	29608
FT WORTH TX	502682	670	42	6.5	36.6	43.1	45.6	88.7	44579
GALVESTON TX	118482	20	39	5.6	35.3	40.9	19.7	60.6	7186
HARLINGEN TX	61658	35	36	5.6	35.3	41.0	22.8	63.8	3933
HOUSTON TX	1139678	55	39	5.7	35.4	41.0	19.7	60.7	69229
LAREDO TX	60678	420	37	6.2	36.0	42.2	22.8	65.0	3942
LUBBOCK TX	129289	3241	42	11.3	46.1	57.4	45.6	103.0	13317
MIDLAND TX	63274	2779	41	10.3	43.9	54.2	45.6	99.8	6314
ODESSA TX	84285	2890	41	10.5	44.4	54.9	45.6	100.5	8473
PORT ARTHUR TX	116365	20	40	5.6	35.3	40.9	22.8	63.7	7418
SAN ANGELO TX	58815	1847	41	8.4	40.2	48.6	45.6	94.2	5540
SAN ANTONIO TX	641965	701	38	6.6	36.6	43.2	22.8	66.0	42371
TEXARKANA TX-AR	33049	336	43	6.0	35.8	41.9	22.8	64.7	2138
TYLER TX	51739	545	42	6.3	36.3	42.6	22.8	65.4	3385
WACO TX	116163	427	41	6.2	36.0	42.2	22.8	65.0	7550

Table A-1. Calculation of average dose equivalents due to terrestrial and cosmic radiation by State urbanized and nonurbanized areas—Continued

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	6 ION	7=5+6 TOTAL	8 TERR DOSE EQ MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
WICHITA FALL TX	102104	946	43	6.9	37.3	44.2	45.6	89.8	9169
TEXAS NU-CP	3040000	250	39	5.9	35.7	41.6	22.8	64.4	195828
TEXAS NU-NCP	1336724	2388	41	9.4	42.3	51.7	45.6	97.3	130089
TEXAS	9579677	863	41	7.0	37.6	44.6	29.0	73.6	705323
OGDEN UT	121927	4300	49	14.0	51.6	65.6	45.6	111.2	13564
PROVO UT	60795	4549	48	14.7	53.1	67.8	45.6	113.4	6896
SALT LAKE CY UT	348661	4260	48	13.9	51.4	65.3	45.6	110.9	38668
UTAH NU	359244	5028	48	16.2	56.1	72.3	45.6	117.9	42366
UTAH	890627	4595	48	14.9	53.5	68.4	45.6	114.0	101494
VERMONT NU	389881	590	55	6.4	36.4	42.8	45.6	88.4	34458
VERMONT	389881	590	55	6.4	36.4	42.8	45.6	88.4	34458
LYNCHBURG VA	59319	648	49	6.5	36.5	43.0	45.6	88.6	5256
NEWPORT NEWS VA	208874	20	48	5.6	35.3	40.9	19.5	60.4	12626
NORFOLK VA	507825	12	48	5.6	35.3	40.9	19.5	60.4	30687
ROANOKE VA	124752	948	48	6.9	37.3	44.2	45.6	89.8	11204
RICHMOND VA	333438	150	49	5.8	35.5	41.3	22.8	64.1	21378
WASH DC(VA)	465487	150	50	5.8	35.5	41.3	35.4	76.7	35710
VIRGINIA NU-CP	560000	100	49	5.7	35.4	41.2	22.8	64.0	35823
VIRGINIA NU-NCP	1707254	1214	49	7.3	38.1	45.4	45.6	91.0	155352
VIRGINIA	3966949	609	49	6.5	36.6	43.1	34.6	77.7	308035
PORTLAND WA-OR	46956	77	52	5.7	35.4	41.1	45.6	86.7	4071
SEATTLE WA	864109	125	54	5.8	35.5	41.2	45.6	86.8	75041
SPOKANE WA	226938	1180	55	7.3	38.0	45.2	45.6	90.8	20615
TACOMA WA	214930	250	53	5.9	35.7	41.6	45.6	87.2	18746
WASHINGTON NU	1500281	577	54	6.4	36.4	42.7	45.6	88.3	132523
WASHINGTON	2853214	455	54	6.2	36.2	42.4	45.6	88.0	250996
CHARLESTON WV	169500	601	49	6.4	36.4	42.8	45.6	88.4	14987
HUNT WV-KY-OH	92744	565	49	6.4	36.3	42.7	45.6	88.3	8188
STEUBENVL WV-OH	34298	715	51	6.6	36.7	43.3	60.5	103.8	3559
WHEELING WV-OH	65480	650	51	6.5	36.5	43.0	68.9	111.9	7328
WEST VA NU	1498399	1421	50	7.7	38.7	46.4	45.6	92.0	137829
WEST VA	1860421	1263	50	7.4	38.3	45.7	46.7	92.4	171891
DULUTH WI-MN	33937	610	56	6.4	36.4	42.9	45.6	88.5	3002
GREEN BAY WI	97162	590	55	6.4	36.4	42.8	45.6	88.4	8587
KENOSHA WI	72852	610	53	6.4	36.4	42.9	45.6	88.5	6444
MADISON WI	157814	860	53	6.8	37.1	43.8	45.6	89.4	14115
MILWAUKEE WI	1149997	610	53	6.4	36.4	42.9	45.6	88.5	101773

1 LOCATION	2 1960 POPULATION	3 ELEVATION FEET	4 MAGLAT DEG NO	COSMIC RADIATION DE MREMS/YR 5 NEUT	6 ION	7=5+6 TOTAL	8 TERR DOSE FO MREMS/YR	9=7+8 TOTAL EXT DE MREMS/YR	10=(2X9)X.001 MAN-REM
RACINE WI	95862	630	53	6.5	36.5	42.9	45.6	88.5	8487
WISCONSIN NU	2344153	968	54	7.0	37.3	44.3	45.6	99.9	210729
WISCONSIN	3951777	832	54	6.9	37.0	43.7	45.6	89.3	353087
WYOMING NU	330066	5800	50	18.8	61.7	80.5	45.6	126.1	41614
WYOMING	330066	5800	50	18.9	61.7	80.5	45.6	126.1	41614

Table A-2. Total calculation of average dose equivalents due to terrestrial and cosmic radiation by States

1	2	3	4	COSMIC RADIATION DE MREMS/YR			8	9=7+8	10=(2X9)X.001
STATE	1960 POPULATION	ELEVATION FEET	MAGLAT DEG NO	5 NEUT	6 ION	7=5+6 TOTAL	TERR DOSE EQ MREMS/YR	TOTAL EXT DE MREMS/YR	MAN-REM
ALABAMA	3266740	498	43	6.3	36.2	42.5	34.9	77.4	252874
ALASKA	226167	250	61	5.9	35.7	41.6	45.6	87.2	19726
ARIZONA	1302161	2191	42	9.2	41.9	51.1	45.6	96.7	125970
ARKANSAS	1786272	649	44	6.5	36.8	43.3	30.1	73.4	131151
CALIFORNIA	15717204	391	43	6.1	36.0	42.2	36.4	78.6	1235310
COLORADO	1753947	5402	48	17.4	58.8	76.2	65.8	142.0	249066
CONN	2535234	169	53	5.8	35.6	41.4	51.1	92.5	234508
DELAWARE	446292	105	51	5.7	35.4	41.2	30.8	72.0	32125
WASH DC	763956	150	50	5.8	35.5	41.3	35.4	76.7	58606
FLORIDA	4951560	56	38	5.7	35.4	41.0	22.3	63.4	313899
GEORGIA	3943116	689	43	6.6	36.7	43.3	38.9	82.2	324130
HAWAII	632772	147	21	5.8	35.5	41.3	45.6	86.9	55003
IDAHO	667191	3659	51	12.3	48.1	60.4	45.6	106.0	70751
ILLINOIS	10081158	641	52	6.5	36.5	43.0	41.7	84.7	853836
INDIANA	4662498	729	50	6.6	36.7	43.3	44.9	88.2	411232
IOWA	2757537	1040	52	7.1	37.6	44.6	45.6	90.2	248803
KANSAS	2178611	1395	49	7.6	38.7	46.3	45.6	91.9	200244
KENTUCKY	3038156	789	48	6.7	36.9	43.6	43.4	87.0	264320
LOUISIANA	3257022	77	41	5.7	35.4	41.1	22.8	63.9	208149
MAINE	969265	339	56	6.0	35.9	41.9	45.6	87.5	84827
MARYLAND	3100689	166	51	5.8	35.6	41.4	31.9	73.3	227316
MASS	5148578	190	54	5.9	35.6	41.5	45.2	86.7	446418
MICHIGAN	7823194	701	54	6.6	36.7	43.2	45.6	88.8	694776
MINNESOTA	3413864	1136	54	7.2	37.9	45.1	39.8	84.9	289815
MISSISSIPPI	2178141	269	43	6.0	35.7	41.7	22.8	64.5	140438
MISSOURI	4319813	719	48	6.6	36.7	43.3	44.8	88.1	380651
MONTANA	674767	3469	54	11.8	47.2	59.0	45.6	104.6	70592
NEBRASKA	1411330	1426	50	7.7	38.8	46.5	45.6	92.1	129915
NEVADA	285278	3754	45	12.8	49.2	62.1	37.5	99.6	28418
N HAMPSHIRE	606921	630	55	6.5	36.5	43.0	45.6	88.6	53750
NEW JERSEY	6066782	81	52	5.7	35.4	41.1	43.5	84.6	513259
NEW MEXICO	951023	5179	43	16.7	57.2	73.8	51.7	125.5	119362
NEW YORK	16782304	217	53	5.9	35.7	41.6	45.0	86.6	1453613
N CAROLINA	4556155	800	47	6.7	37.1	43.8	38.5	82.4	375216
N DAKOTA	632446	1628	56	8.0	39.4	47.5	45.6	93.1	58853
OHIO	9706397	757	52	6.6	36.8	43.4	43.9	87.3	847349
OKLAHOMA	2328284	1314	45	7.5	38.4	45.9	44.9	90.8	211508
OREGON	1768687	691	51	6.6	36.8	43.3	45.6	88.9	157309
PENN	11319366	528	52	6.3	36.3	42.6	36.2	78.8	892089
RHODE ID	859488	113	53	5.7	35.5	41.2	42.9	84.2	72332
S CAROLINA	2382594	424	45	6.2	36.1	42.3	36.6	78.9	188007
S DAKOTA	680514	1919	53	8.6	40.5	49.0	45.6	94.6	64383
TENNESSEE	3567089	723	46	6.6	36.8	43.4	39.4	82.8	295375
TEXAS	9579677	863	41	7.0	37.6	44.6	29.0	73.6	705323
UTAH	890627	4595	48	14.9	53.5	68.4	45.6	114.0	101494
VERMONT	389881	590	55	6.4	36.4	42.8	45.6	88.4	34458
VIRGINIA	3966949	609	49	6.5	36.6	43.1	34.6	77.7	308035
WASHINGTON	2853214	455	54	6.2	36.2	42.4	45.6	88.0	250996
WEST VA	1860421	1263	50	7.4	38.3	45.7	46.7	92.4	171891
WISCONSIN	3951777	832	54	6.8	37.0	43.7	45.6	89.3	353087
WYOMING	330066	5800	50	18.8	61.7	80.5	45.6	126.1	41614

Table A-3. Program to calculate average dose equivalents from terrestrial and cosmic radiation

```
ISN 0002          IMPLICIT REAL*8 (A-H,O-Z)
ISN 0003          DIMENSION POP(350),STAPOP(51),SREM(51),TD(4),ATD(350),ACD(350),
                 1TDOS(350),STATE(51,3),PELEV(51),PCNUT4(51),PCION4(51),ALOC(4,350),
                 2PTODSO(51),SANP(51),SCOSYR(51),SOFD(51),LAT(51),INTERV(49),
                 3AMID(80),PERCT(160)
ISN 0004          DATA IWRITE,IHOLD,ISWTCH,J/4*0/,INTERV/49*0/
ISN 0005          DATA TOTPOP,ANREM,ELMEAN,COSYRM,TODSOM,OEDTOT/6*0.0/
ISN 0006          DATA STAPOP,SREM,PELEV,PCNUT4,PCION4,SCOSYR,SANP,SOFD,PTODSO
                 1/51*0.0,51*0.0,51*0.0,51*0.0,51*0.0,51*0.0,51*0.0,51*0.0,51*0.0/
ISN 0007          DO 10 I=1,9
ISN 0008          I1=I*6-5
ISN 0009          I2=I*6
ISN 0010          IF(I.EQ.9)I2=51
ISN 0012       10 READ(5,904)(((STATE(K,J),J=1,3),LAT(K)),K=I1,I2)
ISN 0013          WRITE(6,907)
ISN 0014          READ (5,905)((TD(I),I=1,3))
ISN 0015          DO 15 I=1,8
ISN 0016          N=I*10
ISN 0017          M=N-9
ISN 0018          READ(5,913) (AMID(K),K=M,N)
ISN 0019       15 CONTINUE
ISN 0020          DO 16 I=1,8
ISN 0021          N=I*10
ISN 0022          M=N-9
ISN 0023          READ(5,914) (PERCT(K),K=M,N)
ISN 0024       16 CONTINUE
ISN 0025          DO 17 I=9,16
ISN 0026          N=I*10
ISN 0027          M=N-9
ISN 0028          READ(5,914) (PERCT(K),K=M,N)
ISN 0029       17 CONTINUE
ISN 0030       20 IWRITE=IWRITE+1
ISN 0031          J=J+1
ISN 0032          READ(5,906)(ALOC(I,J),I=1,4),ISTATE,POP(J),ELEV,GLAT,ITD,TD(4)
ISN 0033          IF(ISTATE.NE.IHOLD)GO TO 70
ISN 0035       30 IF(ITD.EQ.9)GO TO 90
ISN 0037          IF(IWRITE.LT.55)GO TO 40
ISN 0039          IWRITE=0
ISN 0040          WRITE(6,907)
ISN 0041       40 TODSO = TD(ITD)
ISN 0042          POPU=POP(J)
ISN 0043          ELMEAN=ELMEAN+ELEV*POPU
ISN 0044          TOTPOP=TOTPOP+POPU
ISN 0045          FL=ELEV/1000.
ISN 0046          CION1=1.00+.039*FL+.025*FL*FL-.0038*FL**3+.000463*FL**4-.0000156*
                 1 FL**5
ISN 0047          CION2 = 2.44*CION1
ISN 0048          CION3 = 1.65*CION2
ISN 0049          CION4 = 8.766*CION3
ISN 0050          CNUT4= 5.6*DEXP((1033.-1033.*(.999871-.0359535*FL+3.93563D-4*FL
                 1*FL+2.75322D-5*FL**3-3.32146D-6*FL**4+9.30807D-8*FL**5))/165.)
```

Table A-3. Program to calculate average dose equivalents from terrestrial and cosmic radiation—Continued

```
ISN 0051         CNUT3 = CNUT4/8.766
ISN 0052         COSHR = CION3+CNUT3
ISN 0053         COSYR = 8.766*COSHR
ISN 0054         OED=COSYR+TDOSO
ISN 0055         IF(ITD.EQ.1)GO TO 120
ISN 0057         IF(ITD.EQ.2)GO TO 130
ISN 0059         N=1
ISN 0060         DO 60 I=35,271,5
ISN 0061         IF(OED-I)60,50,50
ISN 0062      50 N=N+1
ISN 0063      60 CONTINUE
ISN 0064         INTERV(N)=INTERV(N)+POPU
ISN 0065      65 ANR=OED*POPU
ISN 0066         ANREM=ANREM+ANR
ISN 0067         COSYRM=COSYRM+COSYR*POPU
ISN 0068         TDOSOM=TDOSOM+TDOSO*POPU
ISN 0069         OEDTOT=OEDTOT+OED
ISN 0070         TDOS(J)=OED
ISN 0071         ATD(J)=TDOSO
ISN 0072         ACD(J)=COSYR
ISN 0073         SREM(ISTATE)=SREM(ISTATE)+OED*POPU
ISN 0074         STAPOP(ISTATE)=STAPOP(ISTATE)+POPU
ISN 0075         PELEV(ISTATE)=PELEV(ISTATE)+POPU*ELEV
ISN 0076         PCNUT4(ISTATE)=PCNUT4(ISTATE)+POPU*CNUT4
ISN 0077         PCION4(ISTATE)=PCION4(ISTATE)+POPU*CION4
ISN 0078         SANR(ISTATE)=SANR(ISTATE)+ANR
ISN 0079         SOED(ISTATE)=SOED(ISTATE)+OED*POPU
ISN 0080         PTDOSO(ISTATE)=PTDOSO(ISTATE)+POPU*TDOSO
ISN 0081         SCOSYR(ISTATE)=COSYR*POPU+SCOSYR(ISTATE)
ISN 0082         IPOP=POPU+.5
ISN 0083         IANR = ANR*.001+.5
ISN 0084         LA =GLAT+.5
ISN 0085         IELE =ELEV+.5
ISN 0086         WRITE(6,908)(ALOC(I,J),I=1,4),IPOP,IELE,LA,CNUT4,CION4,COSYR,TDOSO
                1 ,OED,IANR
ISN 0087         GO TO 20
ISN 0088      70 IF(ISWTCH.EQ.1)GO TO 80
ISN 0090         ISWTCH=1
ISN 0091         IHOLD=ISTATE
ISN 0092         GO TO 30
ISN 0093      80 I=IHOLD
ISN 0094         POPU=1.050
ISN 0095         IF(STAPOP(I).GT.0.)POPU=STAPOP(I)
ISN 0097         IPOP = 0
ISN 0098         IF(STAPOP(I).GT.0.)IPOP=POPU+.5
ISN 0100         IELE=PELEV(I)/POPU+.5
ISN 0101         CNUT4=PCNUT4(I)/POPU
ISN 0102         CION4=PCION4(I)/POPU
ISN 0103         COSYR=SCOSYR(I)/POPU
ISN 0104         TDOSO=PTDOSO(I)/POPU
ISN 0105         OED=SOED(I)/POPU
ISN 0106         IANR=SANR(I)*.001+.5
ISN 0107         IWRITE=IWRITE+4
```

Table A-3. Program to calculate average dose equivalents from terrestrial and cosmic radiation—Continued

```
ISN 0108          WRITE(6,900)(STATE(I,M),M=1,3),IPOP,IELE,LAT(I),CNUT4,CION4,COSYR,
                 1 TDOSO,OED,IANR
ISN 0109          IHOLD=ISTATE
ISN 0110          GO TO 30
ISN 0111       90 WRITE(6,909)
ISN 0112          DO 100 I=1,51
ISN 0113          POPU=1.D50
ISN 0114          IF(STAPOP(I).GT.0.)POPU=STAPOP(I)
ISN 0116          IPOP = 0
ISN 0117          IF(STAPOP(I).GT.0.)IPOP=POPU+.5
ISN 0119          IELE=PELEV(I)/POPU+.5
ISN 0120          CNUT4=PCNUT4(I)/POPU
ISN 0121          CION4=PCION4(I)/POPU
ISN 0122          COSYR=SCOSYR(I)/POPU
ISN 0123          TDOSO=PTDOSO(I)/POPU
ISN 0124          OED=SOED(I)/POPU
ISN 0125          IANR=SANR(I)*.001+.5
ISN 0126      100 WRITE(6,910)(STATE(I,J),J=1,3),IPOP,IELE,LAT(I),CNUT4,CION4,COSYR,
                 1 TDOSO,OED,IANR
ISN 0127          WRITE(6,911)
ISN 0128          IANR=ANREM*.001+.5
ISN 0129          ELE =ELMEAN/TOTPOP
ISN 0130          COSYR=COSYRM/TOTPOP
ISN 0131          OEDTOT=ANREM/TOTPOP
ISN 0132          TDOSO=TDOSOM/TOTPOP
ISN 0133          WRITE(6,912)ELE,COSYR,TDOSO,OEDTOT,IANR
ISN 0134          WRITE(6,901)
ISN 0135          L=34
ISN 0136          I=0
ISN 0137          WRITE(6,902)I,L,INTERV(1)
ISN 0138          L=33
ISN 0139          DO 110 I=35,271,5
ISN 0140          J=I+4
ISN 0141          K=I-L
ISN 0142          L=L+4
ISN 0143          IF(I.GT.269)J=999
ISN 0145          WRITE(6,902)I,J,INTERV(K)
ISN 0146      110 CONTINUE
ISN 0147          WRITE(6,903)TOTPOP
ISN 0148          STOP
ISN 0149      120 DO 170 M=1,74
ISN 0150          L=M
ISN 0151      140 NM=AMID(L)+COSYR
ISN 0152          N=1
ISN 0153          DO 160 I=35,271,5
ISN 0154          IF(NM-I)160,150,150
ISN 0155      150 N=N+1
ISN 0156      160 CONTINUE
ISN 0157          INTERV(N)=INTERV(N)+(PERCT(M)*POPU)
ISN 0158      170 CONTINUE
ISN 0159          GO TO 65
ISN 0160      130 DO 220 M=81,154
ISN 0161          L=M-80
```

Table A-3. Program to calculate average dose equivalents from terrestrial and cosmic radiation—Continued

```
ISN 0162      190 NM=AMID(L)+COSYR
ISN 0163          N=1
ISN 0164          DO 210 I=35,271,5
ISN 0165          IF(NM-I)210,200,200
ISN 0166      200 N=N+1
ISN 0167      210 CONTINUE
ISN 0168          INTERV(N)=INTERV(N)+(PERCT(M)*POPU)
ISN 0169      220 CONTINUE
ISN 0170          GO TO 65
ISN 0171      900 FORMAT(/12X,3A4,5X,I8,2X,I5,5X,I2,4X,3(F5.1,2X),6X,F6.1,8X,F6.1,
                 11X,I14//)
ISN 0172      901 FORMAT(1H1,30X,46HDISTRIBUTION OF POPULATION VS. DOSE EQUIVALENT,
                 1//42X,22HTOTAL DE          1960     ,/42X,22HMREMS/YR     POPULATION//)
ISN 0173      902 FORMAT(40X,I4,2H -,I4,5X,I8)
ISN 0174      903 FORMAT(1H1,20X,22HTOTAL POPULATION =     ,F12.0)
ISN 0175      904 FORMAT(6(2A4,A3,I2))
ISN 0176      905 FORMAT (3F5.1,3F4.2)
ISN 0177      906 FORMAT (3A4,A3,I2,F8.0,F6.0,F4.0,I1,F6.1)
ISN 0178      907 FORMAT(1H1,18X,1H1,12X,1H2,10X,1H3,9X,1H4,4X,19HCOSMIC RADIATION D
                 1E,10X,1H8,11X,5H9=7+8,5X,13H10=(2X9)X.001,/,1H ,15X,8HLOCATION,7X,
                 2 4H1960,4X,16HELEVATION MAGLAT,5X,9HMREMS/YR,13X,36HTERR DOSE EQ
                 3TOTAL EXT DE    MAN-REM,/,1H ,27X,10HPOPULATION,3X,4HFEET,4X,6HDEG
                 4N),4X,1H5,5X,1H6,5X,5H7=5+6,8X,8HMREMS/YR,6X,8HMREMS/YR,/,1H ,56X,
                 5 4HNEUT,3X,3HION,4X,5HTOTAL,/)
ISN 0179      908 FORMAT(1H ,11X,3A4,A3,2X,I8,2X,I5,5X,I2,4X,3(F5.1,2X),6X,F6.1,8X,
                 1 F6.1,5X,I10)
ISN 0180      909 FORMAT(1H1,18X,1H1,12X,1H2,10X,1H3,9X,1H4,4X,19HCOSMIC RADIATION D
                 1E,10X,1H8,11X,5H9=7+8,5X,13H10=(2X9)X.001,/,1H ,16X,5HSTATE,9X,
                 2 4H1960,4X,16HELEVATION MAGLAT,5X,9HMREMS/YR,13X,36HTERR DOSE EQ
                 3TOTAL EXT DE    MAN-REM,/,1H ,27X,10HPOPULATION,3X,4HFEET,4X,6HDEG
                 4N),4X,1H5,5X,1H6,5X,5H7=5+6,8X,8HMREMS/YR,6X,8HMREMS/YR,/,1H ,56X,
                 5 4HNEUT,3X,3HION,4X,5HTOTAL,/)
ISN 0181      910 FORMAT(1H ,12X,3A4,4X,I8,2X,I5,5X,I2,4X,3(F5.1,2X),6X,F6.1,8X,F6.1
                 1,5X,I15)
ISN 0182      911 FORMAT(1H1,42X,29HSUMMARY DATA-EXTERNAL DOSE EQ.//,31X,27HMEAN POP
                 1ULATED  MEAN COSMIC,3X,22HMEAN TERR DE  TOTAL DE,3X,13HTOTAL MAN-R
                 2EM,/,31X,28HELEVATION-U.S.  RADIATION DE,5X,9HMREMS/YR,4X,
                 38HMREMS/YR,/,35X,4HFEET,10X,8HMREMS/YR)
ISN 0183      912 FORMAT(1H0,35X,F5.1,10X,F6.1,8X,F6.1,7X,F8.1,2X,I12)
ISN 0184      913 FORMAT(10F5.1)
ISN 0185      914 FORMAT(10F6.5)
ISN 0186          END
```

APPENDIX B

Effect of Building Materials on Exposure

The following assumptions are made in estimating the effect of indoor living on DE:

1. From table 16, it can be seen that the ratio of the indoor to outdoor DE for wood frame houses ranges from 70 percent (Lowder and Condon, 1965) to 82 percent (Yeates et al., 1970).
   Similar ratios for homes of masonry construction range from about 72 percent (Ohlsen, 1969) to 106 percent (Ohlsen, 1969, and Yeates et al., 1970). Based on an analysis of these data, it has been assumed for purposes of this study that the inside to outside DE for frame houses is 70 percent and for masonry houses is 100 percent.
2. Seventy-five percent of the U.S. population is assumed to live in one-family homes, based upon U.S. Census Bureau (1960) estimates that 76.3 percent of all housing units are single homes and that the mean number of occupants per household does not vary significantly according to single or multihousing unit status. During 1964 to 1968, data collected by the Federal Housing Administration (FHA) on financing new and existing homes (U.S. Department of Housing and Urban Development, 1969) showed that the proportion of frame houses sold in the United States ranged from 75.0 percent to 92.2 percent. Although FHA-financed sales account for only a minority of home sales, they represent the only data available on housing construction. On the basis of these data, it has been estimated for purposes of this study that 80 percent of the single homes in the nation are of frame construction. Masonry construction is assumed to account for the balance of single homes. It should be noted that the FHA designation of frame houses refers to the method of roof support, and approximately one-third of all frame homes have some brick or stone facing. The other 25 percent of the U.S. population is assumed to be divided equally between living-in-frame and masonry dwellings.
3. Sixty-eight percent of the U.S. population (U.S. Census Bureau (1969) for 1966) is assumed to be engaged in away-from-home activity (school and work) for 40 hours/week, or 24 percent of the time. This time is assumed to be spent in buildings which are 50 percent frame and 50 percent masonry. The remaining 32 percent of the population is assumed to be at home.
4. Ninety-five percent of an individual's time is assumed to be spent indoors. This value is based on a survey by Robinson and Converse (1966), in which they summarize the ways (27 different categories) in which people spend their time. Only two categories can be clearly identified as outdoor activities (gardening and walking) and these account for 0.1 hours/day. Leisure activities account for 2.1 hours/day; 50 percent of this time is assumed to be outdoors, making a total of 1.2 hours/day (5 percent). Commuting time and nonwork trips are assumed to be indoor activities for the purpose

of this study. Automobiles provide an attenuation of 0.77 (indoor/outdoor terrestrial DE) (Solon et al., 1960), which is similar to that of dwellings. Other modes of transportation are also assumed to similarly reduce the terrestrial DE. An error may be introduced by assuming that all work is done indoors. We must keep in mind that many kinds of work are "outdoor" occupations. On the other hand, much of the work in outdoor occupations, such as police and fire duty, transportation, and construction, take place under cover.

Based on these assumptions, it is possible to estimate a "housing factor," which is the average factor by which indoor living reduces man's exposure to natural sources. The expression for determining the housing factor (HF) is as follows:

$$HF = \underbrace{p_h[(h_f S_f t_i) + (h_m S_m t_i)]}_{\text{Home population}} + \underbrace{p_l[(h_f S_f t_i d_h) + (h_m S_m t_i d_h)]}_{\text{School and labor population at home}} + \underbrace{p_l[(W_f S_f t_i d_w) + (W_m S_m t_i d_w)]}_{\text{School and labor population at work}} + \underbrace{(p_h + p_l)t_o}_{\text{Outside exposure}} \quad \text{(B-1)}$$

where

p_h = proportion of population at home (0.32),
h_f = proportion of population living in frame dwellings [(0.75 × 0.8) + (0.25 × 0.5) = 0.73],
S_f = frame attenuation (0.70),
t_i = proportion of time spent indoors (0.95),
h_m = proportion of population living in masonry dwellings ($1 - h_f = 0.27$),
S_m = masonry attenuation (1.0),
p_l = proportion of population working or attending school (0.68),
d_h = proportion of time spent by workers and students at home ($1 - d_w = 0.76$),
W_f = proportion of workers and students in frame dwellings (0.50),
d_w = proportion of time spent at work (0.24),
W_m = proportion of workers and students in masonry dwellings ($1 - W_f = 0.50$), and
t_o = proportion of time spent outdoors ($1 - t_i = 0.05$).

The housing factor is found to be 0.80, when the above values are substituted in eq. (B-1).

APPENDIX C

Calculation of 2σ Error of Total Dose Equivalent

For the purpose of calculating an estimate of the errors associated with the overall DE estimate, the method suggested by Kline and McClintock (1953) has been used. The overall DE is calculated by

$$DE = X_1 X_2 X_3 + X_4 + X_5, \qquad \text{(C–1)}$$

where

X_1 = terrestrial DE,
X_2 = housing factor,
X_3 = gonadal screening factor,
X_4 = cosmic ray DE, and
X_5 = internal emitter DE.

The estimate of the $\pm 2\sigma$ range may then be calculated by the following equation:

$$W_{DE} = \left[\left(\frac{\partial DE}{\partial X_1} W_1 \right)^2 + \left(\frac{\partial DE}{\partial X_2} W_2 \right)^2 \ldots + \left(\frac{\partial DE}{\partial X_5} W_5 \right)^2 \right]^{1/2} \qquad \text{(C–2)}$$

where

$W_1, W_2, \ldots W_5$ = uncertainty ($\pm 2\sigma$) intervals of parameters
$X_1, X_2, \ldots X_5$, and W_{DE} = the $\pm 2\sigma$ interval of the total DE.

The values for the means and 95 percent confidence interval estimates may then be substituted in eq. (C–1) (partial derivatives are calculated in table C–1). Note that the procedure assumes that the parameters are independent of each other. Thus,

$$\begin{aligned} W_{DE} &= \{[(0.64)(16)]^2 + [(32)(0.32)]^2 \\ &\quad + [(32)(0.16)]^2 + (11)^2 \\ &\quad + (10)^2\}^{1/2} \\ &= (104.86 + 104.86 + 26.21 \\ &\quad + 121 + 100)^{1/2} \\ &= (456.93)^{1/2} \\ &= 21.4, \text{ or } 2\sigma_{DE} = 10.7 \text{ mrem/yr.} \end{aligned}$$

It is interesting to note the relative contributions to the error variance of the overall estimate:

Parameter	Relative contribution
X_1 — terrestrial DE	4
X_2 — housing factor	4
X_3 — gonadal screening factor	1
X_4 — cosmic ray DE	5
X_5 — internal emitter DE	4

For further improvement in the total error, it would appear most useful to improve estimates of X_4, X_1, X_2, and X_5, in that order. Relatively little would be gained in accuracy by improving X_3.

Table C–1. Evaluation of partial derivatives in error calculation

Parameter	Partial derivative
X_1	$\Delta DE = \frac{\partial DE}{\partial X_1} \Delta X_1 = X_2 X_3 \Delta X_1 = 0.64 \Delta X_1$
X_2	$\Delta DE = \frac{\partial DE}{\partial X_2} \Delta X_2 = X_1 X_3 \Delta X_2 = 32 \Delta X_2$
X_3	$\Delta DE = \frac{\partial DE}{\partial X_3} \Delta X_3 = X_1 X_2 \Delta X_3 = 32 \Delta X_3$
X_4	$\Delta DE = \frac{\partial DE}{\partial X_4} \Delta X_4 = 1 \Delta X_4 = \Delta X_4$
X_5	$\Delta DE = 1 \Delta X_5 = \Delta X_5$

THE ABSTRACT CARDS accompanying this report are designed to facilitate information retrieval. They provide suggested key words, bibliographic information, and an abstract. The key word concept of reference material filing is readily adaptable to a variety of filing systems ranging from manual-visual to electronic data processing. The cards are furnished in triplicate to allow for flexibility in their use.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1972 O—465-635

NATURAL RADIATION EXPOSURE IN THE UNITED STATES, (ORP/SID 72-1) by Donald T. Oakley; June 1972; SID, ORP, EPA

ABSTRACT: The exposure of man to natural radiation sources in the United States has been estimated by considering the distribution of the population with respect to certain factors, principally geology and elevation, which influence exposure to terrestrial and cosmic radiation. Data obtained by aerial surveys in the United States have been used to calculate an average dose equivalent (DE) estimate of 40 mrem/yr. to the population. The results also indicate three distinct areas of terrestrial radioactivity in the United States—(1) the Coastal Plain, which consists of all or portions of States from Texas to New Jersey (23 mrem/yr.); (2) a portion of the Colorado Front Range (90 mrem/yr.); and (3) the rest of the United States, i.e., portions of the United States not included in "1" or "2" (46 mrem/yr.).

Since elevation is the primary determinant of cosmic ray DE in the United States, the population distribution with respect to elevation was determined. The average population elevation of the United States was determined to be approximately 700 feet, and the average cosmic ray DE was estimated to be 44 mrem/yr.

(over)

NATURAL RADIATION EXPOSURE IN THE UNITED STATES, (ORP/SID 72-1) by Donald T. Oakley; June 1972; SID, ORP, EPA

ABSTRACT: The exposure of man to natural radiation sources in the United States has been estimated by considering the distribution of the population with respect to certain factors, principally geology and elevation, which influence exposure to terrestrial and cosmic radiation. Data obtained by aerial surveys in the United States have been used to calculate an average dose equivalent (DE) estimate of 40 mrem/yr. to the population. The results also indicate three distinct areas of terrestrial radioactivity in the United States—(1) the Coastal Plain, which consists of all or portions of States from Texas to New Jersey (23 mrem/yr.); (2) a portion of the Colorado Front Range (90 mrem/yr.); and (3) the rest of the United States, i.e., portions of the United States not included in "1" or "2" (46 mrem/yr.).

Since elevation is the primary determinant of cosmic ray DE in the United States, the population distribution with respect to elevation was determined. The average population elevation of the United States was determined to be approximately 700 feet, and the average cosmic ray DE was estimated to be 44 mrem/yr.

(over)

NATURAL RADIATION EXPOSURE IN THE UNITED STATES, (ORP/SID 72-1) by Donald T. Oakley; June 1972; SID, ORP, EPA

ABSTRACT: The exposure of man to natural radiation sources in the United States has been estimated by considering the distribution of the population with respect to certain factors, principally geology and elevation, which influence exposure to terrestrial and cosmic radiation. Data obtained by aerial surveys in the United States have been used to calculate an average dose equivalent (DE) estimate of 40 mrem/yr. to the population. The results also indicate three distinct areas of terrestrial radioactivity in the United States—(1) the Coastal Plain, which consists of all or portions of States from Texas to New Jersey (23 mrem/yr.); (2) a portion of the Colorado Front Range (90 mrem/yr.); and (3) the rest of the United States, i.e., portions of the United States not included in "1" or "2" (46 mrem/yr.).

Since elevation is the primary determinant of cosmic ray DE in the United States, the population distribution with respect to elevation was determined. The average population elevation of the United States was determined to be approximately 700 feet, and the average cosmic ray DE was estimated to be 44 mrem/yr.

(over)

To arrive at an estimate of the gonadal DE, the influence of housing, biological shielding, and the DE contribution from internal emitters was also considered. The first two factors serve to attenuate man's gonadal DE due to terrestrial radiation by about the same amount that is contributed by internal emitters. The average gonadal DE to the U.S. population was calculated to be 88 mrem/yr.

KEY WORDS: Cosmic radiation; dose equivalent; natural radiation; population exposure; surveillance; terrestrial radiation; United States.

To arrive at an estimate of the gonadal DE, the influence of housing, biological shielding, and the DE contribution from internal emitters was also considered. The first two factors serve to attenuate man's gonadal DE due to terrestrial radiation by about the same amount that is contributed by internal emitters. The average gonadal DE to the U.S. population was calculated to be 88 mrem/yr.

KEY WORDS: Cosmic radiation; dose equivalent; natural radiation; population exposure; surveillance; terrestrial radiation; United States.

To arrive at an estimate of the gonadal DE, the influence of housing, biological shielding, and the DE contribution from internal emitters was also considered. The first two factors serve to attenuate man's gonadal DE due to terrestrial radiation by about the same amount that is contributed by internal emitters. The average gonadal DE to the U.S. population was calculated to be 88 mrem/yr.

KEY WORDS: Cosmic radiation; dose equivalent; natural radiation; population exposure; surveillance; terrestrial radiation; United States.