General Safety Considerations

Edited by J. R. Buchanan

Natural Radiation in the Urban Environment

By D. B. Yeates,* A. S. Goldin,† and D. W. Moeller‡

Abstract: *Natural radiation is the largest source of population dose and is important as a base line with which radiation-protection standards may be compared. In this article previous work on natural background radiation levels is summarized, and some new data from Boston, Mass., are reported. Gamma dose rates, corrected for cosmic radiation, were measured with large ionization chambers: dose rates inside wooden single-family dwellings were 25 to 50% lower than those outside; in masonry multiple-family dwellings, they were about 10% lower. Concentrations of radon daughters in the air were measured by predecay and postdecay alpha spectrometry: concentrations in dwellings were comparable with outdoor concentrations, but concentrations in basements were higher by a factor of about 5. Concentrations in office buildings were quite low, the radon daughters being removed by the ventilation system. Effects of building type, construction materials, and ventilation on human dose are discussed, as are possible ways of reducing population dose.*

*Donovan B. Yeates is presently studying for his doctorate at the University of Toronto in the Department of Medical Biophysics. After receiving an undergraduate degree from Perth Technical College, Perth, Western Australia, he read for a Master of Science degree in radiation protection at the University of Surrey, England. Following graduation with distinction, he won a Rotary Award for Technical Training that supported a year of study as a Research Fellow at the Harvard School of Public Health, during which time he collaborated on the preparation of this paper.

†Dr. Abraham S. Goldin has been an Associate Professor of Radiochemistry at the Harvard School of Public Health since 1968. Before that he was with the U. S. Public Health Service from 1951, with major responsibilities in the development of analytical methodology for environmental radionuclides. For much of this time, he was responsible for validation of analytical results in Public Health Service environmental surveillance programs.

‡Dade W. Moeller is Associate Director of the Kresge Center for Environmental Health, Harvard School of Public Health. Prior to taking this position, he was a commissioned officer in the U. S. Public Health Service and served as Officer in Charge of the Northeastern Radiological Health Laboratory (1961–1966) and as Chief, Radiological Health Training Activities, Robert A. Taft Sanitary Engineering Center (1957–1961). He currently serves as a member of the National Council on Radiation Protection and Measurements and is the most recent Past President of the national Health Physics Society. He received his Ph. D. degree in nuclear engineering from North Carolina State University.

Radiation of natural origin is widely recognized as the largest source of human exposure to ionizing radiation. Natural radiation is generally considered to contribute a dose equivalent of 80 to 200 mrems/year to people in the United States.[1] This may be compared with the genetically significant dose-equivalent average of 55 mrems/year[2] from medical radiation and of less than 5 mrems/year from all other man-made radiation sources.

[*Note Added in Proof:* A genetically significant dose from medical radiation of 36 mrems/year was reported from a 1970 survey at the 49th annual meeting of the American Congress of Radiology, Miami Beach, Fla., Apr. 6, 1972, by R. Brown, R. R. Fuchsberg, and J. N. Gitlin in "Preliminary Dose Estimates from the U. S. Public Health Service 1970 X-Ray Exposure Study."]

The natural radiation to which man is exposed in the United States has not yet been delineated in detail; however, it seems that such a description is necessary as a basis for the evaluation of the significance of man-made increments to radiation exposure. Presented in this article is a preliminary report of a study to determine the feasibility of establishing the dose of natural origin and of exploring possible methods for its reduction. Sources of natural origin include cosmic radiation, radiation from naturally occurring radionuclides in the earth or in materials in man's immediate environment, and radiation from radionuclides within the body. However, for purposes of this study, naturally occurring sources were considered only if they had not been intentionally concentrated. Thus masonry materials were included, whereas such sources as uranium mill tailings, radium dials, and medical radium sources were omitted. Also included is a review of previous measurements of natural-radiation doses supplemented by measurements of cosmic-radiation doses, terrestrial gamma doses inside and outside various buildings, and concentrations of radon-daughter products in the air.

BACKGROUND DATA

Measurements of natural background radiation have been made at numerous places throughout the world. In the United States these measurements tend to fall into three categories. First, single measurements were made at widely varying locations selected on the basis of their convenience to a given laboratory or their unusual geological characteristics. Many of these measurements were made in studies of nuclear weapons fallout.[3,4] Second, aerial surveys were conducted in the vicinity of nuclear installations, and, third, special studies were conducted to estimate background radiation dose rates to a particular group of people.[5-7] American studies of natural background radiation have not generally been concerned with the variability of the radiation background over small areas or short spaces of time. This aspect has been studied, however, by some European investigators.[8-10]

The experimental data in this article are expressed in terms of absorbed dose rate in soft tissue (muscle), usually in microrads per hour (1 μrad/hr = 8.77 mrads/year). Data from the literature, many of which were originally given in terms of exposure rates, have been expressed as absorbed dose rates, using a conversion factor of 1 R as equivalent to 0.95 rad. Where a conversion from absorbed dose to dose equivalent was desired, a quality factor of 1 has been assumed for low linear energy-transfer radiation (beta, gamma, and cosmic), so that the absorbed dose rate is the same as the dose-equivalent rate. For the neutronic component of cosmic rays and the alpha radiation from radon and its daughters, the specific quality factor used is given with the data.

Cosmic Radiation

Cosmic rays, at the altitudes where man can live, consist of an ionizing component, mainly muons (μ-mesons) and electrons, and a neutron component.[11] Estimation of the dose equivalent received from cosmic radiation has been difficult because of uncertainties as to the neutron spectrum and its associated quality factor. The dose rate from the ionizing component at sea level in middle latitudes is considered to be about 28 mrads/year (Ref. 11). The best value for the neutron dose rate, again at sea level in middle latitudes, is probably about 0.7 mrad/year (Ref. 11), as compared with a previous estimate of 2 mrads/year (Ref. 1).

The variation of exposure rate from cosmic radiation with altitude and latitude is well documented.[1,11,12] At 50° geomagnetic latitude, the cosmic-ray intensity at 5000 ft is 60% greater than at sea level; at 10,000 ft, it is more than three times the sea-level value. Variation with latitude is much less. At sea level the cosmic-ray intensity at the poles is perhaps 12% greater than at the equator. There is a somewhat greater latitude effect at higher altitudes, but even at 10,000 ft it is only about 50% greater at the poles than at the equator. Within the United States the latitude effect may be neglected for all practical purposes.

The cosmic-ray dose to people in aircraft is of some interest. O'Brien and McLaughlin[13] estimated the dose rate from cosmic radiation at 55° geomagnetic latitude to be 0.24 to 0.29 mrad/hr (0.28 to 0.38 mrem/hr) at 11 km (36,000 ft) and 0.81 to 0.93 mrad/hr (1.05 to 1.35 mrems/hr) at 20 km (65,500 ft). An International Commission on Radiological Protection task group[14] estimated the dose rates in polar latitudes to be 0.70 mrad/hr at 60,000 ft, 0.81 at 70,000 ft, and 1.34 at 80,000 ft. The corresponding dose-equivalent rates are 1.23, 1.80, and 3.10 mrems/hr. The average dose equivalent to the U. S. population from air travel can be estimated at less than 1 mrem/year from data given by Schaefer.[15]

Terrestrial Radiation

Terrestrial radiation includes beta and gamma rays from radionuclides in rock and in soil. The major contributors to terrestrial gamma-radiation dose are ^{40}K and the ^{238}U and ^{232}Th decay series, in the approximate ratio 2 : 1 : 2. A number of literature surveys of terrestrial gamma dose are available.[1,11,12,16-18]

Terrestrial gamma-radiation exposure is strongly influenced by geology.[1,12] Over large freshwater lakes, for example, there is virtually no terrestrial gamma radiation. Highest values are observed over acidic igneous rocks, such as granites, where dose rates up to

350 mrads/year have been found. In a few places, primarily monazite areas, dose rates as high as 1300 mrads/year have been observed. Radiation from terrestrial gamma sources is also affected by meteorological conditions. Probably the most important effect is shielding by snow cover and by moisture in the soil after heavy rains.[8,19]

Published data on the beta contribution to the terrestrial dose differ somewhat. At 1 m above the ground, beta radiation has been estimated to contribute from 4% (Ref. 20) to 25% (Ref. 21) of the total. More recent estimates[4,22] of the beta dose rate at 1 m above the ground are 3 to 4 μrads/hr (26 to 35 mrads/year), or about 30% of the total. The beta contribution to genetic dose is less than this because of shielding by the body.

Radon and Daughters

The naturally occurring radioactive gas radon (^{222}Rn) is a daughter of ^{226}Ra. It reaches the atmosphere by effusion from the earth. The isotope thoron (^{220}Rn), a member of the thorium decay series, reaches the atmosphere in a similar manner but to a much smaller extent since its half-life is much shorter. Both radon and thoron have a number of short-lived radioactive daughter nuclides that become attached to air particulates. Radon concentrations in the atmosphere vary from about 0.01 to 1.0 pCi/liter. Thoron concentrations outdoors vary from about 0.0001 to 0.01 pCi/liter. Concentrations of these gases and of their daughters are markedly affected by geology, by ease of diffusion from the ground, and by meteorological conditions. The daughter products become attached to dust particles and may be removed by natural aerosol clearing processes.

Radiation Within Buildings

The radiation dose within a building is affected by the nature of the building materials, which act as both a source and a shield. Since an average person (in western urbanized cultures) spends upward of 80% of his lifetime indoors, population dose estimates that disregard this fact can be very unrealistic. Exposure levels within brick, concrete, and stone buildings tend to be substantially higher than those in wooden houses or outdoors, as shown in Table 1, which gives data on measurements within buildings in various countries. It should be noted that measurements were made by several techniques, so that the results are not comparable. In particular, several investigators subtracted the cosmic-ray contribution, so that their data refer to terrestrial gamma contribution only, whereas others did not. Scintillation techniques, especially with sodium iodide scintillators, probably underestimate the cosmic-ray component, so that values obtained by these techniques represent dose levels between gamma only and gamma plus cosmic. Most of the results are for one- and two-story buildings. Pensko[9] and Ohlsen[10] have recently provided data for multistory buildings in Poland and East Germany, but no comparably extensive data appear to be available for the United States. The weighted average of Ohlsen's values is 101 mrads/year, but values up to 200 mrads/year were not uncommon. The two highest values were 450 and 1200 mrads/year.

A few authors[32-34] have examined building materials for their radioactive-material content. As would be expected, the dose rates were found to vary

Table 1 Gamma Dose Rates Inside Buildings

Country	Exposure rate, mrads/year	Technique*
Germany (East)[10]	106; up to 1200	a
Germany (West)[23] and Switzerland	120% of outdoor	a
Japan[24]	29 to 41 (wood, Tokyo) 80 to 100 (wood, Kyoto) 48 to 68 (concrete)	e
Japan[25]	20 to 40	c
Poland[9]	84 to 106 (97 apartments, Warsaw, Lodz, Silesia)	c
Sweden[8]	48 to 57 (wood) 99 to 112 (brick) 158 to 202 (concrete)	a
United Kingdom[26]	73 to 94 (wood) 87 to 122 (granite, Leeds, Aberdeen)	d
United Kingdom[27]	26 to 70 (brick, concrete, London, Sutton)	d
United Kingdom[28]	145 (granite, Cornwall)	d
United States[29]	60 (wood) 130 (concrete)	b
United States[30]	55 to 110 (wood) 60 to 120 (brick, stone)	a
United States[6]	70% of outdoor, wood	a
Australia[31]	11 to 35 (wood and asbestos, coastal plain) 41 to 127 (brick, coastal plain) 32 to 193 (brick, Darling range)	b

*a = Ionization chamber, gamma + cosmic; b = ionization chamber, cosmic contribution subtracted; c = sodium iodide scintillator; d = Geiger–Mueller counter, cosmic contribution subtracted; and e = plastic scintillator.

considerably depending on the origin of the building materials.

The concentrations of radon and thoron and of their daughters within buildings are of importance since, in general, the levels indoors are higher than those outdoors and are dependent on the construction materials and on the ventilation rate. Radioactive gases may be evolved readily from some building materials.[35,36] This effect may be particularly great when the materials are warmed, as occurs especially with radiant heating systems. Sievert[17] has summarized the concentrations of radon and its daughters in various types of buildings. The average level of radon in buildings has been estimated[11] as 0.5 pCi/liter, with a corresponding thoron average of 0.02 pCi/liter.

METHODS AND RESULTS

Cosmic Radiation

In the new measurements reported here, two kinds of 16-liter ionization chambers were used for gamma-plus-cosmic-ray exposures. One chamber[37] (MEC) had 6-mm muscle-equivalent walls and contained muscle-equivalent gas. The other chamber[38,39] (FFC) was filled with dry Freon-12 (dichlorodifluoromethane) containing less than 1.5% impurities. The walls of this chamber were polymethylmethacrylate (PMMA), 400 mg/cm^2.

Each chamber was connected to a Cary vibrating-reed electrometer, which in turn was coupled to a chart recorder and to a voltage-to-frequency converter and scaler. The converter–scaler combination made it possible to integrate the very small ion currents over a period of 5 min, giving results reproducible to within 2%.

The two chambers were calibrated with a 1.72-mCi ^{226}Ra standard source. The source–chamber distance was 4 m. Corrections were made for the absorption in air and in the source container and for wall scattering.

A daily calibration check of the FFC showed that the response declined with time. It was also observed that the pressure dropped from 41.7 torrs above atmosphere to 81.0 torrs below atmosphere over a period of 4 months. Both the change in response and the loss of pressure were attributed to loss of Freon-12, apparently by dissolution in the PMMA walls followed by evaporation from the outer surface of the chamber.

Cosmic radiation was measured with these instruments in a boat on Quabbin Reservoir, a large freshwater lake. Under such conditions, virtually the total ionization is due to cosmic radiation since the instruments are shielded from terrestrial radiation by the water and the long air path to shore.

Cosmic-ray physicists normally report their data in terms of I, the number of ion pairs produced per second per cubic centimeter of air. This measurement is essentially the same as the measurement of exposure rate in roentgens, one ion pair per second per cubic centimeter being equivalent to 1.7 μR/hr. Since neither the MEC nor the FFC is air filled, the I values were calculated from the ionization current by correction for the nature of the gas.

With the FFC, the ionization density I was found to be 2.18 ion pairs per cubic centimeter per second, or 2.06 when corrected to sea level.[38] This measurement compares well with reported values of 2.1 (Ref. 40) and 2.18 (Ref. 38) ion pairs per cubic centimeter per second. The measurement of I with the MEC was 2.57, corrected to sea level, or 25% higher. This discrepancy may be due to an incorrect ionization-efficiency factor for the gas (as compared with air), to response to the neutron component, or to some unknown effect. It was not due to instrument malfunction, since the exposure-rate measurements on the instruments, which are relative to radium calibrations, agreed. They were 4.27 μR/hr (37 mR/year) for the FFC and 4.43 μR/hr (39 mR/year) for the MEC, both corrected to sea level. In terms of absorbed dose, these measurements become 4.06 μrads/hr (35 mrads/year) and 4.21 μrads/hr (37 mrads/year) for the two instruments.

When these measurements were made, the air concentrations of radon daughters were not determined. Failure to correct for their contribution introduced an error into the measurements. However, this error can be estimated as about 3% from the work of Pensko,[41] in Poland, who found the contribution to gamma radiation from radon daughters to be 0.13 μrad/hr in 1964 and 0.14 μrad/hr in 1965. In spite of diurnal variations in radon content, the error is not expected to be greater than this because the readings were made during the afternoon on a clear, sunny day. Under these circumstances, radon-daughter concentrations are generally not at a maximum.

Gamma Radiation

Gamma-radiation dose was measured at 1 m above the ground or floor with the MEC and FFC chambers described previously. Use of two chambers simultaneously provided a check against spurious readings that sometimes occur in measuring extremely small currents through very high resistors. These chambers had been calibrated in roentgens, using gamma radiation from radium. The readings have been converted to absorbed dose, however, as previously described. To the extent that beta radiation can penetrate the chamber walls and produce ions, the beta dose is also included. In the actual situation, of course, the ionization in the chambers is produced by gamma radiation from the surroundings (plus beta, if any) and also by cosmic radiation. The dose from terrestrial sources is therefore obtained by subtracting the cosmic-ray dose values from the total. The values obtained at Quabbin Reservoir, corrected for the difference in altitude between Quabbin and Boston, were used for the subtraction. No correction was made for absorption of cosmic rays by building materials, since the cosmic radiation at sea level is very hard.

In these measurements the chief concern was the radiation levels within buildings. In many cases, outdoor levels were also measured for comparison.

Single-Family Dwellings. Table 2 shows the absorbed dose rates due to natural gamma radiation in seven single-family dwellings. These were wood-frame houses with poured-concrete basements. Since no significant differences were found between measurements with the MEC and the FFC, the dose readings were averaged.

Table 2 Gamma Dose Rates (μrads/hr) in Single-Family Dwellings*

Place	Outdoors	Basement	First floor	Second floor
ASG	6.2	5.3	5.0	
MWT			7.3	
FSH	9.0		6.8	
WAB	4.9	4.9	4.2	2.5
SP	8.1	6.2	4.3	4.1
FJV	5.8	6.0	4.4	
DWM	6.5	6.8	6.2	3.2

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.

It can be seen that the dose from natural gamma radiation is reduced by 25% inside on the first floor and 50% on the second floor (assuming cosmic rays are not attenuated in a wooden building). The dose rates will of course not be reduced by this large a percentage, since a constant cosmic-ray contribution of 4.1 μrads/hr must be added to all values to obtain the total dose rate.

Multiple-Family Dwellings. Measurements were made in three multifamily dwellings. These were what are normally called "brick" buildings, but details of their construction were not available. For example, it is not known whether these buildings were solid brick, brick facing on concrete block, or some other type of construction. Measurements were made in one residence in each apartment building. Each residence happened to be on the second floor. Only in one case was a corresponding outdoor measurement made. The measurements are given in Table 3.

Table 3 Gamma Dose Rates (μrads/hr) in Multiple-Family Dwellings*

Place	Outdoors	Second floor
MLC		6.2
JS		7.5
OG	7.2	5.5

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.

The average for the three apartments, 6.4 μrads/hr, is substantially greater than the average value for the three second-floor readings in single-family dwellings (Table 2). This indicates additional dose, which may be attributed to radioactive nuclides in the construction materials. In the one case where a comparison with the outdoor exposure is available, the gamma radiation is lower by 24%, showing that the terrestrial radiation is attenuated by the building materials. In this case the attenuation more than compensates for the radiation contributed by radionuclides in the construction material.

Multistory Office Buildings. Measurements were made in four office or office-plus-laboratory buildings. The most extensive series of measurements was made in the Harvard School of Public Health (HSPH) Research Building 1. This is a modern 14-story office-plus-laboratory building of reinforced-concrete construction with interior wall facings of cinder block. Measurements were made in the corridors of several floors to investigate the variation of exposure rate with height in the building (Table 4).

These measurements were made in part to test whether the attenuation of terrestrial gamma radiation on the upper floors would be greater or less than the possible attenuation of cosmic radiation on the lower floors. The data of Table 4 show a fairly constant

Table 4 Gamma Dose Rates in Office Buildings

Building	Year completed	Construction	Interior walls	Height, stories	Floor	Gamma dose rate,* μrads/hr
JFK	1966	Reinforced concrete	Sheetrock partitions	23	Basement	6.7
					5	4.8
					20	4.9
					23	6.5
HC	1962	Reinforced concrete	Sheetrock partitions	10	2	9.0
SO	1917	Steel and concrete	Sheetrock partitions	12	Basement	5.5
					5	7.2
					12	7.3
HSPH†	1969	Reinforced concrete	Cinder block	14	Basement	7.3
					1	7.5
					3	7.4
					7	8.9
					9	7.8
					11	4.6
					12	6.7
					13	5.8
					14	6.8

*A cosmic-ray contribution of 4.1 μrads/hr has been subtracted from all values.
†First four floors, 1962; next 10 floors, 1969.

radiation level for the first eight floors in the HSPH building and then a slight decrease. These data were supported by nonspectrometric gamma measurements with a 3- by 3-in. NaI(Tl) crystal (Fig. 1). A possible explanation is shielding by heavy machinery on the 10th floor.

Measurements were also made on four floors of the John F. Kennedy Federal Building (JFK) in Government Center, Boston. This is a 23-story steel-and-concrete building that was completed in 1966. Interior walls are Sheetrock partitions. All measurements in this building were taken in office spaces. In addition, measurements were made on three levels of an older office building (SO) housing part of the Massachusetts Department of Public Health and on the second-floor level in the main building at the Holyoke Center (HC) of Harvard University. The HC building had a slightly higher dose rate than the other buildings tested. This may be attributed to differences in the radionuclide content of the concrete. The data for these three buildings are also presented in Table 4. The average gamma dose rate in these buildings was 7.3 μrads/hr, the cosmic-ray contribution having been subtracted.

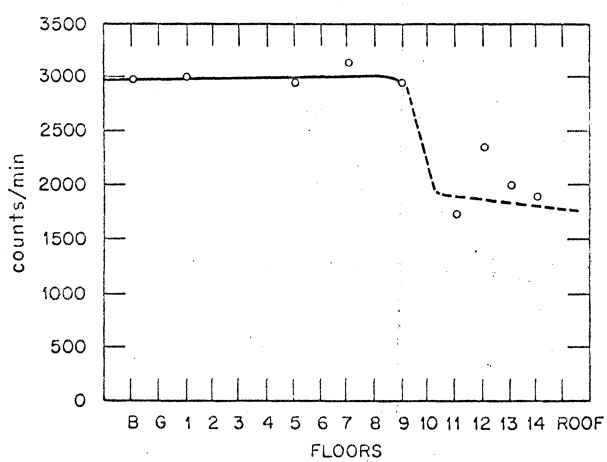

Fig. 1 Total gamma count rates on various floors.

The data of Table 4 fail to show any significant change with height in the buildings. It can be inferred that the gamma dose measured originates primarily in the building itself and that the cosmic-ray dose is not significantly attenuated. This is in agreement with Ohlsen,[10] who reported no change in radiation-exposure rates on various floors of multistory buildings.

Radon-Daughter Concentrations

The daughter products of ^{222}Rn are not generally present in the air in equilibrium concentrations. It was therefore necessary to measure the absolute concentration of each daughter, using a modification of Duggan's[42] method. Radon-daughter products, attached to air particulates, were collected on a membrane-filter apparatus, shown in exploded view in Fig. 2. An alpha spectrum of these particulates was taken during the 30-min sampling period and again after a 30-min decay period. Figures 3 and 4 show typical examples of these two spectra. The first is characterized by peaks at alpha energies of 6.00 and 7.68 MeV, corresponding to ^{218}Po and ^{214}Po; the second shows only the single 7.68-MeV peak. The counting rates in each peak were corrected for geometric efficiency[43] and peak overlap. Self-absorption loss was taken to be zero. At a flow rate of 15 to 20 liters/min, sensitivity was about 0.01 pCi/liter for each of the three significant short-lived daughters ^{218}Po, ^{214}Pb, and ^{214}Bi. At this level precision is poor, but the method is quite satisfactory over the range 0.1 to 100 pCi/liter. The determination does not give the concentration of ^{222}Rn itself, but this can be approximated[44] by using the ratio $^{222}Rn/^{218}Po = 1.12$.

Ventilation rates, which affect the state of equilibrium of the radon daughters, were measured by injecting about 0.5 lb of CO_2 into the room from a CO_2 fire extinguisher. The CO_2 concentration was measured with Kitagawa low-range tubes after a mixing period of several minutes and again at a suitable later time. The ventilation rate (air changes per hour) was then calculated.[45]

Because of the exchange of air between the room being measured and the remainder of the building, the ventilation rate obtained by this method may have been greater than that for the whole apartment or building in which the room was located. In some cases, however, it was not feasible to fill the whole apartment or building with an equal concentration of CO_2, so more accurate determinations were not possible.

All measurements of radon-daughter concentrations in this study were made in the summer months and therefore are limited by any seasonal effects that may exist. The concentrations of the various nuclides and the ratios of these concentrations for single- and multiple-family dwellings are summarized in Table 5. It can be seen that the concentrations in basements were 4 to 23 times those found on the first floors, with the exception of the basement of WAB, which was ventilated just before this measurement. The concentrations outside and inside wood houses are not significantly different. The low levels of concentration in apartment buildings are thought to be due to better ventilation.

Concentrations of radon daughters in the four office buildings were also quite low. All the buildings had central air conditioning except the SO building,

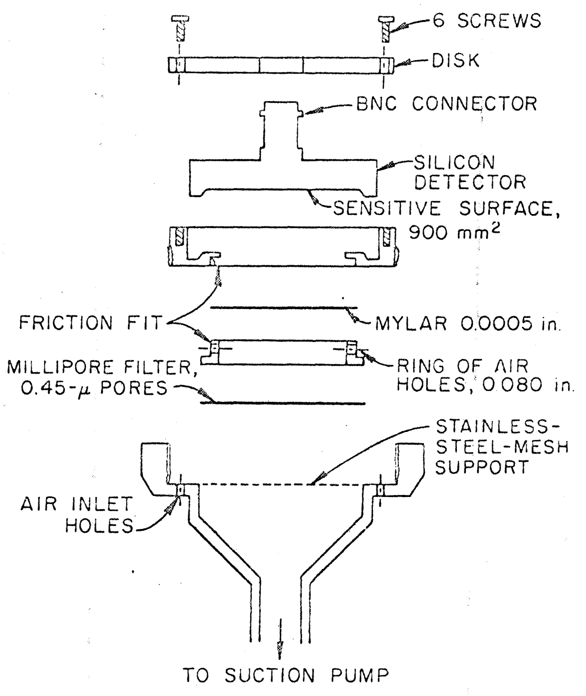

Fig. 2 Air filter and alpha-spectrum detector (exploded view).

which had a number of individual units. Most of the radon daughters in office buildings were thus removed by the filtering system and the rapid circulation of air. Table 6 shows the concentrations measured.

The data of Tables 5 and 6 show a general decline of radon-daughter concentrations with increased ventilation. The concentration of the third radioactive daughter, ^{214}Po, relative to the others, seems to be a little lower in dwellings with three or more air changes per hour, but this trend is not apparent in the office buildings (Table 6). It may be that the filtration provided by the air-conditioning systems in the office buildings removes all the daughters to an extent sufficient to hide the depletion of ^{214}Po.

Calculation of the absorbed dose and of the dose equivalent from radon daughters is not straightforward, primarily because of uneven distribution of the daughters in the respiratory tract and in the body. Much work has been done on this problem, particularly in connection with uranium miners. Parker[46] has aptly described the situation as "The Dilemma of Lung Dosimetry." He has suggested that exposure to radon daughters amounting to one "working-level-month" (WLM) corresponds to a dose of 7 rads to a portion of the bronchial epithelium. An approximate calibration for the levels observed in air in buildings may be obtained from this. The "working level" was defined[47]

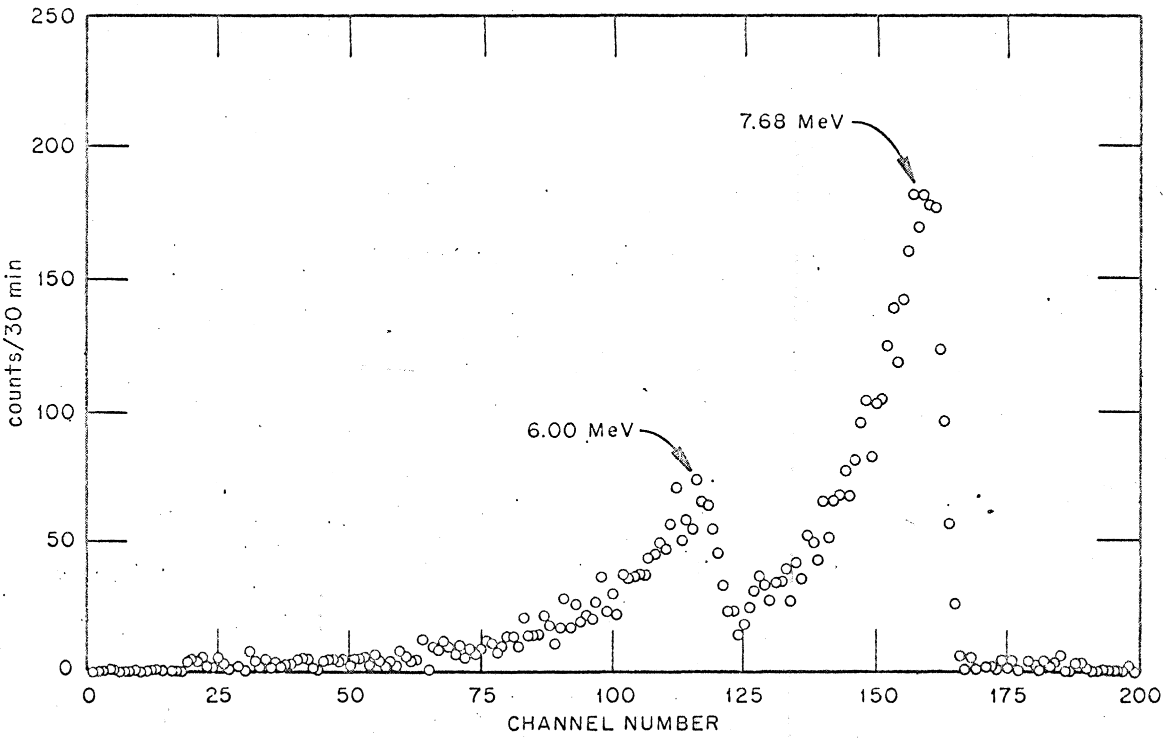

Fig. 3 Radon-daughter alpha spectrum during collection period.

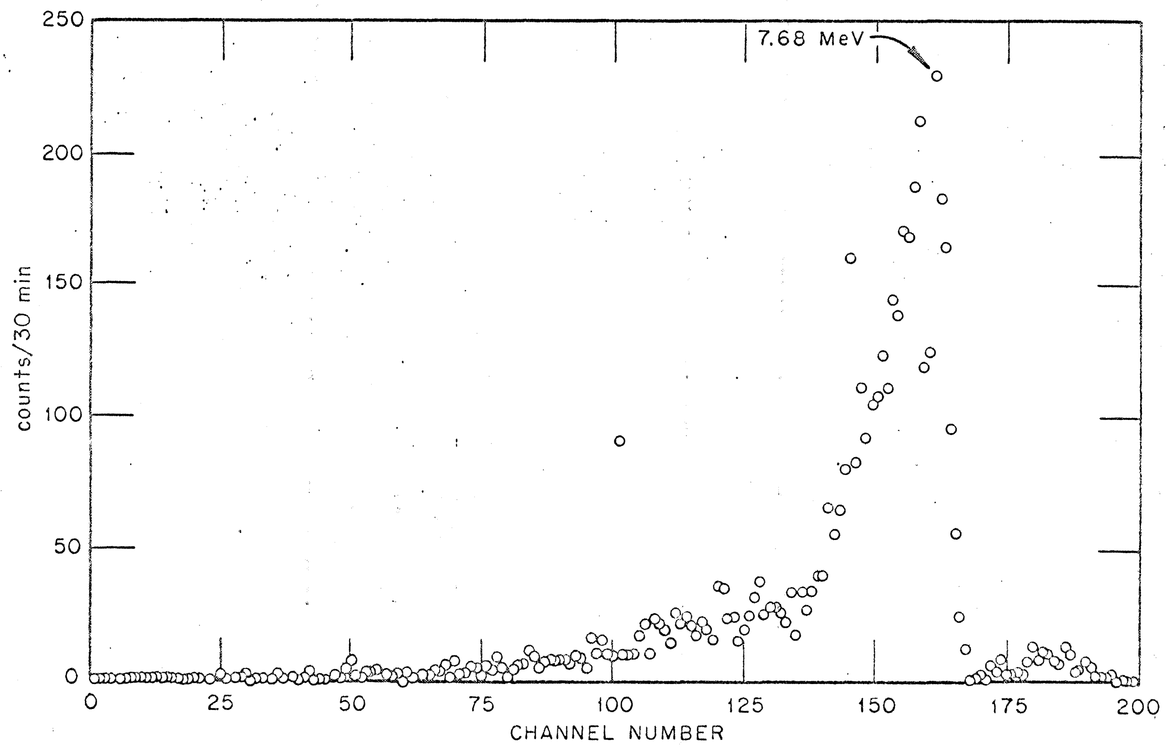

Fig. 4 Radon-daughter alpha spectrum after 30-min delay.

Table 5 Radon-Daughter Concentrations in Dwellings

Code	Location	Concentrations, pCi/liter ^{218}Po	^{214}Pb	^{214}Po	Ratio	Number of air changes per hour
		Single-Family Dwellings*				
ASG	Outside	0.04	0.04	0.03	1 : 1 : 0.8	
	1st floor	<0.005				
	Basement	~0.1				
MWF	1st floor	0.04	0.04	0.02	1 : 1 : 0.5	6
FSH	Outside	0.01	0.01	0.007	1 : 1 : 0.7	
	Inside	0.06	0.06	.06	1 : 1 : 1	2
WAB	Outside					
	1st floor	0.23	0.17	0.17	1 : 0.7 : 0.7	2
	2nd floor					
	Basement	0.14	0.16	0.05	1 : 1.2 : 0.4	3
SP	Outside	0.03	0.02	0.04	1 : 0.7 : 1.3	
	1st floor	0.03	0.03	0.02	1 : 1 : 0.7	
	2nd floor	0.03	0.02	0.01	1 : 0.7 : 0.3	
	Basement	0.30	0.26	0.16	1 : 0.9 : 0.3	3
FJV	Outside	<0.01				
	1st floor	0.04	0.04	0.04	1 : 1 : 1	3
	Basement	0.94	0.97	0.84	1 : 1 : 0.9	1
DWM	Outside					
	1st floor	0.12	0.15	0.13	1 : 1.2 : 1.1	2
	2nd floor					
	Basement	0.52	0.46	0.34	1 : 0.9 : 0.6	1
		Multiple-Family Dwellings†				
MLC	2nd floor	0.01	0.01	0.01	1 : 1 : 1	
JS	2nd floor	0.07	0.07	0.03	1 : 1 : 0.4	9
OG	Outside	0.15	0.09	0.07	1 : 0.6 : 0.5	
	2nd floor	0.19	0.18	0.13		5

*All single-family dwellings were wood frame with poured-concrete basements.
†All multiple-family dwellings were brick.

Table 6 Radon-Daughter Concentrations in Office Buildings

Code	Type of building	Interior walls	Location	Concentration, pCi/liter RaA	RaB	RaC	Number of air changes per hour
HSPH	Offices and laboratories	Cinder block	Basement				
			1st floor	~0.02	0.02	0.02	6
State offices	Offices	Sheetrock	5th floor	0.08	0.08	0.08	6
			12th floor	0.10	0.11	0.13	7
			Basement	0.05	0.04	0.05	
Holyoke Center	Offices	Sheetrock	2nd floor	0.05	0.04	0.04	7
JFK	Offices	Sheetrock	5th floor	0.03	0.02	0.02	12
			20th floor	0.05	0.04	0.01	5
			23rd floor	0.04	0.03	0.03	14
			Basement	0.07	0.07	0.03	

as that amount of radon daughters that would liberate 1.3×10^5 MeV of alpha energy per liter. This corresponds to a concentration of 100 pCi/liter of each of the three nuclides ^{218}Po, ^{214}Pb, and ^{214}Bi. The WLM is equivalent to exposure at this level for 173 hr. If these values are translated to the building situation and if exposure for 24 hr/day, 365 days/year is assumed, then a concentration of 1 pCi/liter would correspond to

$$\frac{(7000)\,(365)\,(24)}{(173)\,(100)} = 3500 \text{ mrads/year}$$

Quality factors of 10 to 20 have been recommended for alpha radiation, so that a concentration of 1 pCi/liter corresponds to 35 or 70 rems/year.

DISCUSSION

The data presented in this paper indicate that there can be substantial differences in the doses received from sources of natural origin, depending on the mode of life of the individual. For example, cosmic dose would be highest for those population groups living at high altitudes or latitudes, for those whose recreation involves skiing or mountain climbing, and for those whose work or pleasure includes considerable air travel. The greatest dose from terrestrial sources would be received by those population groups living on land containing high concentrations of naturally occurring radionuclides and those living in certain brick, stone, or concrete buildings. Those living in poorly ventilated homes, especially in basement apartments, or working in poorly ventilated buildings would receive the greatest dose to the lungs.

The increased doses received by some people under the above-mentioned conditions are not trivial. Based on data collected in the greater Boston area, the differences in dose rates for persons living on the second floor are as much as 35 mrads/year. These dose (rad) values are the same as dose-equivalent (rem) values since the quality factor of this beta–gamma and cosmic radiation is 1. A difference of 35 mrems/year is more than half as much as the estimated genetically significant population dose from medical uses of radiation[2] and far higher than any projections of population dose from nuclear power applications in the near future. Of course, the population or genetic significance of dose differences from various kinds of buildings depends on the fraction of the population living in each type. Relatively few people live in basement apartments; a much greater percentage live in brick or masonry homes.

More dramatic differences exist in the dose equivalents to lung, specifically to basal cells in small bronchi. Radon daughters are the major contributors to the dose equivalent. The concentrations of these daughters in basements with one air change per hour were from 4 to 15 times higher than those on the first floors of the same houses, with two to three air changes per hour. The average level of ^{218}Po in five basements was about 0.4 pCi/liter. Using the previously calculated relation between dose and radon-daughter concentration, this average level would correspond to a dose rate of 1400 mrads/year. Reduction of radon-daughter concentrations by a factor of 10, which is approximately the average ratio between basements and first floors, would amount to a dose reduction of 1250 mrads/year. Application of the recommended quality factor of 10 to 20 for alpha radiation would convert this to 12.5 or 25 rems/year to some basal cells in the bronchial epithelium.

Implications

Health physicists generally have paid little attention to the control of radiation exposure received by the population from natural sources. It appears probable, however, that significant reduction of radiation dose may be achieved in the design of living and working environments. The relative constancy of dose levels on various floors of masonry office buildings, noted here and by Ohlsen, suggests that most of the gamma radiation originates in construction materials rather than in the ground. Provision of better ventilation and air-filtration systems, reduction of the number of basement dwelling units, and screening of construction materials to eliminate those which emit excessive radiation would seem to be promising areas of investigation. Such reduction of population dose equivalent received from buildings may well be comparable with the projected increase from development of nuclear power.

Although definitive data are lacking, it may well be that some people, because of the nature of their environments, are experiencing unnecessarily increased exposure to radiation from sources of natural origin and that this increased exposure is greater than that expected from many man-made sources. Considering this possibility, it would seem wise that greater attention be given to obtaining data on the population dose equivalent from natural sources and the influence of man's living habits on this dose.

Prospectus

Older construction, even in central cities, was largely wood. The data for Boston[48] may be cited as an example. As of January 1968, 68.5% (96,689) of all buildings in Boston were of wood construction. The remaining 31.5% (44,546) were made up of a variety of types, the older ones being predominantly brick and the newer ones concrete or cinder block.

In the newer construction, there is a shift from predominantly single- to multiple-family-dwelling construction. The Boston building-permit records for the period 1959 to 1968 indicate that the number of single-family dwellings decreased from 95% of the total number constructed to 33% and that multifamily (three or more) dwellings increased from 1% of the number constructed to 58%. There was an increase in two-family dwelling construction from 2% in 1959 to a high of 26% in 1965, followed by a decline to 8% in 1968.

The large increase in the number of multifamily dwellings implies a large increase in the fraction of the Boston population living in masonry buildings since virtually all the new multifamily dwellings are of masonry construction. Although quantitative data are not available, observations indicate that more masonry apartment buildings are being built in the suburbs as well. It therefore appears that the urbanization and suburbanization of the population are accompanied by an increase in the fraction living in masonry construction.

To the extent that masonry construction is increasing, higher external exposure of occupants may be expected. To the extent that newer buildings include modern ventilation systems, lung exposure to radon daughters may be decreased.

REFERENCES

1. Radiation from Natural Sources, United Nations Scientific Committee on the Effects of Atomic Radiation, Official Records: Seventeenth Session, Supplement No. 16 (A/5216), pp. 202–232, 1962.
2. *Population Dose from X-Rays, U. S., 1964,* U. S. Public Health Service Publication No. 2001, Superintendent of Documents, U. S. Government Printing Office, 1969.
3. H. L. Beck, W. J. Condon, and W. M. Lowder, Environmental Radiation Measurements in the Southeastern, Central, and Western United States, 1962–1963, USAEC Report HASL-145, New York Operations Office, Health and Safety Laboratory, 1964.
4. H. L. Beck, W. M. Lowder, B. G. Bennett, and W. J. Condon, Further Studies of External Environmental Radiation, USAEC Report HASL-170, New York Operations Office, Health and Safety Laboratory, 1966.
5. A Segall and R. Reed, Human Exposure to External Background Radiation, *Arch. Environ. Health,* 9: 492–499 (1964).
6. W. M. Lowder and W. J. Condon, Measurement of the Exposure of Human Populations to Environmental Radiation, *Nature,* 206: 658–662 (1965).
7. S. G. Levin and R. K. Stoms, Natural Background Gamma-Radiation Dose Rate Measurements in Michigan, Colorado, and Minnesota, *Amer. J. Pub. Health,* 59: 102–109 (1969).
8. B. Hultqvist, Studies on Naturally Occurring Ionizing Radiations, *Kgl. Sv. Vetenskapsakad Handl.,* 6(3): (1956).
9. J. Pensko, Environmental Radiation Measurement in Poland by Means of Scintillation Methods, in International Congress on the Environmental Radiological Protection Connected with the Development of the Peaceful Uses of Nuclear Energy, Toulouse, Mar. 14–16, 1967.
10. H. Ohlsen, Zur Ermittlung der Bevölkerungsbelastung durch natürliche äussere Strahlung auf dem Gebiet der DDR (Messungen in Häusern), *Kernenergie,* 13: 91–96 (March 1970).
11. Radiation from Natural Sources, United Nations Scientific Committee on the Effects of Atomic Radiation, Official Records: Twenty-first Session, Supplement No. 14 (A/6314), pp. 13–43, 1966.
12. Radiation from Natural Sources, United Nations Scientific Committee on the Effects of Atomic Radiation, Official Records: Thirteenth Session, Supplement No. 17 (A/3838), pp. 49–59, 1958.
13. K. O'Brien and J. E. McLaughlin, Calculation of Dose and Dose-Equivalent Rates to Man in the Atmosphere from Galactic Cosmic Rays, USAEC Report HASL-228, New York Operations Office, Health and Safety Laboratory, 1970.
14. A. C. Upton et al., Radiobiological Aspects of the Supersonic Transport, *Health Phys.,* 12: 209–226 (1966).
15. H. J. Schaefer, Radiation Exposure in Air Travel, *Science,* 173: 780–783 (1971).
16. W. M. Lowder and L. R. Solon, Background Radiation: A Literature Search, USAEC Report NYO-4712, New York Operations Office, Health and Safety Laboratory, 1956.
17. R. M. Sievert, G. A. Swedjemark, and J. C. Wilson, Exposure of Man to Ionizing Radiation from Natural and Artificial Sources, *Handbuch Med. Radiol.,* 2(2): 334–371 (1966).
18. D. B. Yeates, A. S. Goldin, and D. W. Moeller, Radiation from Natural Sources in the Urban Environment, Report HSPH/EHS 70-2, Harvard School of Public Health, 1970.
19. Effect of Radiation on Human Heredity, World Health Organization, Study Group Report, Geneva, pp. 74–75, 1957.
20. V. F. Hess and G. A. O'Donnell, The Rate of Ion Formation at Ground Level and at One Meter Above the Ground, *J. Geophys. Res.,* 56(4): 557–562 (1951).
21. K. O'Brien, W. M. Lowder, and L. R. Solon, Beta and Gamma Dose Rates from Terrestrially Distributed Sources, *Radiat. Res.,* 9: 216 (1958); also USAEC Report HASL-3, New York Operations Office, Health and Safety Laboratory, 1957.
22. New York University, The Measurement of Environmental Radiation, Department of Physics Annual Report, July 1, 1966.

23. W. Herbst, Investigations of Environmental Radiation and Its Variability, *Proceedings of the 1st International Symposium on the Natural Radiation Environment*, Houston, Texas, 1963, pp. 781–796, 1964.

24. T. Doke, Y. Takami, and A. Sasaki, Measurements of Radiation Doses Due to Background Gamma Rays by Plastic Scintillators, Japanese Report A/AC.82/G/L.397, Rikkya University, Tokyo, 1960.

25. M. Yamashita, S. M. Oguchi, and H. Watanabe, Measurement of Natural Gamma Radiations Inside Residential Structures, in National Institute of Radiological Sciences, Annual Report, USAEC Report NIRS-5, p. 65, National Institute of Radiological Sciences, Chiba, Japan, 1966.

26. F. W. Spiers and H. D. Griffith, Measurements of Local Gamma-Ray Background in Leeds and Aberdeen, *Brit. J. Radiol.*, 29: 175–176 (1956).

27. J. Vennart, Measurement of Local Gamma-Ray Background at Sutton, Surrey, and in London, *Brit. J. Radiol.*, 30: 55–56 (1957).

28. E. J. B. Willey, Natural Levels of Radioactivity in Cornwall, *Brit. J. Radiol.*, **31**: 31, 56 (1958).

29. H. V. Neher, Gamma Rays from Local Radioactive Sources, *Science*, **125**: 1088–1089 (1957).

30. L. R. Solon et al., Investigations of Natural Environmental Radiation, *Science*, **131**: 903–906 (1960).

31. D. B. Yeates and B. E. King, Estimation of the Population Dose Due to External Natural Gamma Radiation to the People Living in Perth, Western Australia, State X-Ray Laboratory, Perth, Western Australia, in preparation.

32. J. Pensko and M. Bysick, The Gamma Radioactivity of Building Materials for the Construction of Low-Background Laboratories, Polish Report CLOR-20, 1963.

33. H. A. Wollenberg and A. R. Smith, Earth Materials for Low-Background Radiation Shielding, USAEC Report UCRL-9970, University of California, Lawrence Radiation Laboratory, 1962.

34. H. A. Wollenberg and A. R. Smith, A Concrete Low-Background Counting Enclosure, *Health Phys.*, **12**: 53–60 (1966).

35. A. F. Gabrysh and F. J. Davis, Radon Released from Concrete in Radiant Heating, *Nucleonics*, **13**(1): 50 (January 1955).

36. A. F. Gabrysh, N. D. McKee, and H. Eyring, Determination of the Radon Emanation from Carbonate Rocks and Its Potential Hazard in Building Materials, *Mater. Res. Stand.*, 2: 265–268 (1962).

37. J. Kastner, F. R. Shonka, and J. E. Rose, A Muscle-Equivalent Environmental Radiation Meter of Extreme Sensitivity, in *Proceedings of 1st International Symposium on the Natural Radiation Environment*, Houston, Texas, 1963, pp. 655–660, 1964.

38. M. H. Shamos and A. R. Liboff, A New Measurement of the Intensity of Cosmic-Ray Ionization at Sea Level, *J. Geophys. Res.*, 71(19): 4651–4659 (1966).

39. M. H. Shamos and A. R. Liboff, New Ionization Chamber Technique for the Measurement of Environmental Radiation, *Rev. Sci. Instrum.*, 39(2): 223–229 (February 1968).

40. W. M. Lowder and H. L. Beck, Cosmic-Ray Ionization in the Lower Atmosphere, *J. Geophys. Res.*, 71: 4661–4668 (1966).

41. J. Pensko, Sodium Iodide Scintillation Counter for Accurate Measurements of Gamma-Ray Background, in *Solid-State and Chemical Radiation Dosimetry in Medicine and Biology*, Symposium Proceedings, Vienna, 1966, pp. 421–443, International Atomic Energy Agency, Vienna, 1967 (STI/PUB/138).

42. M. J. Duggan and D. M. Howell, Method for Measuring the Concentrations of the Short-Lived Daughter Products of ^{222}Rn in the Atmosphere, *Int. J. Appl. Radiat. Isotop.*, 19: 865–870 (December 1968).

43. M. P. Ruffle, Geometrical Efficiency of a Parallel-Disc Source and Detector System, *Nucl. Instrum. Methods*, **52**: 354–356 (1967).

44. A. Toth, Metrological Problems of Determining the Concentration of Radon-Daughter Products in the Air of Living Rooms, in *Symposium on Health Physics*, Pécs, Hungary, 1966 (CONF-660948), Vol. II, pp. 75–79, 1968.

45. W. L. C. Hemeon, *Plant and Process Ventilation*, p. 231, Industrial Press Inc., New York, 1955.

46. H. M. Parker, The Dilemma of Lung Dosimetry, *Health Phys.*, **16**: 553–561 (1969).

47. D. A. Holadayet et al., *Control of Radon and Daughters in Uranium Mines and Calculations of Biologic Effects*, U. S. Public Health Service Publication No. 494, Superintendent of Documents, U. S. Government Printing Office, Washington, 1957.

48. City of Boston, Building Department.