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The Organisation for Economic Co-operation and Development (OECD) was set up under a Convention signed in Paris on 14th December, 1960, which provides that the OECD shall promote policies designed:

— to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
— to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development;
— to contribute to the expansion of world trade on a multilateral, non discriminatory basis in accordance with international obligations.

The Members of OECD are Australia, Austria, Belgium, Canada, Denmark, Finland, France, the Federal Republic of Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

The OECD Nuclear Energy Agency (NEA) was established on 20th April 1972, replacing OECD's European Nuclear Energy Agency (ENEA) on the adhesion of Japan as a full Member.

NEA now groups all the European Member countries of OECD and Australia, Canada, Japan, and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objectives of NEA are to promote co-operation between its Member governments on the safety and regulatory aspects of nuclear development, and on assessing the future role of nuclear energy as a contributor to economic progress.

This is achieved by:

— *encouraging harmonisation of governments' regulatory policies and practices in the nuclear field, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
— *keeping under review the technical and economic characteristics of nuclear power growth and of the nuclear fuel cycle, and assessing demand and supply for the different phases of the nuclear fuel cycle and the potential future contribution of nuclear power to overall energy demand;*
— *developing exchanges of scientific and technical information on nuclear energy, particularly through participation in common services;*
— *setting up international research and development programmes and undertakings jointly organised and operated by OECD countries.*

In these and related tasks, NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

EXPOSURE TO RADIATION FROM THE NATURAL RADIOACTIVITY IN BUILDING MATERIALS

Report by a Group of Experts of
the OECD Nuclear Energy Agency

May 1979

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

FOREWORD

This report was prepared by a Group of Experts for the Committee on Radiation Protection and Public Health of the OECD Nuclear Energy Agency. Estimates are given of the extra exposure to gamma rays and radon daughters that persons incur through living in masonry dwellings instead of outdoors. Summary Tables III and V contain results for three levels of radioactivity in building materials.

The publication by the OECD of reports such as this may contribute to the development of an international consensus on matters of public concern. It does not commit Member governments or the Organisation in any way.

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CONTENTS

1. INTRODUCTION

Radiation exposure of members of the public can be increased appreciably by the use of building materials containing above-normal levels of natural radioactivity. This phenomenon has attracted attention in recent years, and in this review, an attempt is made to the quantify exposures incurred under various circumstances.

The second section of the review is a general survey of those building materials, mostly industrial wastes, that have aroused interest in Member countries. The probability that environmental pressures may cause such wastes to be used more and more by building industries may lead to similar situations in the future. Other review material of a relevant nature is described in the third section.

Primordial radionuclides only are considered here. They are : potassium-40 (K-40) ; radium-226 (Ra-226) and its decay products ; the series headed by thorium-232 (Th-232). The precursors of Ra-226 in the uranium-238 (U-238) series are ignored because they emit non-penetrating radiation in the main and because the question of the state of radioactive equilibrium between U-238 and Ra-226, irrelevant in this context, would complicate matters needlessly. Although rubidium-87 is relatively abundant in the lithosphere and of some interest as an incorporated source, it too is ignored because its radiation is not penetrating. Other non-series primordial radionuclides and the series beginning with uranium-235 are relatively scarce ; they are also ignored.

The important radiological consequences of the natural radioactivity in building materials are two-fold, irradiation of the body by gamma rays and irradiation of the lung tissues by radon-222 (Rn-222) decay products or daughters. These consequences cannot be explored quantitatively except in relation to the specific activities of the nuclides of interest, and the approach adopted in this review is to assess the consequences in terms of the incremental radiation exposures that would be incurred by occupants of substantial dwellings entirely constructed of materials with various specific activities or combinations thereof. Gamma rays are dealt with in the fourth section and radon daughters in the fifth.

It is impossible, in radiological terms, to consider a building in complete isolation from the ground on which it stands ; in this review, therefore, the term "building materials" will be considered to embrace not only the materials used in the construction of a building, but also those immediately subjacent to it. Broad geological factors affecting exposure are not treated, however.

Building materials are not alone in elevating radiation exposure indoors. Other contributing sources, such as gas and water supplies, are identified in the last section. Although they are, in a strict sense, outside the scope of this review, they would need to be taken into account when considering the total exposure of persons.

The references in the review span three decades. Some radiation units have changed during that period, and to avoid confusion, the contemporaneous units are employed. Units are therefore historically correct, but discussion is conducted in the present units. Conversion factors are provided in Appendix I.

2. RADIOLOGICAL INTEREST IN CERTAIN BUILDING MATERIALS

The building industry requires large quantities of low-cost raw materials, and there is increasing interest in industrial and extractive wastes as substitutes for natural products. This practice may conserve natural resources, prevent land sterilization, reduce pollution of rivers and coastal waters, and cut overall costs, but it may also cause radiological concern.

One of the stimuli to the production of this review is the case of phosphogypsum (1). This material arises as a waste in the manufacture of phosphoric acid from calcium phosphate ore and sulphuric acid (2). The term phosphogypsum tends to be applied loosely to by-product calcium sulphate either as the dihydrate, hemihydrate, or anhydrite. The waste gypsum may contain specific activities of Ra-226 between one and two orders of magnitude higher than natural gypsum, depending on the uranium content of the ore (3)(4), and could appreciably increase the radiation exposure of inhabitants if used in credible configurations in representative houses. In the United Kingdom, for example, the use of phosphogypsum has been restricted (5). These comments refer to wastes from sedimentary phosphate ores ; such ores tend to have high concentrations of uranium, whereas magmatic ores do not.

Phosphogypsum can replace natural gypsum in plaster and plaster-board manufacture ; as a retarder in cement, or as a raw material in the cement-sulphuric acid process ; and in the production of glass-reinforced gypsum which could partly replace asbestos products. It is also used for making partition blocks (2). At the time of writing, the utilization of phosphogypsum in countries with large reserves of natural gypsum is not high, but in countries without much natural gypsum, the artificial product is more widely used. There is also some international trading in building components made of phosphogypsum. The potential for exploitation is considerable, since, in 1975, the phosphate rock production world-wide was about 10^8 tonnes (6) implying about as much phosphogypsum. No practical technology appears to be in use for removing the Ra-226, although, in a British patent (7) for instance, the claim is made that it can be decreased by fractionating the waste according to particle size.

The United States is by far the world's biggest producer of raw phosphate rock, with the bulk of its present capacity to be found in Florida (6). Land is reclaimed following strip mining, and the Ra-226 specific activity in the fill is an order of magnitude higher than in ordinary soil. In a preliminary study of buildings on this reclaimed land (8), elevated gamma-ray and Rn-222 decay product exposures were discovered. A follow-up evaluation of the control of the radon daughter concentrations in new structures has been published (9), and interim recommendations, based on an experimental relationship between outdoor gamma-ray exposure rates and indoor radon daughter concentrations, have been made (10) for screening land sites for new buildings. This work is part of an extensive study of radiation exposures in the Florida phosphate industry (11).

Fluorogypsum, another artificial gypsum, is obtained from the anhydrite waste created by the manufacture of hydrofluoric acid from fluorspar and sulphuric acid. Both the waste gypsum and the anhydrite are used as building materials. The radioactivity content does not appear to have been studied systematically, but the Ra-226 concentration might exceed that of the natural equivalents.

A further building material causing radiological interest in the Federal Republic of Germany is brick made from red mud. This mud is a waste from the production of alumina from bauxite by the Bayer process, the first stage of manufacture of aluminium. The main constituents of red mud are iron oxide, titanium oxide, and silica.

Measurements of gamma-ray emission have shown that the specific activity of red mud bricks can be three times higher than ordinary clay bricks (12).

The marked effect of an additional artificial building material has been demonstrated in a large-scale survey of population exposure to ionising radiation also in the Federal Republic of Germany (13). Gamma-ray exposure rates in houses in the Saar are noticeably high because of the concentrated use in that state of slag building blocks with elevated activity. Blast-furnace slag is a by-product of iron manufacture ; it results from the fusion of limestone, coke, ash, and gangue.

A serious radiological problem was created in the United States by the use of uranium mine tailings around and under houses in Colorado. When the uranium is separated from the ores, Ra-226 at high specific activity remains in the tailings. The discovery of the problem brought about extensive studies of the gamma-ray and Rn-222 decay product exposures of occupants (14). The National Authority issued guidelines for action based on these exposures, the action to include remedial measures such as tailings removal, the use of sealants, or ventilation improvement.

The misuse of contaminated waste around buildings in an Ontario township (15) occasioned a programme of assessment and remedial measures in Canadian communities associated with uranium mining and milling. Clean-up criteria related to indoor and outdoor exposures were established (16). Studies of background levels of radon daughters indoors have followed in other communities (17) with emphasis being placed on measurements in the basements of houses.

Some difficulties have also arisen in Australia (18). A number of properties in a suburb of Sydney were found to be contaminated with tailings from a radium factory that had operated in the area at the time of the First World War. Elevated gamma-ray and radon daughter exposures were recorded. The authorities decided on remedial measures including demolition of some houses, removal of affected soil, and continuing medical supervision of the occupants.

Difficulties may also be experienced by mining companies and Controlling Authorities when planning townships for uranium mining projects. They may encounter outcrops of uraniferous rock in the locality or elevated soil concentrations at some distance from superficial deposits with the attendant risk of excessive radiation exposures if these materials are inadvertently used for building purposes or even if housing is located on such ground.

Other industrial by-products that are used or could be used in the building industry include : colliery spoil ; china clay waste ; slate waste ; pulverised fuel ash and furnace bottom ash ; furnace clinker ; incinerator ash ; zinc-lead slags ; tin mine tailings ; fluorspar mine tailings ; quarry wastes (2). It is not suggested that this list is exhaustive nor that all of these materials contain abnormal radioactivity, but some at least merit systematic measurement.

As far as raw materials extracted primarily for building purposes are concerned (materials that are not by-products of other processes) the most widely used higher-activity materials are granites. Granites are coarse-grained igneous rocks consisting essentially of quartz, alkali feldspar, and mica. The use of granite is normally restricted to the immediate areas in which natural outcrops of suitable rocks occur. Clear differences in exposure to gamma rays have been established between populations in sedimentary and granite districts (19) and this is linked to the high radioactivity contents of granites (3) (20).

Table

MEAN SPECIFIC ACTIVITIES OF SOME BU[illegible]

Country	Material	Number of samples
Finland	Building sand and gravel	1[illegible]
	Clay bricks	33
	White bricks	3
	Cement	7
	Aerated concrete	[illegible]
	Natural gypsum	1
	Slag aggregate	3
Federal Republic of Germany	Building sand and gravel	50
	Granite	3[illegible]
	Bricks (traditional constituents)	10[illegible]
	Pumice-aggregate concrete blocks	31
	Slag-aggregate concrete blocks	[illegible]
	Portland cement	1[illegible]
	Natural gypsum	[illegible]
	Chemical gypsum (phosphogypsum)	33
	Red mud bricks	[illegible]3
	Fly ash	[illegible]
Italy	Lithoid tuff (tufo litoide, Mount Cimino)	–
	Nenfro (a variety of tuff, Tuscania)	–
Norway	Brick	[illegible]
	Concrete	[illegible]
	Lightweight concrete	[illegible]
	Clinker	[illegible]
	Natural gypsum	[illegible]
	Cement	[illegible]
Sweden	Concrete ballast (gravel, shingle, macadam)	29[illegible]
	Brick	–
	Cement	–
	Aerated concrete without alum shale	–
	Aerated concrete with alum shale (in production 1947-75)	–
	Aerated concrete with alum shale (in production since 1974)	–
	Gypsum plasterboard (Swedish manufacture)	–
	By-product gypsum (phosphogypsum)	–
	Lightweight aggregate	–
United Kingdom	Granites	7
	Sand and gravel	10
	Cement	[illegible]
	Clay bricks	2[illegible]
	White bricks (autoclaved flint and quicklime)	5
	Natural gypsum	73
	Lightweight blocks various aggregates	10
	Phosphogypsum from sedimentary ores	60
United States	Phosphate land fill, Florida	–
	Gypsum from Florida phosphate rock	–
	Uranium mine tailings	–

' RT.LS USED IN MEMBER COUNTRIES

Mean specific activity, Bq/kg[1]			Ref.	Comment
C_K	C_{Ra}	C_{Th}		
1034	37	43	29	Interim results
962	78	62	29	Interim results
577	22	23	29	Interim results
241	44	25	29	Interim results
359	49	36	29	Interim results
25	7	2	29	Interim results
193	102	69	29	Interim results
241	<15	<18	30	Many sources
1299	100	80	30	Different types
673	59	67	30	Different types
770	74	80	30	Adequate sampling
529	151	101	30	Depends on feed materials
241	<26	<18	30	Several sources
96	<18	<10	30	Many sources
96	592	<15	30	Depends on source of rock
337	281	233	30	Variable composition
721	211	129	30	Many sources
1539	129	122	21	Commonly used for house building
2068	241	218	21	Wall cladding material
1058	104	62	31	Oslo region
721	26	36	31	Oslo region
241	33	26	31	Oslo region
818	96	60	31	Oslo region
11	11	3	31	Oslo region
241	30	18	31	Oslo region
818	48	73	25	Standard deviation 38 %. Different types
962	96	127	25	Inadequate sampling
241	55	47	25	Adequate sampling
1299	55	18	25	Adequate sampling
770	1295	67	25	Adequate sampling
529	333	28	25	Adequate sampling
22	4	<1	25	Adequate sampling
48	15	62	25	Adequate sampling. Probably Kola apatite
1010	144	158	25	Adequate sampling. Different types
1103	89	81	3	Inadequate sampling
33	4	7	32	Inadequate sampling
155	22	18	32	Inadequate sampling
703	52	44	3	Sampling probably adequate
12	4	5	3	Aggregate may vary
141	22	7	3	Adequate sampling
370	59	26	3	Inadequate sampling
41	629	13	32	Depends on ore source
–	740	–	8	Estimate depends on geological structure and reclamation procedure
–	1221	10	33	Samples from several processing facilities
–	4625	–	34	Personal assay of complex situation

Bq/kg = 0.027 pCi/g

Another example of a raw material that has a pronounced effect on population exposure is the pyroclastic rock commonly used in the Lazio region of Italy (21) ; the resulting terrestrial dose rate there is twice the national average (22).

The case of the alum shales in Sweden has had considerable radiological impact in that country. This is a unraniferous argillaceous rock which has been used for several decades for making aerated concrete. It has extraordinarily high specific activities of Ra-226 and raises the gamma-ray dose rates and airborne activity concentrations in houses markedly (23) (24). At one time, aerated concrete based on alum shale took up about a third of the market for building materials in Sweden, but it has not been produced since 1975 (25).

Against this background, the need for assessment of the radiological significance and possible effects on public health of exposure to radiation from building materials becomes apparent.

Table I contains a selection of data on the specific activities of various building materials in several countries. The presentation is restricted to Member countries of OECD so as to make the data manageable. Other compilations exist (26-28) and other sources of information in this field are described in the next section.

3. OTHER RELEVANT SOURCES OF INFORMATION

The primary intention here is to note a few recent publications that are relevant to the subject of radioactivity in building materials thus supplementing the preceding section. These notes are not exhaustive, but merely indicate some of the more readily available review material. It is not considered necessary to refer to the relevant individual publications of the International Commission on Radiological Protection and of the International Commission on Radiation Units and Measurements, since these would inevitably be consulted. The opportunity is also taken to highlight certain references that have special utility.

From time to time, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) presents reviews on human exposure to ionizing radiation in reports that it makes to the General Assembly. The seventh report (26) contains an extended treatment of the doses arising from primordial radionuclides. Data on the activity in building materials is provided as well as an estimate of the average absorbed dose rate indoors. Special attention is paid to the dosimetry of the short-lived decay products of Rn-222, and exposure to these nuclides indoors is analysed. In a section on enhanced exposure to natural radiation, the specific activities of primordial nuclides in some coal residues are listed ; these are potential aggregates.

The US National Council on Radiation Protection and Measurements issued, in 1975, a report entitled "Natural background radiation in the United States" (35) which presents a comprehensive picture of exposure to environmental radiation in that country.

A literature search concerned specifically with the problem of natural radioactivity in building materials was conducted by the US Environmental Protection Agency. A report by G.C. Eadie was published in April 1975 (36). It deals with foreign as well as US literature and consolidates the position as of February 1975.

The proceedings of two international symposia on the natural radiation environment edited by Adams and Lowder (the second with T. Gesell) are very useful sources of information on environmental radioactivity. The first was held in 1963, the second in 1972. (See references 20 and 22 for citation.) Another was held in 1978.

The degree of exposure to airborne radioactivity is a critical factor in the radiological evaluation of a building material, and ventilation is a key element in the analysis. An example of a review of ventilation data for radiological purposes is given in a US report by T.H. Handley and C.J. Barton (37).

For a coherent treatment of the whole topic of environmental radioactivity, both natural and artificial, reference may be made to the second edition of a book by M. Eisenbud, called "Environmental Radioactivity" (38).

Reference 2 to a publication by Gutt et al. in 1974 merits special attention. It is a thorough analysis of the position in the major parts of the United Kingdom with regard to the actual and potential utilization of large-volume industrial and extractive wastes, but illustrations are also given of overseas practices, and the work is being extended. The report highlights the pressures for conservation at work in an industrialized country and indicates the range of materials likely to be encountered by National Authorities.

Special mention must also be made of the originative reports by Hultqvist (24) and by Krisiuk and his co-workers (27) as well as the paper on radon daughters by Evans (39).

4. INCREMENTAL EXPOSURE TO GAMMA RAYS

The information in Table I indicates that representative specific activities of extractive types of materials used traditionally by the building industry are as follows : K-40, 500 Bq/kg ; Ra-226, 50 Bq/kg ; Th-232, 50 Bq/kg. These values are rounded to avoid any suggestion of undue accuracy and to facilitate subsequent manipulation. Similar values are indicated by UNSCEAR (26).

Since the main stimulus to this review is the potential problem posed by materials that enhance exposure to ionizing radiation, two levels of enhancement will be examined, the first corresponding to twice the representative values, the second to quadrupled values. These are 1000 and 2000 Bq/kg of K-40 and 100 and 200 Bq/kg of both Ra-226 and Th-232, and are chosen to illustrate the incremental exposure incurred at such levels.

It is, of course, essential not to link the analysis of gamma-irradiation to particular combinations of specific activities. The nuclides of interest contribute to the external irradiation of persons roughly according to the ratios of their specific exposure rate constants, namely K-40 : Ra-226 : Th-232 :: 1 : 10 : 15. This suggests a method of generalizing the treatment of exposure to gamma rays.

The procedure adopted is to use as an index of gamma-irradiation the sum of three specific activity quotients with the denominators chosen to reflect specific exposure rate and yield a sum equal to unity. Let C_K, C_{Ra} and C_{Th} be the specific activities of K-40, Ra-226 and Th-232 in units of Bq/kg. Then, the expression :

$$\frac{C_K}{3000} + \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} = 1$$

is considered as defining the first enhanced level regardless of the values of the numerators.

Similarly, the expression :

$$\frac{C_K}{6000} + \frac{C_{Ra}}{600} + \frac{C_{Th}}{400} = 1$$

is considered as defining the second enhanced level in a generalized way. It is worth repeating that these are illustrative levels.

For completeness, the definition of the representative level is as follows :

$$\frac{C_K}{1500} + \frac{C_{Ra}}{150} + \frac{C_{Th}}{100} = 1$$

These general definitions have the effect of under-estimating slightly the gamma-ray exposure at each level.

Several investigators have established relationships between specific activities in building materials and gamma-ray dose rates inside buildings constructed of them. These investigations and other studies will now be surveyed with a view to describing the radiological implications of the two enhanced levels.

Hultqvist (24) developed formulas (mainly from early reactor shielding literature) to relate air ionisation above the earth's surface to the nuclide content of the ground. These are $I_{Ra} = 1.26 \times 10^{12}\ S_{Ra}$, $I_{Th} = 0.21 \times 10^{6}\ S_{Th}$, and $I_K = 91\ S_K$, where I is the ionization in units of ion pair/cm^3.s and S is the nuclide content in g/g. Note, however, that S_K refers to the common potassium content and that the author assumed an abundance of 0.0119 % for K-40. Note also that 1 ion pair/cm^3.s corresponds to 1.50 µrad/h in air.

He then suggested that the ionization inside an unspecified type of dwelling (probably flats) with a uniform distribution of activity might be 1.5 to 2.0 times the values given by the preceding formulas. Let the factor be 1.75. The dose rate $\dot{D}$ within a building is then given by :

$$\dot{D} = 4.37 \times 10^{-3}\ C_K + 5.11 \times 10^{-2}\ C_{Ra} + 7.82 \times 10^{-2}\ C_{Th}\ \mu rad/h$$

in air, where C is in Bq/kg.

If one now adopts the data in UNSCEAR (26) on the mean outdoor dose rate (4.5 µrad/h in air 1m above ground) the indoor occupancy factor (0.8) and the conversion factors from absorbed dose in air to gonad dose (0.8 for outdoor irradiation and 0.7 for indoor irradiation) one finds that the first enhanced level implies an increase in annual gonad dose of 47 mrad over that which would be incurred through living permanently out of doors. For the second enhanced level, the implied increment is 119 mrad in a year. It is reasonable to suggest that the increase in gonad dose applies to the organism as a whole ; therefore, the incremental dose-equivalent to the whole body is 0.47 mSv in a year at the first and 1.19 mSv in a year at the second enhanced level. Incidentally, the Hultqvist formulas imply an annual increase of 0.11 mSv at the representative level of specific activity.

Krisiuk et al. (27) put forward an expression for the exposure rate $\dot{X}$ in a hole in an infinite medium in which medium the nuclides of interest are evenly dispersed :

$$\dot{X} = 4.66\ C_{Ra} + 6.7\ C_{Th} + 0.37\ C_K\ \mu R/h$$

They expressed C in units of pCi/g. Then, allowing for a mean outdoor exposure rate of 8.9 μR/h, 18 hours per day indoors, and a coefficient of gonad shielding of 0.63 (their conversion factor from μR/h to μrad/h in gonads) they suggest that the increase in the annual gonad dose inside a room is :

$$\dot{D} = 18.5\ C_{Ra} + 26.7\ C_{Th} + 1.47\ C_K - 35.4\ \text{mrad/y}$$

Once again, C is in pCi/g.

This is an extreme prediction, of course, and the authors later suggest a correction of about 0.7 for windows and doors and another correction of about 0.7 for the absence of saturation thickness in a structure. Thus they predict the following increase in annual dose equivalent to the whole body from living in realistic structures as opposed to living entirely out of doors : representative level of specific activity, 0.16 mSv ; first enhanced level, 0.50 mSv ; second enhanced level, 1.18 mSv. This approach was validated by measurements in an experimental two-room flat.

Swedjemark (40) has conducted an extensive experiment in Sweden so as to relate the dose rate in dwellings to the specific activities of the building materials employed. She made measurements in multi-family houses and in single-family houses and specifically designed her experiment to answer the following question : what is the yearly gonad dose above background (outdoor) to the inhabitants of buildings in which the sum of certain quotients of the specific activities of the materials has a certain value ? The author chose the following conditions :

$$\frac{C_K}{4800} + \frac{C_{Ra}}{370} + \frac{C_{Th}}{260} = 1$$

where C is in Bq/kg. She found that the excess over background (which she took as 0.3 mGy/y) for multi-family houses (flats, apartments) was 0.95 mGy/y and for single-family houses 0.52 mGy/y, both referring to the absorbed dose in the gonads.

If allowance is now made for an occupancy factor of 0.8, as in UNSCEAR (26), the following increases in annual dose equivalent to the whole body are predicted at the specific activity levels of interest :

Structure	mSv in a year increment		
	Representative	1st Enhanced	2nd Enhanced
Flats	0.12	0.49	1.22
Houses	0.00	0.24	0.72

The identity of the Swedjemark (40), Krisiuk (27), and Hultqvist (24) values for apartments is noteworthy and so is the disparity between flats and houses.

Another estimate of the increments may be obtained from the extensive UK survey by Spiers (19) the results being predominantly for single-family houses.

Inside substantial granite houses made from local stone [which had (3) the following average specific activities in pCi/g : K-40, 27.6 ; Ra-226, 1.82 ; Th-232, 2.68] Spiers recorded a mean dose rate of 85.3 mrad/y to the gonads. Out of doors in another area of Lower Carboniferous sandstone, the mean was 48.5 mrad/y to the gonads. Allowing, with Spiers, for an indoor occupancy factor of 0.75, one finds that the incremental dose equivalents to the whole body in a year are : representative specific activity level, - 0.06 mSv (negative) ; first enhanced level, 0.24 mSv ; second enhanced level, 0.84 mSv. For the enhanced levels, at least, these results are in good agreement with Swedjemark's values for houses (40).

On the basis of measurements in and near modern houses in the Oslo region of Norway and the specific activities of the main building materials in the district, Stranden (31) too established a relationship between the sum of certain quotients of the specific activities and the increase in yearly gonad dose. The sum of quotients chosen by him was :

$$\frac{C_K}{120} + \frac{C_{Ra}}{10} + \frac{C_{Th}}{7} = 1$$

where C is expressed in pCi/g ; the increase in gonad dose under these conditions was 50 mrad in a year. The houses were principally single-family ones in a mixture of rural and suburban areas. An occupancy factor of 0.7 was assumed, and the annual dose rate out of doors was taken as 36 mrad to the gonads. His experimental results imply an annual whole body increment of 0.02 mSv at the representative specific activity, 0.30 mSv at the first enhanced level, and 0.85 mSv at the second.

Koblinger (41) in Hungary devised a Monte Carlo program to calculate the exposure rates in rooms as a function of the specific activities of the nuclides of interest in the building materials. For homogeneous activity distribution, radioactive equilibrium in the series, and a room measuring 5.6 x 3.1 x 2.5 m^3 with 14 cm thick concrete walls, density 2.5 g/cm^3, he obtained the following expression :

$$\dot{X} = 0.267\ C_K + 2.37\ C_{Ra} + 3.29\ C_{Th}\ \mu R/h$$

In this instance, C is in terms of pCi/g.

Adopting the occupancy and gonad screening factors of 0.66 and 0.8 used by Fehér et al. (42) in Hungary as well as the UNSCEAR (26) estimate of dose rate out of doors (4.5 µrad/h in air) one finds that this model predicts the following increments in annual whole body dose-equivalents : representative specific activity level, 0.24 mSv ; first enhanced level, 0.70 mSv ; second enhanced level, 1.60 mSv. Although these values are already somewhat higher than previous sets, it must be noted that experimental work indicated that the computer program underestimated the exposure rate by a factor of 1.5 to 2.2, which would cause the outcome to be even more at variance with other experience. The author attributes the disagreement between theory and experiment to the omission of surrounding rooms (he was considering apartment blocks) in the calculations and to errors in activity and exposure measurements.

In the Federal Republic of Germany (12), it has been concluded by a panel of experts advising the Ministry of the Interior that a normal solid building could be entirely made of material with a certain level of specific activity without the incremental dose equivalent exceeding 100 mrem in a year to the gonads. That level was represented by the expression :

$$\frac{C_K}{130} + \frac{C_{Ra}}{10} + \frac{C_{Th}}{7} = 1$$

where C is in pCi/g. If one assumes, following UNSCEAR (26) that occupancy factor is 0.8 and that the annual absorbed dose out of doors is 31.5 mrad to the gonads, one finds that the experts' advice has the following implications : the annual increase in whole body dose equivalent is < 0.04 mSv at the representative specific activity level, < 0.33 mSv at the first stage of enhancement, and < 0.92 at the second. The experts' conclusion was apparently based on an experimental model (43).

Another estimate may be obtained from survey results in the Saarland, where slag-aggregate concrete is widely used. Kolb and Schmier (44) report an average indoor exposure rate there of 12.1 μR/h. Schmier (30) reports separately that the average specific activities of the three nuclides of interest in that material are : K-40, 14 pCi/g ; Ra-226, 4.1 pCi/g ; Th-232, 2.7 pCi/g. Using a conversion factor of 0.7 from exposure to whole body dose equivalent and an occupancy factor of 0.8, one may estimate the incremental annual dose equivalent for the representative specific activity level as - 0.13 mSv (negative), for the first enhanced level as 0.12 mSv, and for the second enhanced level as 0.62 mSv.

These values are the lowest encountered so far, but it must be noted that the estimate does not take into account the presence of substantial amounts of less-active building materials in Saarland dwellings. In other words, the answer is for realistic utilization rather that the total utilization considered in some other cases, and it gives some idea of the degree of overestimation in this section.

In the USA, Beck (45) computed conversion factors from material specific activity to total exposure rate near the surface of an infinite half-space. He used a material density of 1.6 g/cm^3 (which corresponds to clay brick) and assumed uniform activity distribution and full equilibrium in series radionuclides. The conversion factors are as follows :

Nuclide	μR/h per pCi/g
K-40	0.179
U-238 series	1.82
Th-232 series	2.82

If the assumption is made that the conversion factors are doubled in value for an aperture-less room with thick walls and floors, and if the UNSCEAR (26) values for occupancy factor (0.8) outdoor dose rate (4.5 μrad/h in air) and gonad conversion factors (0.8 outdoors, 0.7 indoors) are used, then the following estimates of the annual increments in dose equivalent emerge : representative specific activity level, 0.37 mSv ; first enhanced level, 1.00 mSv ; second enhanced level 2.24 mSv.

These high values call for cantionary comment : calculated as they are for an infinite block of brick, they represent nothing other than the theoretical upper limit of dose equivalent increment and are in no way realistic estimates for dwellings.

Table II

PREDICTIONS FROM VARIOUS INVESTIGATIONS OF THE INCREASES IN WHOLE BODY DOSE EQUIVALENT ABOVE PURELY OUTDOOR VALUES CAUSED BY INHABITING SUBSTANTIAL MASONRY BUILDINGS IN WHICH VIRTUALLY ALL THE MASONRY CONTAINS RADIOACTIVITY AT VARIOUS LEVELS OF SPECIFIC ACTIVITY. UNIT : mSv IN A YEAR

Investigation	Country	Structure	Specific activity level[a]		
			Representative[a]	1st enhanced[a,b]	2nd enhanced[a,c]
Hultqvist (24)	Sweden	Unspecified (flats ?)	0.11	0.47	1.19
Krisiuk et al. (27)	USSR	Flats	0.16	0.50	1.18
Swedjemark (40)	Sweden	Multi-family houses (flats)	0.12	0.49	1.22
		Single-family houses	0.00	0.24	0.72
Spiers (19)	UK	Single-family houses	-0.06	0.24	0.84
Stranden (31)	Norway	Modern single-family houses	0.02	0.30	0.85
Koblinger (41)	Hungary	Apartment blocks (flats)	0.24	0.70	1.60
UMWELT (12)	FRG	Normal solid dwelling	<0.04	<0.33	<0.92
Kolb & Schmier (44)	FRG	Unspecified[d]	-0.13	0.12	0.62
Beck (45)	USA	Infinitely large solid brick	0.37	1.00	2.24
UNSCEAR (26)	Several	Average masonry	0.035	-	-

[a] See text for full definitions.

[b] Twice the representative value.

[c] Four times the representative value.

[d] Limited utilization : see text.

Also in the USA, Moeller et al. (46) have described a computer program to determine the whole-body gamma-ray dose rates inside rooms of a given construction. In this program, which takes account of radon diffusion in the building elements, each element is divided into one hundred sections, and the dose rate is summed from each section.

The program could be run for various specific activities for the case of a room with dimensions typical of those in an apartment block and with unsealed walls and floors of appropriate thickness and density and also with the appropriate openings for a door and a window. Furthermore, the effect of having a substantial thickness of fill of known specific activity under the ground floor slab could be calculated. Data are not, however, presented in the report.

Before summing up, it is interesting to calculate from UNSCEAR (26) that the excess whole body dose equivalent through living in an average masonry building (indoor occupancy factor 0.8) as opposed to living full-time outdoors is 0.035 mSv in a year.

All the data from this section are now collected in Table II. It is necessary to stress that the values tabulated are estimates of the extra dose equivalents that humans incur by living indoors in the normal way rather than living in the open.

One point clearly emerges from Table II : there is a distinct difference between the increments in apartment blocks and single-family houses due to the greater amount of building material surrounding the occupants of flats. This influenced the construction of Table III, which summarizes the radiological implications of living in flats and houses insofar as gamma irradiation is concerned. Much weight was given to the results of those investigations designed to establish a relationship between specific activity and dose, but the final choice takes account of all valid data. The values are rounded for mnemonic purposes and to underline the approximate nature of the estimates.

5. INCREMENTAL EXPOSURE TO RADON DAUGHTERS

There are two main factors controlling the indoor increment in radon daughter exposure. One is the Ra-226 content of the building material, the other is the air change rate. The influx of radon from underneath the building and the effect of radon emanation factor are discussed later.

Following the precedent set in the section on gamma rays, the radiological implications of three levels of Ra-226 specific activity will be assessed : the representative level of 50 Bq/kg ; the first elevated level of 100 Bq/kg corresponding to twice the representative value ; the second elevated level of 200 Bq/kg, which is four times the representative value.

Air is changed in dwellings either by infiltration or ventilation. Infiltration is caused by leakage through discontinuities in the fabric and normally is not controlled by the occupants, whereas ventilation is the controlled replacement of air in the building either by natural or mechanical means. Some of the factors affecting the air change rate are : ventilation design ; the temperature difference between indoors and outdoors ; wind speed and direction ; the quality of the structure ; the topography ; the behaviour of occupants ; the type of heating employed (37).

There is relatively little information available on air change rates in dwellings, and with the present concern for fuel reserves, several countries have devised, or are likely to devise,

Table III

SUMMARY OF ANNUAL INCREMENTS IN DOSE EQUIVALENT TO WHOLE BODY THROUGH LIVING IN MASONRY BUILDINGS

UNIT : mSv IN A YEAR

Specific activity of masonry	Representative[a] level	First[b] enhanced	Second[c] enhanced
Flats (apartment blocks)	0.1	0.5	1.2
Single-family houses	0.03	0.3	0.8

a Defined as $\frac{C_K}{1500} + \frac{C_{Ra}}{150} + \frac{C_{Th}}{100} = 1,$

where C is in Bq/kg.

b Defined as $\frac{C_K}{3000} + \frac{C_{Ra}}{300} + \frac{C_{Th}}{200} = 1,$

that is, twice the representative value.

c Defined as $\frac{C_K}{6000} + \frac{C_{Ra}}{600} + \frac{C_{Th}}{400} = 1,$

that is, four times the representative value.

energy-saving ventilation codes. Therefore, the choice of a representative air change rate for estimating the radiological consequences of exposure to radon daughters is very much a matter of judgement at this time. The fact that radon daughter concentration does not vary linearly with air change rate also complicates matters. Nevertheless, the use of a single value greatly facilitates further assessment. Furthermore, the simultaneous use of several air change rates and several specific activities would yield a matrix of results and would probably confuse rather than clarify the situation.

Handley and Barton in the USA (37), reviewing air change rates specifically for radiological purposes, suggested a range of 0.5 to 1.5 per hour on an annual basis for houses, with the range possibly extended to 2 per hour for modern high-rise apartment blocks. If one were to assume that either end of the range applied for half the year and made allowance for the shift in radon daughter equilibrium, one would obtain an effective air change rate for the year of about 0.8.

Krisiuk et al. (27) adopted a mean value of 1 air change per hour in their study on radioactivity in building materials. This apparently is the appropriate value for modern buildings in the USSR, the most probable minimum rate being in the range 0.3 to 0.7 per hour.

On the advice of experts in the UK, O'Riordan et al. (5) adopted one air change per hour averaged throughout the year when considering the radiological implications of using phosphogypsum as a building material. This was later modified by Duggan and Bradford (47) to one air change per hour in winter and two per hour in summer. A recent detailed survey of about 90 houses by Cliff (48) throughout Great Britain yielded a median infiltration rate of 0.7 air changes per hour for closed rooms. If this is taken to correspond to winter conditions (a very cautious assumption) and two per hour is taken as the summer practice, the effective annual rate as far as radon daughters are concerned is 0.93 air changes per hour. He went on to select unity as his reference value.

Of some interest in this connection is the value of 0.5 for the equilibrium factor F adopted by UNSCEAR (26) is estimating the annual absorbed dose from the inhalation of radon decay products. F is the ratio of the total potential alpha-energy of the given daughter concentrations to the total potential alpha-energy of the daughters if they were in equilibrium with the radon gas. Two phenomena determine F, one being air change and the other deposition of the daughters onto surfaces, plateout. If plateout is disregarded, one may calculate (49) that the implied air change rate here is somewhat more than one per hour, so that a value of unity might seem to be consonant with the UNSCEAR (26) approach.

There is a measure of uncertainty about the magnitude of plateout, but some evidence can be offered to the effect that it is a relatively minor determinant of the state of equilibrium in dwellings. In the UK survey previously mentioned (48) the author measured the air change rate and F in each dwelling (the latter by observing the individual daughters) so that it is possible to calculate F without plateout and compare this with the observed value. Although the calculated to observed ratio varied about unity, the average for a sample of his data was virtually unity, suggesting that daughter loss is not systematically significant.

In Sweden, however, the design value for controlled ventilation is 0.5 air changes per hour, and a radiological investigation of over 60 new houses in the winter and early spring of 1975-76 showed that this value actually prevailed when windows were closed (40). One must conclude, with the report, that even if consideration is given to ventilation practices during the summer season, the air change rate may not greatly exceed 0.5 per hour on an annual basis. The same is probably true of other Scandinavian countries, although data are lacking.

Measurements of radon and daughters in 343 homes in a Canadian community (17) yielded a value of 0.38 for F, implying an air change rate of 1.8 per hour (49). The survey was conducted in the autumn, prior to the heating season, and the measurements were mostly made in basements.

On the basis of the foregoing evidence, one air change per hour is adopted here as a reference rate. The arbitrary elements in this choice are fully recognised. It is recognised also that some countries with severe climates and strict energy conservation practices may wish to adopt a more cautious value of say 0.5 air changes per hour for reference purposes. A change in rate from a constant 1.0 to a constant 0.5 per hour implies an increase by a factor of 2.5 approximately in radon daughter concentration, other things being equal. A more plausible ventilation pattern, even in such countries, is perhaps one or even two air changes per hour during the day when the occupants are active and 0.5 while the dwelling is secured for the night. This pattern implies 80 % or 50 % increase in radon daughter increment.

Krisiuk et al. (27) developed a model to predict the radon concentration in rooms constructed of material with known Ra-226 specific activity.

Their first step was to determine the radon emanation rate Q as follows :

$$Q = C_{Ra}\eta\lambda\, d\rho\, 10^{-8}\ \mathrm{Ci/m^2 s}\ ;$$

C_{Ra} = specific activity of Ra-226, pCi/g ;

η = radon emanation factor, dimensionless ;

λ = radon decay constant, $2.1 \times 10^{-6}\ s^{-1}$;

d = wall or floor half-thickness, cm ;

ρ = material density, g/cm^3.

The following values for each quantity are those which are deemed appropriate to modern structures : $\eta = 0.04$; $d = 7.5$ cm ; $\rho = 2.35\ g/cm^3$. The value of C_{Ra} and hence Q varies, of course.

Their second step was to compute the radon concentration as follows :

$$\chi_{Rn} = \frac{3.6\ QS}{KV}\ \mathrm{Ci/l}\ ;$$

K = air change rate, h^{-1} ;

S = surface area of room, m^2 ;

V = volume of room, m^3.

The reference air change rate of 1 per hour implies an equilibrium factor F of 0.54 if plateout is disregarded (49). For a typical room, they suggest that $S/V = 1.8\ m^{-1}$. Considering all the foregoing information and adopting the authors' occupancy factor of 0.75, one may calculate the incremental radon daughter concentrations and yearly exposures for the Ra-226 specific activities of interest. The results, with some rounding, are shown below :

Specific activity	Radon daughter increment*	
	Concentration, mWL	Exposure, WLM/y
Representative level	0.7	0.03
1st enhanced level	1.4	0.05
2nd enhanced level	2.8	0.11

* See footnotes for definitions of these units.

The authors tested the predictions experimentally and found them to be satisfactory.

The preceding analysis refers solely to the building elements and may be adequate, as it stands, for isolated dwelling units high up in a block of flats. The important question of fill around and under the building may be dealt with as follows, using material from the same reference.

The authors record that the soil has a specific radon emanation rate of about 0.5 pCi/m^2s per pCi/g. For a substantial thickness of fill with a certain specific activity, the value of Q is therefore calculable. The value of S/V in this case is 0.33 m^{-1}.

Suppose, first, that the floor slab is so badly cracked or emplaced as virtually to be fully permeable to the radon. Once again the value of K is unity. Then :

$$x_{Rn} = \frac{3.6\ QS}{KV} = 1.19Q \text{ pCi/l}$$

The incremental exposures to radon daughters from the fill (for an equilibrium factor of 0.54 and an occupancy factor of 0.75) added to that from the building elements themselves, are shown after the next paragraph.

Alternatively, suppose that the slab is absolutely intact and the radon has to diffuse through it. The authors show that the relaxation length of concrete is 12.7 cm on average. A floor thickness of 15 cm therefore corresponds to 1.18 relaxation lengths, so that the slab brings about a reduction of 3.3 in the value of Q and a similar reduction in the radon daughter exposure. Total values for an intact floor and the other elements follow.

* Working Level (WL) : Any combination of the short-lived decay products of radon-222 (Rn-222) in one litre of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha-ray energy during decay to Pb-210. 1 WL is equivalent to 100 pCi/l Rn-222 in equilibrium with its short-lived decay products.

Working Level Month (WLM) : Exposure to a Rn-222 decay product concentration of 1 WL for 1 working month (170 h).

Specific activity	Total radon daughter increment			
	Concentration, mWL		Exposure, WLM/y	
	Cracked floor slab	Intact floor slab	Cracked floor slab	Intact floor slab
Representative level	5.1	2.1	0.20	0.09
1st enhanced level	10.1	4.3	0.39	0.16
2nd enhanced level	20.1	8.5	0.78	0.33

Since real concrete is neither fully permeable nor absolutely intact, the alternative columns represent extreme conditions. If one were obliged to put forward a single value of exposure increment for each level of specific activity, one might reasonably suggest the following rounded values :

Representative level	0.15 WLM in a year
1st enhanced level	0.3 WLM in a year
2nd enhanced level	0.6 WLM in a year

These values might then be supposed to apply to single-family masonry houses and to ground-floor units in apartment blocks.

There are three important parameters in the foregoing analysis, and supporting values of them may be obtained elsewhere. The specific radon emanation rates for concrete and soil, in pCi/m^{2}s per pCi/g Ra-226, put forward by the authors may be compared with values in UNSCEAR (26) and Wilkening et al. (50) respectively : the reported value for 10 cm thick concrete is 5×10^{-3}, whereas a value of 1×10^{-2} is implied in the analysis. The reported value for the emanation rate for soil is 4.26×10^{-1} pCi/m^{2}s, which when coupled with the world average Ra-226 specific activity in soil of 0.7 pCi/g, UNSCEAR (26), yields a specific value of 6.1×10^{-1} pCi/m^{2}s per pCi/g compared with the value of 5×10^{-1} used by the authors. Finally, the relaxation length of 12.7 cm used by the authors may be compared with the value obtained by Culot et al. (51) for dense low - porosity concrete, namely 12.7 cm also.

In Sweden recently, Swedjemark (40) determined the relationship between Ra-226 specific activity and indoor radon daughter concentration. In multi-family houses, she found that the total radon daughter concentration was about 22 mWL for a normalized air change rate of one per hour and a normalized Ra-226 specific activity of 370 Bq/kg. For the specific activities of interest here, this result implies the following incremental concentrations and annual exposures at an occupancy of 0.8 (26).

Specific activity	Radon daughter increments	
	Concentration, mWL	Exposure, WLM/y
Representative level	3	0.12
1st enhanced level	6	0.24
2nd enhanced level	12	0.49

The foregoing results exclude those for ground-floor flats, where twice higher values, attributed to a variety of factors including infusion from the earth, were recorded.

The use here of gross values to characterize the increments probably involves an overestimate of about 10 %.

Stranden in Norway (31) has endorsed the model developed by Krisiuk and his co-workers (27). He suggested that for $C_{Ra} = 2$ pCi/g, the exposure in a year would amount to 2.9×10^{-2} WLM at an air change rate of one per hour. The occupancy factor chosen by Stranden was 0.7, and he also chose typical values of η as 0.02, d as 15 cm, and ρ as 2 g/cm^3. It has been suggested more recently by Stranden and his colleagues (52) that $\eta = 0.1$ might be more representative of concrete. The Norwegian analysis, therefore, points to the following incremental radon daughter exposures in concrete dwellings isolated from ground infusion : representative specific activity level, 0.1 WLM in a year ; 1st enhanced level, 0.2 WLM in a year ; 2nd enhanced level, 0.3 WLM in a year.

In a wide-ranging survey in Great Britain, Cliff (48) found that the average radon daughter concentration indoors, normalized to one air change per hour, was 3.5 mWL. This number incorporates the contribution from radon daughters in the ventilating air, which he estimates at 0.5 mWL, so that the increment is 3 mWL. The dwellings surveyed were, in the main, single-family houses made of clay brick, many with concrete floors at ground level. Typical Ra-226 specific activities for clay bricks and concrete in the UK are (32) 1.4 and 0.2 pCi/g, so that if allowance is made for the amount of each in a typical house, the effective specific activity in the whole structure is about 1.2 pCi/g. The annual exposure for 0.8 occupancy at 50 Bq/kg would therefore be 0.14 WLM, and at the first and second enhanced levels, 0.28 and 0.56 WLM. These results offer strong support to the previous prediction for such houses.

From Finland, Castrén (29) reports on the measurement of radon daughters in a group of apartments in the region of Helsinki. The average concentration is 4.7 mWL, and the weighted average specific activity of Ra-226 in the materials is 40 Bq/kg. Air change rates were not measured, but it might be reasonable to assume 0.5 per hour as in neighbouring Sweden (40). The contribution from the daughters in the ventilating air is likely to be about 0.9 mWL at this air change rate, so that the concentration attributable to the building materials is approximately 3.8 mWL. Normalized to one air change per hour, the nett concentration becomes 1.5 mWL. Thus, for an occupancy factor of 0.8, the Finnish results for flats would be : representative specific activity level, 0.08 WLM/y ; first enhanced level, 0.16 WLM/y ; second enhanced level, 0.32 WLM/y.

Fehér et al. in Hungary (42) also provide a model to link Ra-226 specific activity and radon concentration. This model is not unlike that developed by Krisiuk et al. (27), although it was derived independently. If the report is interpreted correctly, the radon

Table IV

PREDICTIONS FROM VARIOUS INVESTIGATIONS OF THE INCREASES IN EXPOSURE TO RADON DAUGHTERS ABOVE PURELY OUTDOOR VALUES CAUSED BY INHABITING SUBSTANTIAL MASONRY BUILDINGS IN WHICH VIRTUALLY ALL THE MASONRY CONTAINS RADIUM-226 AT VARIOUS LEVELS OF SPECIFIC ACTIVITY. UNIT : WLM IN A YEAR

Investigation	Country	Structure	Specific activity level[a]		
			Representative[a]	1st enhanced[a,b]	2nd enhanced[a,c]
Krisiuk et al. (27)	USSR	Flats other than ground-floor	0.03	0.05	0.11
		Single-family houses and ground-floor flats	0.15	0.3	0.6
Swedjemark (40)	Sweden	Flats other than ground-floor	0.12	0.24	0.49
Stranden et al. (31,52)	Norway	Flats other than ground-floor	0.10	0.20	0.30
Cliff (48)	UK	Single-family houses	0.14	0.28	0.56
Castrén (29)	Finland	Flats other than ground-floor	0.08	0.16	0.32
Fehér et al. (42)	Hungary	Isolated room	0.2(?)	0.4(?)	0.9(?)
Jonassen and McLaughlin (53,54)	Denmark	Basement room, thick structural elements	0.03	0.06	0.13
UNSCEAR (26)	Several	Mainly masonry houses and apartments	0.17	-	-

[a] See text for full definitions.
[b] Twice the representative value.
[c] Four times the representative value.

concentration is 0.5 pCi/l in an isolated room having an air change rate of 0.36 per hour and constructed of concrete with a Ra-226 specific activity of 0.2 pCi/g. Allowing for the effect of ventilation rate on radon daughter equilibrium and assuming no plateout, one finds that this report indicates an incremental exposure to radon daughters of about 0.2 WLM in a year at the representative Ra-226 specific activity, 0.4 approximately at the first enhanced level, and 0.9 or so at the second. These results are somewhat out of line with the others recorded here ; this may be due to misinterpretation by the reviewer or to the unusually high value of the emanation factor quoted by the authors.

Jonassen and McLaughlin in Denmark (53,54), studying the radon concentrations in a basement room with 30 cm concrete elements at 0.55 pCi/g Ra-226 and an extremely low air change rate (effectively 1.4×10^{-4} per minute) found a Rn-222 concentration of 6.9 pCi/l. If the result is normalized to one air change per hour (plateout being ignored) and 50 Bq/kg, the incremental concentration of daughters is 0.8 mWL, implying 0.03 WLM in a year exposure. The authors suggest that infusion from the earth is a minor contributor - a reasonable proposition given that the structural elements are 2.4 relaxation lengths thick. The incremental exposure at the first enhanced level of specific activity is 0.06 WLM in a year and at the second 0.13 WLM in a year. The values are somewhat lower than one might expect in a basement, where radon daughter concentrations are usually higher than in ground-floor rooms (55) but the extrapolations introduced here are rather extreme.

More information is expected from studies currently under way in the Federal Republic of Germany (56) as foreshadowed in the preliminary report by Wicke et al. (57).

Moeller et al. (46) in the USA have devised a computer program to predict radon and daughter concentrations from building materials using basic data on building configuration, specific activity of Ra-226, and air change rates. Calculations can be made for a room high up in a building with no significant contribution from radon infusing from the soil. Calculations can also be made for a ground-floor room with an intact floor over soil with a certain Ra-226 specific activity as well as for a floor absolutely permeable to radon (a board floor for example). Data are not available in their report.

Before summing up in this section, one may calculate from UNSCEAR (26) that the gross radon daughter concentration indoors is typically 5 mWL, so that the nett contribution from the building materials is about 4.2 mWL. This broadly implies 0.17 WLM in a year incremental exposure. Firm data on ventilation are not provided.

All the data from this section are presented in Table IV. The results indicate the extra exposures to radon daughters that persons experience through living indoors as opposed to outdoors.

A pattern emerges here too, virtually the reverse of the gamma-ray one. As illustrated in the summary Table V, exposures in houses are higher than in flats above ground level because of the greater amount of radon from the ground entering houses. In selecting the values for Table V, considerable weight was given to the results of the investigations designed to relate the specific activity of Ra-226 in building materials to the ambient radon daughter concentrations, but the values from the UK national survey (48) were also influential.

It must be recorded that these estimates of incremental exposure are rather crude. Relatively little data of an appropriate nature are available, and the topic is extremely complex. No account has been taken, for instance, of the multiplicity of meteorological variables that affect activity concentrations (58,37), nor of the effects of air cleaning (9), nor, in a detailed fashion, of the effects of periodic changes in ventilation rates (27). The effect of heating is briefly considered later (59), but no account has been taken of the surface finishes and moisture content of the materials (60). Despite these shortcommings in the review, the estimates are believed to be reasonably realistic and robust.

Table V

SUMMARY OF ANNUAL INCREMENTS IN RADON DAUGHTER EXPOSURE THROUGH LIVING IN MASONRY BUILDINGS. UNIT : WLM IN A YEAR

Specific activity of masonry	Representative[a] level	First[b] enhanced	Second[c] enhanced
Flats (other than ground-floor)	0.08	0.15	0.3
Single-family houses & ground-floor flats	0.15	0.3	0.6

[a] Defined as 50 Bq/kg Ra-226.

[b] Defined as 100 Bq/kg Ra-226, that is, twice the representative value.

[c] Defined as 200 Bq/kg Ra-226, that is, four times the representative value.

6. OTHER ASPECTS OF AIRBORNE ACTIVITY

When assessing the significance of the increments in radon daughter exposure presented in the previous section, one must bear in mind that the mere act of enclosing a space will increase the exposure of occupants of that space.

If one could imagine a radium-free room-like structure isolated from the ground and with an air-change rate of one per hour, the shift in daughter equilibrium would cause the concentration in the ventilating air to increase from a nominal 0.6 mWL to 0.8 mWL(61). If one then imagined a similar structure on the ground, but without a base, the concentration due to radon emanating from the soil (50) would be 2.7 mWL implying 0.1 WLM in a year incremental exposure. This increment might well be discounted in any evaluation of the radiological consequences of radon emanation from building materials.

Building materials are not the only source of Rn-222 in houses ; natural gas is another one. It would appear (26) that the concentration of Rn-222 at some well-heads might reach 1000 pCi/l. Storage and processing bring about an order of magnitude reduction in concentration, and modelling of consumption in the home suggests that the annual exposure increment might be of the order of 1 mWLM or about 1 % of the increment from building materials of representative Ra-226 specific activity. This source of exposure is not of great importance therefore. A potentially more important source is radon in the water-supply to the dwelling.

In a study in Finland, Castrén et al. (62) measured concentrations of unsupported Rn-222 at approximately 10^5 pCi/l in some ground-water supplies near Helsinki and values of 10^3 pCi/l or so in other ground-waters. They also measured the Rn-222 concentration in indoor air in some dwellings where high-level water was used and then calculated the air-to-water concentration quotient : this was effectively 10^{-4}. Calculations for a dwelling in the UK with typical dimensions, water consumption, and air-change rate (61) yield an air-to-water concentration quotient of 1.5×10^{-4} if full desorption of Rn-222 is assumed, but this postulate seems rather unreasonable when one considers the kinetics of radon removal : 50 % desorption overall for domestic uses of water is probably more realistic (63).

If therefore a rounded value of 10^{-4} is chosen for the quotient, it is possible to calculate the incremental exposure to radon daughters from water supplies. A concentration of 10 pCi/l will be assumed for surface waters (26). The results are presented below for an indoor occupancy factor of 0.8 and the reference air change rate of 1 per hour.

Water supply	Rn-222 concentration		Exposure increment, WLM in a year
	Water, pCi/l	Air, pCi/l	
Abnormal ground	10^5	10^1	2
Typical ground	10^3	10^{-1}	0.02
Typical surface	10^1	10^{-3}	0.0002

Typical surface water would therefore add about 0.2 % to the incremental exposure from representative building materials ; typical ground-water would add about 20 %.

When underfloor heating is employed in a dwelling, one might expect enhanced radon emission because convection would add to diffusion in transporting the Rn-222 through the slab. When storage heaters containing bricks (or other such materials) are employed, the effect might be more pronounced because higher temperatures obtain. Very little information is available in this area. Auxier et al. (60) report that emission is not significantly enhanced when concrete is taken from 20°C to about 40°C, but Gabrysh and Davis (59) report a 30 % enhancement between 20°C and 60°C. More data are essential for proper assessment here.

The foregoing phenomena need to be taken into account when making an inventory of the sources of Rn-222 affecting the occupants of dwellings. Compared with this isotope and its decay products, exposure to Rn-220 (thoron) and its daughters may be ignored. Krisiuk et al. (27) demonstrate the unimportance of Rn-220 relative to Rn-222, from the point of view of radiation hygiene, for equal specific activities of the precursors and for normal air-change rates. This is supported by data from UNSCEAR (26) also for precursors likely to have approximately equal specific activities. Moeller et al. (46) do suggest, however, that there should be improved calculations regarding thoron emanation and the dosimetry of its decay products.

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Appendix I

CONVERSION FACTORS FROM OLD TO NEW RADIATION UNITS

Quantity	Old unit	Symbol	New unit	Symbol	Conversion factor
Activity	curie	Ci	becquerel	Bq	$1 Ci = 3.7 \times 10^{10}$ Bq
Absorbed dose	rad	rad	gray	Gy	$1 rad = 1 cGy = 10^{-2}$ Gy
Dose equivalent	rem	rem	sievert	Sv	$1 rem = 1 cSv = 10^{-2}$ Sv
Exposure	röntgen	R	-	-	$1 R = 2.58 \times 10^{-4}$ C/kg*

* Value in SI units

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