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POSSIBLE HEALTH EFFECTS OF ENERGY CONSERVATION: IMPAIRMENT OF INDOOR AIR QUALITY DUE TO REDUCTION OF VENTILATION RATE

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Efforts to reduce the energy needs to heat or cool dwellings have the potential to create new health hazards. Increases in indoor levels of radon and its progeny from the reduction in air exchange rates add a substantial radioactive burden to the general population. Other indoor pollutants reaching critical concentrations in homes with low air exchange rates are CO and NO_2 from unvented combustion in gas stoves and heaters, tobacco smoke, and asbestos fibers. In addition, insulation materials and certain types of furniture may contribute the toxicant formaldehyde diffusing from foam injected walls or chipboard. Risk estimations using linear dose-response relationships show risk factors per kWh saved which are orders of magnitude greater than for a kWh produced by large power plants using coal, oil, gas, or uranium.

Introduction

The quantitative assessment of health effects of various sources of energy should provide guidelines not only for the selection of power plant sites but also for future energy policies in a risk-conscious public. However, not only activities involved in the production of energy but also modification of construction and use in dwellings to reduce energy consumption may pose substantial long-term hazards to the general public. Similar to the risk per unit energy delivered from an energy-producing technology, the risk to human health per unit energy saved can be estimated. This paper attempts to quantify the risk from the increase in radon and radon daughters levels in indoor air due to the reduction of the air exchange rate. The findings for a range of conditions are compared with the results of studies on the health impact of different sources of energy.

Radon and its progeny is only one in a long list of potentially hazardous substances produced in or entering dwellings. Table 1 gives an overview of the most important pollutants and their sources for the indoor environment, together with the possible associated health effects. Radon and its daughters are singled out for an assessment of health effects because of their chemical form (noble gas) and mode of action (i.e., irradiation of lung tissue—health impairments can be more easily quantified than can effects from reactive chemicals). In addition, a large body of human epidemiological data on occupational exposure to radon and its progeny, and the resulting elevated lung cancer risk, yielded quite consistent risk factors down to doses encountered in some dwellings (BEIR III, 1980).

Health Risk Associated with a Reduction in Air Exchange Rates

Due to the rapid increase in energy costs during the past few years, much effort has been devoted to reducing the heating and cooling bills of dwellings. The single most effective measure to achieve savings at unchanged temperature settings is to decrease the rate of air ex-

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Table 1. Important sources and components of indoor air pollution (modified from Wanner, 1983).

Sources	Potential Pollutants	Potential Health Effects
Structural materials Chipboards Subsoil Building materials Paints	 Formaldehyde Radon and daughters Asbestos Solvents Organic compounds	 Allergies, rashes (Gupta *et al.,* 1982) Changes in pulmonary and cardiac functions Irritation of eyes, skin and mucous membranes
Inhabitants, pets, arthropods	Odors Carbon dioxide Water vapour Particles, microorg. Antigens	Chronic lung diseases Cancer of the lung (and other sites?) Reduced resistance to respiratory infections
Unvented gas stoves (hot water, cooking) Fireplaces	Carbon monoxide Nitrogen dioxide Particles Polycyclic aromatic compounds	Neurological changes: attention loss? memory storage deficits? (Schenker, 1982)
Consumer products Sprays Detergents Solvents	 Odors Halogenated propellants Organic compounds	

change. This can easily be achieved (and at low expense) by means of weatherstripping and caulking. Radioactive radon and its progeny are naturally present in indoor air due to emanation of the noble gas radon from the underlying ground and building materials containing its precursor radium. As buildings become more air-tight, radon and its daughters will increase to higher levels. In general, it can be assumed that the radon concentration at a constant source term is inversely proportional to the air exchange rate. In conventional homes with a typical exchange rate of about 1/h, an average concentration of 0.8 pCi/L (29.6 Bq/m^3) Rn-222 was measured (Evans *et al.,* 1981). In Central Europe, where concrete and bricks play a more significant role in construction, a value of 1 pCi/L (37 Bq/m^3) radon as used in the following assessment is more appropriate.

Table 2 lists the assumptions used to calculate the additional exposure in working level months (WLM) per saved kWh in a home that was sealed to reduce the air exchange rate from 1/h to 0.3/h. Rates as low as 0.1 h^{-1}

Table 2. Parameters assumed for the calculation of WLM/kWh saved: Four-person-family with 100 m^2 of fully heated living quarters leading to 260 m^3 indoor air volume, or 65 m^3/person; 150-day heating period/yr with an average outside temperature of 5 °C leading to a temperature difference of 15 °C.

	Conventional House		Energy-Efficient House
Air exchange rate (h^{-1})	1		0.3
Radon indoor concentration (pCi/L)	1		3.3
(Bq/m^3)	37		123
Radon daughter equilibrium factor	0.4		0.6
Working levels	0.004		0.020
Time spent indoors		80%	
Correction factor for low indoor breathing rates		0.5	
Working level months/year	0.081		0.407
difference		0.326 (1)	
Air to be warmed up (in 1000 m^3/heating period-person)	234		70
Energy needed (in kWh)[a]	1,181		354
difference		827 (2)	
WLM/kWh saved (1)/(2)		3.94×10^{-4}	

[a] Specific heat of air: 1.005 kJ(kWs)/kg-°C; density of air: 1.205 kg/m^3.

are found in new, empty dwellings but the influence of airtightening in occupied buildings is less pronounced (Fleischer *et al.*, 1982; Nero *et al.*, 1983; Burkart *et al.*, 1984). 1 WLM corresponds to an exposure to 1 working level (WL) for 170 h. 1 WL is any combination of radon-222 and short-lived decay products per liter of air that will result in the emission of 2.08×10^{-8} J of alpha energy during complete decay (Evans *et al.*, 1981). 1 WL corresponds to 3.7 Bq/L (100 pCi/L) Rn-222 in equilibrium with its daughters. Since the WLM is based on miners with large lung capacities and high breathing rates during physical work, a factor of 2 was introduced to correct for the reduced breathing indoors (light activities, sleeping).

Lung cancer mortality, the main risk from exposure to radon and its progeny, was measured in several groups of uranium miners. Figure 1 shows that, in the concentration range studied, the risk seems to be approximately proportional to the dose received. Even more important, doses accumulated over a time of 30 yr in dwellings having radon levels of 1.5 pCi/L (55 Bq/m^3, arrow A) and 10 pCi/L (370 Bq/m^3, arrow B), respectively, approach or even exceed (arrow B) the radiation doses received by some miner groups that express a significantly elevated risk of contracting lung cancer (Fig. 1).

Although an extensive review of the miner's data in the BEIR III report (1980), resulted in the proposition of more elaborate age dependent risk factors, the single average value from BEIR I report (1972), which fits well into the bracket given by ICRP 32 (1981), is used for our assessment. Taking this factor of 6.5×10^{-6} lung cancer cases/yr-WLM (Fig. 1) and assuming 40 yr of exposure and 20 yr of expression of the higher risk, an additional lifetime risk of dying from lung cancer in an energy efficient home of 0.0017 or 1700 deaths per million results. In areas with elevated radium concentrations in soil or building materials, this value will be proportionally higher.

Figure 2 depicts the dependence of exposure to radon and its daughters on the air exchange rate. The steep increase in the radon level, accompanied by a diminishing potential for additional energy savings at air exchange rates below 0.5 h^{-1}, results in high risk/benefit ratios in this ventilation range. The graphic display of our calculations in Fig. 3 shows the tremendous increase in WLMs per kWh saved as a function of decreasing ventilation. Since the possibility of a concomitant increase in the radon/radon daughter equilibrium factor is not taken into account, the real health impact may even be higher. In many air-tight dwellings, however, other easily detected indoor pollutants, such as odors or humidity,

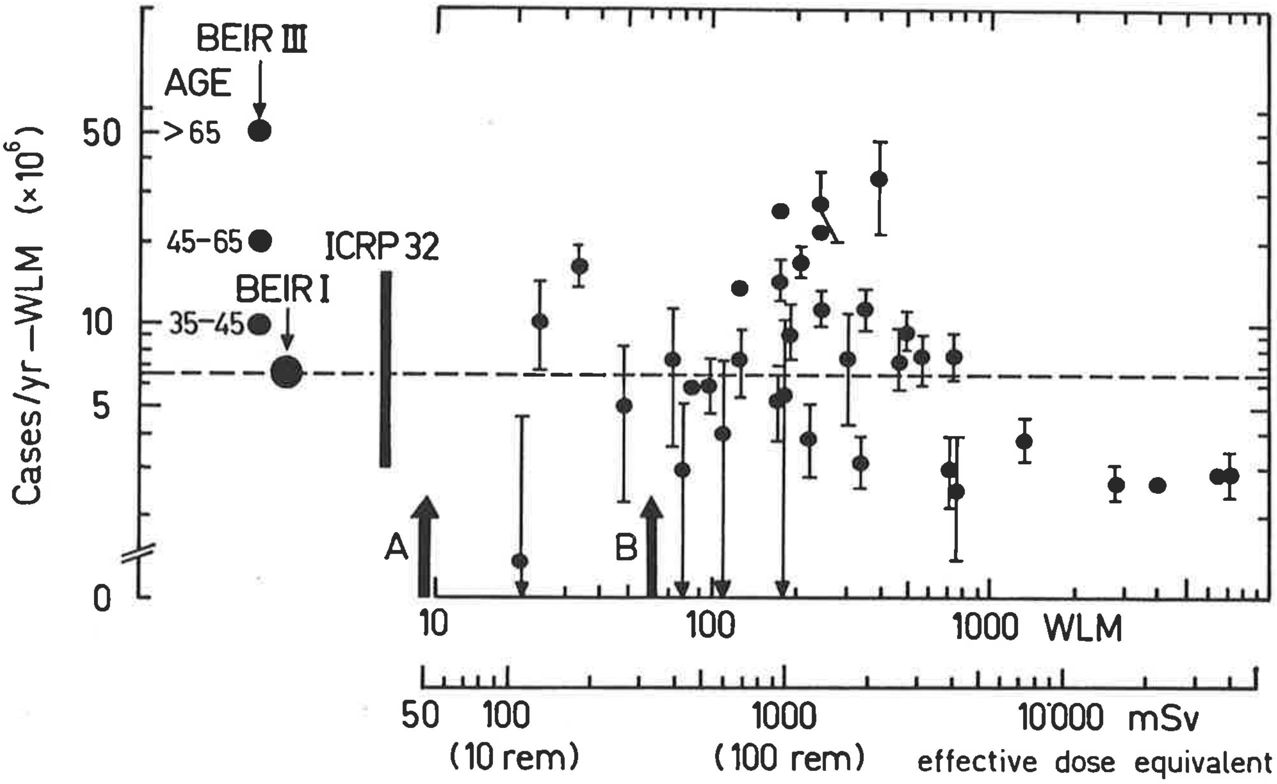

Fig. 1. Risk factors for radon-induced lung cancer. Each point denotes a group of miners from the United States, Canada, Sweden, United Kingdom, and Czechoslovakia (Cohen, 1980). On the left are the risk factors from BEIR I (1972): 6.5×10^{-6}/WLM-yr (broken horizontal line); BEIR III (1980): age-dependent, from 0 to 50×10^{-6}/WLM-yr; ICRP (1981): total lifetime risk (30 yr manifestation period assumed) $1.5–4.5 \times 10^{-4}$/WLM or 0.043–0.13 J h m^{-3}.

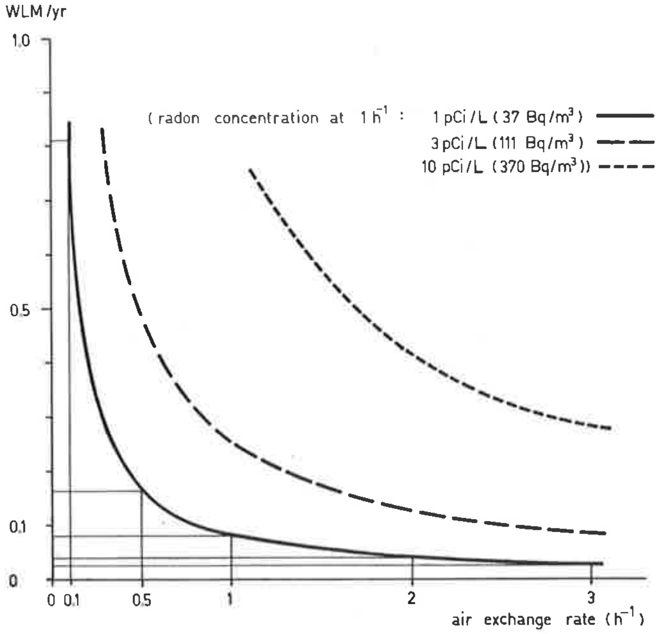

Fig. 2. Dependence of exposure to radon and its progeny on the air exchange rate (assuming constant radon source strength).

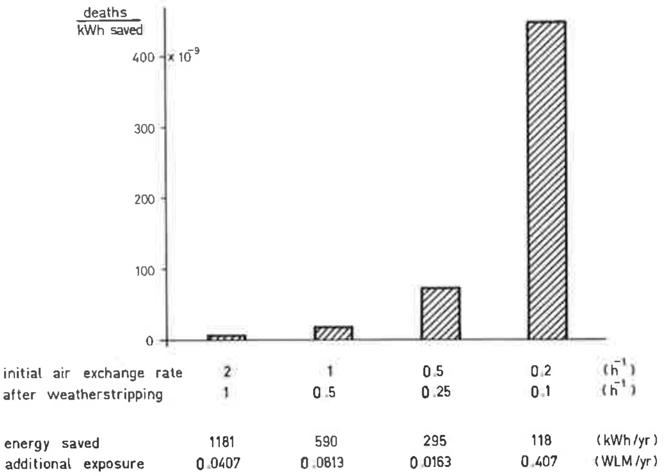

Fig. 3. Risk per kWh saved in dependence of absolute air exchange rate (for assumptions see Table 2 and text).

may prevent inhabitants to live for long periods at low air exchange rates with the concomitant high exposures to indoor radioactivity.

Radon concentrations in European dwellings were measured in several countries. By far the best knowledge about the exposure of the general public exists in Sweden, where radon and its decay products became a matter of public concern in the 1970s (UNSCEAR, 1982). This is partially due to specific problems with building materials (aerated alum shale concrete) and generally high radium content in the subsoil. Table 3 gives an incomplete list of compiled national and international data on radon concentrations in indoor air, proposed dose conversion factor and, where available, proposed limits for remedial action. Using the conversion factors adopted in UNSCEAR (1982), i.e., (109 mrem/yr)/(pCi/L), quite large segments of the population in countries such as Sweden, Canada, and Switzerland would receive individual effective dose equivalents above 1 rem/yr. The annual limit for occupational exposure is 5 rem; exposure for critical segments of the general population due to industrial activities (medicine excluded) is 500 mrem (0.5 rem) (ICRP, 1977). To our knowledge, the latter value is an upper theoretical limit rarely approached in European countries. One notable exception are inhabitants of homes built on mine tailings (uranium, phosphate) or on waste materials from dial painting containing high amounts of radium (Roessler *et al.*, 1983).

Many additional indoor pollutants merit further study. Two important examples of widespread noxious agents in the indoor environment are nitrogen dioxide in dwellings with unvented gas stoves or heaters, and formaldehyde in homes insulated with formaldehyde urea. Measurements of nitrogen dioxide by Palmes *et al.* (1977) yielded 49 and 25 ppb (nL/L) NO_2 for the kitchen and nonkitchen area, respectively, in gas stove dwellings. Electric stove dwellings measured as a control contained only 8 ppb in the kitchen and 7 ppb (nL/L) outside the kitchen. Since nitrogen dioxide is quite stable as compared to the mean residence time indoors, its concentration will also be inversely proportional to the air exchange rate. Average values of about 100 ppb (nL/L) would result if the energy efficient home of Table 1 would contain a gas stove. Since the U.S. time-weighted average threshold limit value (TLV-TWA) at the working place is only 3 ppm (μL/L) for a 170-h week (ACGIH, 1981), the exposure in such a home is about 10% of the occupational limit.

Cigarette smoke and asbestos fibers are additional noxious agents that are suspected to cause detrimental effects at low concentrations. Their concentration is also a function of the air exchange rate.

Injection of insulation foam into walls led in many cases to considerable releases of formaldehyde, a suspected carcinogen. Indoor concentrations up to 1 μL/L (TLV-TWA 2 μL/L) were reported, with concomitant acute effects such as headaches, sore eyes, etc. Extreme values seem to be due to improper polymerization by unqualified construction workers. Although the extent of chronic effects cannot be quantified today, many states in the United States banned the use of urea formaldehyde for home insulation.

In the case of formaldehyde also, a reduction in the air exchange rate will aggravate the problem. Due to a lack of human epidemiological data and the absence of

Table 3. Results of national and international surveys, resulting doses, proposed limits for remedial action.

International body/country	Indoor radon levels (pCi/L)	Proposed limits for remedial action (pCi/L Rn)
ICRP (1984)		Existing exposure: 200 Bq/m^3 equilibrium equivalent radon conc. (about 10-20 pCi/L radon)[a] Future exposure: 100 Bq/m^3
UNSCEAR (1982)	0.8	
Sweden (Buren, 1982)	2.83 (mean value) 3.26 (single family homes) 1.59 (new single family homes) 180 (highest value found)	21 (10.8 for radon daughters) (new buildings should be kept below 4 or 1.9 for Rn daughters)
Federal Republic of Germany	1 (mean for measurements in Baden-Württemberg)	
United Kingdom	3 (living rooms in one study) 2 (bedrooms)	
Switzerland (Burkart, 1984)	1.5 (average in living quarters in first study) 51 (highest value in a living room)	
Finland		1.5 rem/yr (about 15 pCi/L) from man made sources
Canada	3.6	0.1 WL[b] (about 20 pCi/L) from all sources 0.02 WL (about 4 pCi/L) from industrial activities
United States	0.8 (mean from several states) 2.4 (Eastern Pennsylvania) 0.4 (Texas)	

[a] Not considered a generally applicable value for an action level. Suggested if "the remedial action considered is fairly simple".

[b] $1\ \mathrm{WL} = 2.08 \times 10^{-5}\ \mathrm{J/m^3}$

information on the dose-effect relationship for carcinogenesis in the animal model, no risk factors can be given at this time. Most important and contrary to the effects of alpha-irradiation due to radon exposure, experiments with rats do not suggest a risk proportional to the dose received. Although 103 out of 232 rats exposed by inhalation to 14.3 ppm (μL/L) of formaldehyde for 30 months developed squamous cell nasal carcinomas, only two such nasal cancers were observed in 235 rats exposed to 5.6 ppm (μL/L) of formaldehyde (CIIT, 1981). At the dose levels applied, unspecific transformation due to long-term irritation of nasal tissues cannot be exluded.

Comparison with Risks from Energy Production

Many studies (Cohen and Pritchard, 1980; Coppola and Hall, 1981; Niehaus, 1980; Inhaber, 1982; Paskievici, 1982) have been undertaken to compare the impacts of different energy systems producing electric power. The major uncertainties in the risk estimates stem from the unsolved problem of quantifying the health effects on the general population of fossil-fuel burning. This is due to the difficulties encountered in attempting to correlate increased mortality with air pollution such as SO_2 and particulate concentration in the environment of fossil fuel plants and variations in the sulfur content of the fuel. In Table 4, data from the studies mentioned above are converted to deaths per kWh and compared to the risk from energy conservation.

Table 4. Comparison of risks from energy production and conservation (deaths per kWh).

Energy Production Risk	
Considering gas, nuclear, oil, and coal	$0.1\text{-}5.7 \times 10^{-9}$
Energy Conservation Risk	
Radon through lower air exchange rates (based on assumptions made in Table 2)	51.22×10^{-9}
NO_x through lower air exchange rates: epidemiological evidence for increased infection rates, bronchoconstriction, and pulmonary edema (Spengler *et al.*, 1983)	No risk factor available
Formaldehyde from insulation: Acute effects (headache, nausea) reported	Carcinogenic in animal studies but no human risk factor available (Perera and Petito, 1982)

Control of Indoor Pollution

Radon levels in indoor air can be controlled by several means. For existing buildings, diffusion barriers, which reduce emanation from soil or building materials, and heat exchangers, which allow higher air exchange rates without extensive heat losses, are the only low-cost possibilities of reducing the radioactive burden. Sheaths of polyamide or polyethylene reduce emanation by at least 97%. The much easier applicable paints reduce emanation by only 32% to 67% for latex and 47% to 87% for epoxy paint (Eichholz *et al.,* 1980; Pohl-Rühling *et al.*, 1980). Heat exchangers, which transfer a large part of the thermal energy above the ambient level of the outgoing air to the fresh incoming air, can be installed at costs of approximately US $1000 (Roseme, 1979; Persily, 1982). The higher air exchange rates achieved also have beneficial impact on several other indoor pollutants.

Calculations of the cost-benefit ratio of control measures to reduce indoor radon show that such measures compare favorably with the cost-effectiveness of techniques to reduce routine radionuclide release from power plants. The costs per person-rem prevented are US $50 (US $5000 per person-sievert) in the former and US $1000 (US $100,000 per person-sievert) in the latter (Moeller *et al.,* 1980).

Discussion

The above assessment based on linear dose-effect relationships yields high risk factors for energy conservation, as compared to electricity production in large power plants including the fuel cycle. Although this approach is justified because the health impact of new technologies such as nuclear power plants are assessed on the same basis, it must be kept in mind that contrary to the real deaths involved in mine accidents and other occupational risks, linear extrapolation to low doses may overestimate the effects (BEIR III, 1980). In the case of radon, however, the high linear energy transfer of the alpha radiation involved and the amount of radiation delivered to the critical tissue, which cannot be considered low at environmental exposure levels, speak against beneficial threshold effects in this case (UNSCEAR, 1982; Burkart, 1983). In an energy-efficient home built on ground with elevated radium levels, the lifetime exposure may be in the same range as for some groups of uranium miners having well-documented risks for lung neoplasms (Stranden, 1980; Fig. 1).

For other indoor pollutants causing some concern, such as nitrogen oxides, formaldehyde, or asbestos fibers, the link to distinct health effects is much weaker or, as in the case of asbestos, only a small segment of the population is involved. It seems precocious to make an effort to quantify these health effects on the general public with today's knowledge. However, the quality of indoor air affects human performance and well-being to a great extent. Hence, the knowledge of indoor air pollution should be improved for the development of working and living environments that are comfortable and without risk.

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