THE EFFECTS OF RADON EXPOSURE ON PHYSICAL AND PSYCHOLOGICAL HEALTH

1991

WEISS

UNIFORMED SERVICES UNIVERSITY OF THE HEALTH SCIENCES
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Title of Thesis: **"The Effects of Radon Exposure on Physical and Psychological Health"**

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Master of Science
1991

Thesis and Abstract Approved:

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Abstract

Title of Thesis: The effects of radon exposure on physical and psychological health

Linda Jean Weiss, Master of Science, 1991

Thesis directed by: Andrew S. Baum, Ph.D., Professor, Department of Medical Psychology

This research was designed to address the psychological consequences of living in communities where high concentrations of indoor radon have been detected. Occupational exposure to this gas has been shown to be associated with a significant increase in lung cancer among miners. High factor insulation materials, porous foundations, and sump pumps installed in dwellings facilitate entry and trap this naturally-occurring gas within buildings exposing inhabitants to radon levels similar to mining environments.

The logistical difficulties in identifying high-risk areas, concentration variability in homes a few hundred yards apart, and the latency of disease development associated with exposure contribute to uncertainty associated with this environmental threat.

Research documenting the carcinogenic effects of this gas, sources of indoor contanmination, and measurement techniques provide a background for addressing psychological response to indoor radon.

The literature addressing risk communication and response to similar environmental hazards form a basis for exploring further psychological research.

THE EFFECTS OF RADON EXPOSURE

ON

PHYSICAL AND PSYCHOLOGICAL HEALTH

by

Linda J. Weiss

Thesis submitted to the Faculty of the Department of Medical Psychology of the Uniformed Services University of the Health Sciences in partial fulfillment of the requirements for the degree of Master of Science 1991

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Introduction

Overview

On September 12, 1988 the Surgeon General and the Environmental Protection Agency (EPA) issued a joint national health advisory recommending that all homes in the United States be tested for levels of radioactive gas (Hilts, 1988). This advisory was based on recent research examining the adverse effects of indoor exposure to radon (^{222}Rn) gas. Studies suggest that occupational exposure to high levels of radon are associated with increased cancer risk (Holaday, 1969; Hurwitz, 1983; Lundin, Wagoner, & Archer, 1971). Unfortunately research on the health effects of indoor radon exposure affecting the general public is sparse and studies on the potential role of psychological response to this threat have only recently appeared in the literature. This paper will describe the current understanding of the effects of radon with particular emphasis on health consequences. In addition, data from studies assessing psychological response to similar threats will be discussed in order to support the hypothesis that psychological sequelae associated with the knowledge that one's self and family have been exposed to radioactive gas may contribute to the development of somatic illness.

Research indicates that radon is the dominant source of natural radiation (Nazaroff, 1988). Studies examining the effects of radon exposure in miners have documented a significant relationship between inhalation of ^{222}Rn decay products and subsequent development of respiratory cancer (Donaldson, 1969; Saccomanno, Archer, Saunders, James, & Beckler, 1964). During the 1960's implementation of more rigorous mining safety standards led to a reduction in occupational exposure and a shift in the research efforts addressing the problems associated with radon. Current evidence suggests that in some cases indoor concentrations measured in private homes approach or exceed the levels found in mining environments (Hurwitz, 1983).

<u>The indoor radon problem</u>

Radon and its by-products are colorless and odorless. The Environmental Protection Agency (EPA) estimates that in the United States alone, as many as 10,000 cases of lung cancer each year are attributable to indoor radon exposure (U.S. EPA & Centers for Disease Control,1986). Bale (1980) has offered evidence that elevated radon levels due to a reduction of air flow in energy-efficient homes may significantly increase the lifetime cancer risk of occupants. The impact of this noxious gas has already been felt in communities located on or near geological deposits of radon precursors. In one case, a family living in a rural Pennsylvania community was forced to evacuate their home when the Pennsylvania Bureau of Radiation Protection confirmed contamination exceeding 13.5 working levels (Gerusky, 1987; Lafavore, 1987). Radon concentrations of one working level bear a comparable risk of lung cancer sixty times greater than nonsmokers or the equivalent of smoking approximately seven packs of cigarettes per day (U.S. EPA & CDC, 1986).

Radon testing of private homes in the U.S. is in its infancy. In most cases homeowners must initiate action and bear the financial burden of remediation. Several other issues compound the indoor radon problem.

A direct causal chain between indoor exposure and the development of lung cancer is difficult to prove. Some researchers hypothesize that as testing methods are standardized and the extent of public exposure is more accurately assessed the cancer risk associated with indoor radon may approach that of cigarette smoking (Jackson, Geraci, & Bodansky, 1987). Although radon has been identified as a potent carcinogen many people are not aware of the risks it poses or underestimate them (Weinstein, Sandman, & Klotz, 1987).

Finally, assume for the moment people are knowledgeable about radon and motivated to take necessary measures to reduce levels of this gas in their homes. Would their actions alleviate concerns regarding the long-term cancer risks affecting one's self and family members, the financial burden of correcting such a problem, or reduce the psychological consequences related to the uncertainty of how radon affects well-being? Unfortunately, due to the nature of this threat many people may continue to be concerned even after action has been taken.

Psychological issues

The psychological literature on response to environmental threats encompasses events or situations of natural and technological origin. An environmental event or force is considered a stressor when it threatens an individual's existence or well-being. Response to a stressor includes perception of the threat, coping, and adaptation (Baum, Singer, & Baum, 1981). When changes in one's surroundings are sufficiently severe and threatening a breakdown in this process results in a stress reaction affecting psychophysiological response.

Although there are obvious differences between catastrophes such as floods, living near a damaged nuclear power plant, or the presence of radioactivity in one's home there are parallels in psychological response. Perception and appraisal of environmental stressors may tax peoples' abilities to effectively manage their emotional lives (Lazarus, 1966). Behavior deficits may occur as the demand to cope with the threat exceeds available resources (Cohen, 1980; Glass & Singer, 1972). Finally, stress affects physiological function often resulting in sustained autonomic arousal and immune dysfunction (Tache, Selye, & Day, 1979).

Indoor radon does not share most attributes normally associated with natural threats. There is no overt indication that contamination exists. Most natural hazards have an acute impact and an identifiable point where "the worst has happened". Disease resulting from radon exposure may not reach the symptomatic phase for many years and mitigative action reduces contamination but does not eliminate the problem.

These factors and the public's limited understanding of the consequences of long-term exposure may result in inaccurate perceptions of this threat and challenge a person's ability to respond appropriately. Stress resulting from an inability to resolve these issues eventually affects physiological function and contributes to disease development.

Summary

Radon is a naturally-occurring radioactive gas that cannot be detected by sensory faculties. Respiratory cancer is the principal health risk associated with exposure to this environmental threat. Testing of private homes indicates a significant number of American families are exposed to high cumulative levels of this gas. Measurement problems and the wide-spread occurrence of this gas hamper detection efforts. This paper will first present a brief synopsis of sources and measurement techniques followed by a review of the research addressing the health risks associated with this toxin. In order to compensate for the paucity of literature addressing psychological response to radon exposure the data provided by similar studies will be used to support the notion that the uncertainty surrounding the indoor radon threat, the manner in which people cope, and controllability of exposure may be factors in the potentiation of somatic illness.

Radon sources and measurement

Radon is formed and given off during the radioactive decay of uranium (^{238}U) and thorium (^{232}Th). As a noble gas, radon does not combine with other elements under normal conditions. This property allows the gas to escape unchanged from the earth's crust where it readily enters structures through cracks in foundations, sump pumps, and similar pathways. Radium (^{226}Ra) and one of its isotopes (^{224}Ra) are the immediate progenitors of radon and thoron. As ^{226}Ra and ^{224}Ra decay they emit alpha particles creating a recoil action transporting the newly formed radon and thoron atoms into the atmosphere and water sources (Nero, 1988). Due to the short half-life of thoron and lack of evidence regarding its effects of human health the focus of this paper will be the effects of radon and its by-products.

The radon decay products (progeny or daughters) include isotopes of polonium (Po), lead (Pb), and bismuth (Bi). When these atoms attach to particulates in the air and are inhaled, they are densely distributed in sensitive body tissue (Nero, 1988). Airborne concentrations of these progeny are therefore of prime interest due to their potential retention in the lung leading to the carcinogenic effects of alpha decay.

World-wide deposits of these precursor elements, their longevity, and the continual decay process are central factors in the study of this environmental threat. Although several isotopes in these chains play a positive role in energy production and medical procedures, radon itself poses a significant health risk to a large portion of the world's population.

Variations in concentrations are due to a complex transport process that may increase or decrease precursor accumulations over several geological eras (Hurwitz, 1983). It is estimated that 100 megacuries of radon radioactivity per year are released from U.S. soil alone with 30,000 curies being directly released into homes and buildings (Travis et al., 1967).

There are several methods used to detect the presence of radon in soils and bedrock that enable investigators to focus on regions identified for their high concentrations of uranium and radium (Myrick, Berven, & Haywood, 1983; Nazaroff, Moed, & Sextro, 1988). These forms of geological mapping are important in identifying terrain suspected of high radon levels but cannot detect the extreme variations known to occur within homes several hundred yards apart.

Similar to the outdoor techniques indoor procedures detect emissions occurring during the radioactive decay process. Most indoor measurement techniques assess alpha particle emission. Lead and bismuth progeny emitting beta particles are extremely short-lived and are not generally considered as significant as radon and polonium isotopes in terms of biological damage. Gamma radiation from these isotopes pose a health risk only when radon and progeny concentrations are extremely high and decrease significantly when mitigative action is taken to reduce radon levels (Miller & George, 1988). Samples may be gathered over a short period of time (analysis of a single data point); integrating methods determine a single concentration averaged over time (several days to a year); and finally, continuous monitors provide time dependence of concentrations over a protracted periods (Cohen & Gromicko, 1988; Lucas, 1957; Prichard, 1983; Thomas & LeClare, 1970). Depending on the purpose of the testing procedure each technique has its advantages. As may be expected the accuracy of measurements is subject to question due to the random nature of radioactive decay, imprecise results on level concentrations, and the problem of variation in detection methods (Nazaroff, 1988).

Radon and progeny levels are described in terms of concentration or the product of concentration and time (See table 1). The literature reports test results in picocuries per liter (pCi/l) or working levels (WL). One pCi/l is equal to .005 WL. The picocurie is a standard measure of concentration and is equivalent to the becquerel (Bq) or a decay rate of one atom per second (Nero, 1988). Working levels express concentrations over time and are reported in terms of hours (WLH) or more commonly months (WLM).

Summary

This overview has provided an outline of the sequence of the decay chains, monitoring processes, detection methods, and measurement units crucial to an accurate interpretation of the literature examining the health risks associated with indoor radon. Its purpose was to demonstrate the complexities affecting the public's knowledge of radon. Misunderstanding regarding sources and measurement of radon is hypothesized as one of the factors affecting psychological response to this environmental threat. Biological damage resulting from exposure to radon and its progeny supercedes this concern. Epidemiological data documenting the increased incidence of respiratory cancer demonstrates the validity of the current concerns regarding this threat.

Occupational radon exposure and respiratory cancer

Evidence of pulmonary disease resulting from occupational exposure to radioactive gas was noted as early as the 1500's in the Erz mountains of Europe. The effects of radon and its by-products were often misdiagnosed as tuberculosis until 1879 when Harting and Hesse identified ^{222}Rn as a cancer inducing agent. A high incidence of respiratory disease among residents of the Schneeburg region of Germany and Joachimsthal, Czechoslovakia provides the earliest documentation of the relationship between radon exposure and lung cancer. Despite the excessive number of fatalities in these communities, deaths attributed to pulmonary disease were only significant among miners employed in the region.

Harting and Hesse's work correlating exposure to radioactive ores with lung carcinoma generated investigative concern resulting in over 16 studies between 1879 and 1939 examining histopathological evidence of respiratory cancer in humans and animals subjected to these mining environments (Hueper, 1942). Comparisons of mortality rates between Schneeberg underground miners, their family members, ore processors, and miners working with non-radioactive ores offered evidence that heredity, climate, and working conditions could not account for the disproportional mortality rate attributable to pulmonary malignancies. The carcinogenic effects of other mine contaminants were addressed by researchers and found to be non-significantly related to cancer development.

Hueper (1942) and Lorenz (1944) were the first to present summaries of the foreign literature gathered over a 70 year period on the toxic effects of radon. The presence of radium and its by-products in mines was found to be correlated with a high incidence of respiratory cancer among underground workers. Physiological data indicated that miners exposed to these environments were absorbing radioactivity. Lung tissue samples taken from workers who had died of respiratory cancer confirmed radon as a carcinogenic agent and identified the cause of death as squamous-cell carcinoma. Despite these data the health-impairing effects of radon progeny were not fully recognized until the 1950's.

Preliminary measurements of radon concentrations in several U.S. mines and the reported correlation between exposure to this gas and a high cancer rate documented in the European literature prompted a longitudinal investigation by the U.S. Public Health Service (PHS) between 1950 and 1968.

Cancer mortality patterns among uranium miners and millers working in the Colorado plateau region (Arizona, Colorado, New Mexico, and Utah) were first reported by Wagoner, Archer, Carroll, Holaday, and Lawrence in 1964. Comprehensive health examinations were made six times during this 10 year study. Mortality in the study group was compared to the expected number of deaths typically found in males residing in the Colorado plateau area. Subjects were assigned to one of three categories: nonwhite (predominately American Indians) millers and miners; white millers; and, white miners.

The results of the Wagoner et al. (1964) study indicated that within the first two groups fatalities were either lower than or comparable to expected mortality rates. Differences did emerge in the third cohort (white uranium miners). When compared to statistical estimates, a significant number of deaths were documented in this group with accidents and malignant neoplasms of the respiratory system accounting for the excessive fatalities. The high incidence of accident-related deaths was attributed to other hazardous conditions (equipment failure, cave-ins, etc...) encountered by the miners. Age, cigarette smoking, race, genetic predisposition, urbanization, self-selection bias, and inaccuracies in reported cause of death did not account for the excess of respiratory malignancies in the group members.

General incidence of lung cancer in men residing in the Colorado plateau region was examined by Saccomanno et al. (1964). An extensive effort was made to locate males in a 15 county area who had been diagnosed as having respiratory cancer between January 1948 and December 1963. Histories were obtained from these individuals, family members, hospitals, physicians, and the on-going PHS miner study. Information regarding occupation, clinical symptoms, and location as well as tumor cell type was recorded. Subjects (N=276) were divided into three groups: uranium miners having lived in the specified areas; other male residents of the 15 counties; and, a group of "transient" men who had either sought medical attention or had died within the Colorado plateau region. Results from this study suggested a quantitative relationship between radon and respiratory cancer and indicated that uranium miners evidence a higher ratio of undifferentiated small cell tumors of the lung at an earlier age than matched controls.

The cancer-inducing effects of radon were examined by Wagoner, Archer, Lundin, Holaday, and Lloyd in 1965. The dose-response relationship between progeny exposure and respiratory cancer was calculated based on 12,000 measurements taken in 1,200 mines. Occupational history, progeny levels, and cumulative exposure time adjusted for seasonal variation were ascertained for each miner. Results of this study show that the incidence of lung cancer in this population is a direct function of cumulative radiation exposure. These data also suggested a possible effect for tobacco use but it was not conclusively demonstrated.

Discrepancies in studies examining the possible additive effects of cigarette smoking at significant exposure rates were addressed by Cross, Harley, and Hofmann (1985). The review cites Axelson and Sundell's 1978 report on Swedish zinc and lead miners noting a lower lifetime lung cancer incidence among workers who smoke and suggested a protective effect of the increase or thickening of the mucosal lining due to "smokers" bronchitis. A similar pattern was observed by

Cross, Palmer, Filipy, Busch, and Stuart (1978) in dogs. Research by Chameaud, Perraud, Chretien, Masse, and Lafuma (1980) is also cited for their data on the cocarcinogenic effects of tobacco smoke in rats following exposure to Rn progeny but not when the presentations were reversed.

Other studies were reported in the 1960's addressing mortality rates in these miners with similar findings (Archer, Brinton, & Wagoner, 1964; Archer, Magnuson, Holaday, & Lawrence, 1962). Further evidence of the carcinogenic effects of radon progeny was documented in non-uranium miners (DeVilliers & Windish, 1964; Wagoner, Miller, Lundin, Fraumeni, & Haij, 1963). These investigations left little doubt that humans exposed to high concentrations of radon progeny over time were more likely to develop undifferentiated small cell tumors of the lung than unexposed controls.

The final PHS report on the quantitative and temporal aspects of radon daughter exposure was released in 1971 (Lundin et al.). As a result of these data the occupational standard was lowered in July 1971 from 12 WLM to four WLM. These data point toward the cumulative effects of radon exposure and suggest as well that no predisposition to pulmonary cancer was apparent in members of the study group.

Research on other situations where humans were exposed to high radiation levels (patients receiving therapy and atomic bomb survivors) were consistent with the PHS data (Donaldson, 1979). Concurrently, animal studies confirmed the radiosensitivity of the lung and indicated that carcinogenesis may result from relatively low radiation levels (Cember, 1964). Studies on Swedish hard-rock miners (Edling & Axelson, 1983), New Foundland fluorspar workers (DeVilliers & Windish, 1964, and Norwegian niobium miners (Solli, Andersen, Stranden, & Langard, 1985) support the Schneeberg, Joachimsthal, and U.S. studies.

Summary

Retrospective studies conducted over a 70 year period revealed that excessive exposure to radon progeny was responsible for excessive mortality rates among miners in the Erz mountain region of Germany and Czechoslovakia. A high incidence of bronchial carcinoma pointed toward a specific cause-effect relationship between exposure to radon and disease development. The PHS study initiated in 1950 found a similar mortality rate among uranium miners in the Colorado plateau region. Exposure to radon progeny in other occupational settings confirmed these findings.

This research firmly established that occupational exposure to radon and its progeny resulted in an increased incidence of lung cancer. Due to this relationship and the wide-spread deposits of radon precursors investigators hypothesized that the risks associated with this gas were not limited to these populations.

Indoor radon

In the early 1970's attention was drawn to the hazards associated with radon spas. Due to a relatively short exposure time patients using these facilities rarely received a sufficient dose to put them at risk; however, spa employees and nearby residents were believed to have been exposed to cumulative levels approaching those found in the miner studies.

One study found that employees were exposed to an average cumulative dose of one to five WLM per year and among long-term residents reported incidence of lung cancer doubled between 1949 and 1968 (Pohl-Ruling & Scheminzky, 1972). In 1973 Vaskov (cited in Steinhausler, 1988) reported a significant increase in the frequency of atypical cells in sputum samples obtained from Bulgarian spa employees as compared to controls. Pohl-Ruling and Fischer (1983) found progeny-related chromosomal abnormalities among residents living near spa facilities and the following year Clemente, Renzeiti, Santori, Steinhausler, and Pohl-Ruling reported elevated levels of ^{210}Po and ^{210}Pb in a sample of spa workers and patients.

Sources of indoor radon

Elevated levels of radon gas in dwellings can be traced to three sources. Building materials, especially alum shale-based concrete and cements containing radioactive additives have been implicated in the indoor radon problem (Guimond, Ellett, Fitzgerald, Windham, & Cuny, 1979; Stranden, 1988). Although several studies have documented high concentrations of radon due to these materials consensus among researchers indicates that this source contributes fairly little to the indoor radon problem and is more readily controllable than other sources.

Radon entry via potable water is the second potential source of contamination. In 1982 Bean, Isacson, Hahne, and Kohler reported their findings on Iowa residents drawing their water from six aquifers providing 75% of the state's supply. Cancer incidence was documented from 1969 through 1978 based on 328 bladder cancer patients (Hoover & Strasser, 1980) ,and a mail survey of 4,107 diagnosed cancer patients. Bean and colleagues found that lung cancer incidence was greater among male residents of communities with a radium sample of five pCi/l or greater. The data could not be explained by smoking patterns, water treatment factors, water quality measurement error, or known socio-demographic features. The study by Bean et al. (1982) provides the only human data correlating lung cancer incidence with ^{226}Ra contaminated water sources. Uncontestable proof of the relationship between irradiated water sources and subsequent cancer development has not been demonstrated.

In 1985 Cross et al. reviewed the literature on inhalation and ingestion of radon and its progeny from water supplies. Evidence suggests that the carcinogenic effects of radon progeny are primarily due to the deposition of ^{218}Po (RaA) and ^{214}Po (RaC') in lung tissue (Bale, 1980). Due to the sensitivity of the respiratory tract the majority of research had focused on the effects of radon/progeny inhalation although there is some data suggesting a higher bladder/intestinal cancer rate among humans and animals ingesting high concentrations of these toxins via drinking water.

The last and most potent source of indoor radon is the direct entry of the gas from soil and bedrock rich in radon precursors. By the mid-1980's results of indoor studies conducted in European and Scandinavian countries began to appear in the literature (Steinhausler, 1985).

Residential studies

Two longitudinal studies undertaken by the French Atomic Energy Commission and the Federal Republic of Germany assessed indoor and outdoor radon progeny concentrations (Rannou, Madelmont, & Renouard, 1985; Schmier & Wicke, 1985). Insufficient sample size and wide variability in bedrock formations accounted for the lack of statistical significance in both studies. It was determined that future research efforts should focus on communities on or near geological outcroppings of radioactive strata.

Research conducted in Sweden, Finland, and Denmark found similar results (Castren, Winqvist, Makelainen, & Voutilainen, 1984; Sorensen, Botter-Jensen, Majborn, & Neielsen; 1982; Swedjemark & Mjones; 1984). Regional variation, climate and ventilation techniques affected indoor readings that averaged between 54 and 124Bqm^{-3} (~1-3 pCi/l).

Green et al. (1985) reported findings of two surveys conducted in the United Kingdom. Initially, a sample of 2,000 dwellings were monitored for indoor gamma dose and radon levels. A more detailed study was conducted in areas with suspected high radiation levels. Factors considered in this study included geographic location, housing type, construction materials, and living habits of the occupants. Again, regional differences were evident and ascribed to radioactive strata.

The emphasis of U.S. research has been directed toward identification of high risk communities. These investigations have produced conflicting results due to differences in measurement procedures and geographic selection of homes (Hurwitz, 1983). Federal, state, and local officials have been hampered by lack of funding and personnel needed to conduct these studies as well as a conflicting policy stance regarding the energy conservation programs developed in the 1970's (Nero, 1983). Despite these problems substantial evidence of radon contamination has been accrued for certain portions of the U.S. The following studies are representative of findings in high concentration areas.

In 1979 Travis et al. reported the results of a project assessing radon levels and inhalation dose of ^{222}Rn for both natural and TENR sources. The term "technologically enhanced natural radiation" (TENR) refers to naturally occurring radiation sources that would not normally exist without the presence of technological activity not expressly designed to produce radiation. The investigation revealed that technologically enhanced and natural sources accounted for 55% of the radiation dose affecting the general public.

In 1980 Spitz et al. reported results of measurements taken in Grand Junction, Colorado and Teaneck, New Jersey. These two locales were selected based on expected differences in natural and TENR radon sources. The Colorado community represented an area where uranium mill tailings were being used in residential construction with an active deposit of mill tailings existing within the city limits. In contrast, the New Jersey site was selected due to previous research indicating no technological enhancement of ^{226}Ra in soil or building materials. As expected, outdoor radon levels in both communities were similar ranging between 0.3 and 1.6 pCi/l. Both temperature variations and ventilation changes significantly affected radon concentrations. Data derived from this study points toward the extreme fluctuations in indoor levels independent of contamination resulting from mining by-products.

In 1986 Nero, Schwehr, Nazaroff, and Revzan analyzed 38 data sets collected in the U.S. and found average concentrations between 0.3 and 5.7 pCi/l. These data indicated that 7% of U.S. single family homes (~4,000,000) have levels exceeding four pCi/l and that on the average one million homes have radon concentrations above eight pCi/l. These data are based on samples taken from both suspected high concentration areas (16 studies) and communities where there was no reason to believe significant radon would be found.

In a 1983 review of the indoor radiation literature, Hurwitz suggested that the primary goal of future investigations should be to inform the public of the health risks associated with radon in more familiar terms. Citing the common use of whole body equivalent dose (rem or mrem) when reporting exposure to other forms of ionizing radiation Hurwitz states that conversion from lung exposure quantities to whole body equivalent is not difficult and would permit more accurate comparisons by the public between the different types of radiation (eg. x-rays, occupational vulnerability, and nuclear detonations/accidents). Two methods are available to convert pCi/l or WLM to rem or mrem measurement. The first takes into account the relative biological effectiveness (RBE) factor that is used to convert rads to rems. The second approach involves a comparison of any two pollutants based on imputed lifetime risk.

A second factor discussed by Hurwitz is the disproportionate research emphasis placed on small incremental exposures. The average radon concentration in U.S. homes is 0.8 pCi/l corresponding to a whole body exposure of ~80 mrem per year. At this level radon exposure is comparable to the lifetime lung cancer incidence in nonsmokers. Hurwitz criticizes this research for failing to concentrate on the millions of homes known to have levels associated with respiratory cancer.

Summary

The indoor studies article reflect the ubiquitous nature of radon. Diurnal and seasonal variations contribute to the difficulties encountered in assessment efforts. It had been demonstrated that energy-conservation measures contributed significantly to indoor contamination levels (Hurwitz, 1983; Nazaroff et al., 1988; Nero, 1988). Research had produced preliminary identification of high-risk areas; however, logistical and financial restraints hampered government efforts to institute a house-by-house monitoring program. By the mid 1980's government agencies had begun to develop programs designed to alert the public about the dangers of radon and to provide guidelines for testing and remedial procedures.

Risk communication

The Reading Prong is a uranium-rich belt encompassing portions of New York, New Jersey, Connecticut, and Pennsylvania. Extreme indoor radon concentrations found near Boyertown, PA and subsequent evidence that all homes located along this geological formation were at high risk prompted state and federal agencies to determine what forms of communication would maximize public cooperation to reduce this environmental threat. Two studies documented these efforts and represent the first research addressing the psychological issues associated with radon contamination.

In 1985 the New York State Energy Research and Development Authority (NYSERDA) began a longitudinal monitoring study of 2,300 randomly selected homeowners. These individuals and 252 others serving as a comparison group participated in a risk communication study designed to test the efficacy of different information formats. Four criteria were selected as indicators of effectiveness: learning about radon; subjective risk perceptions; demand for further information; and, mitigative action. An interim report was released in 1987 describing data on the first three variables (Smith, Desvousges, & Fisher).

Baseline data for both groups were gathered during a three month period in 1986 via telephone interviews. Although subjects in the monitoring sample had received test kits (both short and long term) prior to this time they had not been apprised of results or how to interpret them. This initial contact assessed current knowledge, risk perception, action or intended action to reduce radon levels, and demographics. Six months after the first interview subjects in the monitoring group received results from the short-term tests and one of six brochures including: a NYSERDA "fact sheet"; the EPA's Citizen's Guide to Radon (U.S. EPA & CDC, 1986); and four pamphlets (based on the EPA guide) in which quantitative vs. qualitative information varied within a directive vs. evaluative format. All six contained the same basic information. A follow-up telephone interview assessed the manipulation effects. Members of the comparison group were contacted during the same time periods but did not receive any radon literature.

The two issues addressed in the mid-course evaluation were: first, whether certain forms of communication could enhance learning and encourage appropriate action; and second, to determine if homeowners were accurately perceiving the risks associated with radon documented in the technical literature.

Radon "quizzes" administered during baseline and follow-up interviews indicated that all six treatments positively affected the subjects' over-all understanding of radon issues. Although it was apparent that participants in the comparison group increased their knowledge on risk, measurement, and mitigation it was substantially lower that the learning evidenced by the NYSERDA monitoring sample.

Among the NYSERDA participants those receiving the fact sheet did not demonstrate any improvement on the health risk portion of the follow-up quiz.

An overall evaluation of the five brochures examined effects on learning, risk perception, and information demand (lower demand suggests the brochure met the homeowner's information needs). The directive/quantitative brochure improved risk perception and reduced demands for further information. The four other pamphlets were effective in only one of the three categories: learning (evaluative/qualitative), risk perception (evaluative/quantitative), and information demand (directive/qualitative & EPA guide).

In summary, the five pamphlets were more effective than the brief fact sheet with all six NYSERDA groups benefiting significantly more than members of the comparison group. It was evident from these data that the effectiveness of the different information formats depended on the targeted aspect under study. The final phase of the study will focus on participants' response to results of long-term testing specifically mitigation efforts, adjustments in risk perceptions, and the feasibility of alternative communication channels.

The second study addressing public response to indoor radon was reported by Weinstein, Sandman, and Klotz in 1987. Unlike the NYSERDA sample drawn from all geographical NY regions (the average indoor level in NY is 1 pCi/l) subjects in this study lived on or near the Reading Prong in several NJ counties. Two groups were recruited; a random sample of 657 homeowners living in these areas and 121 individuals taking part in a confirmatory monitoring program sponsored by the NJ Department of Environmental Protection (DEP). Subjects in the latter sample had previously tested their homes and received a reading of 4 pCi/l or greater while over 90% of the random sample had not tested for radon. The purpose of this research was to provide data that would improve future government programs and to evaluate the effectiveness of on-going efforts. Questionnaires were mailed to subjects in both groups and home interviews were conducted with 16 members of the confirmatory sample. Results are discussed in terms of the subjects': assessment of information sources; knowledge and information needs; use of sources; emotional response to the problem; and, intentions and monitoring experiences.

Participants in both samples expressed a high degree of confidence in the ability of state and federal agencies to provide accurate information about radon. In response to a question on what types of information they would like to receive the random sample preferred material on health risks (81.8%) while the confirmatory monitoring group indicated a need for information on mitigative procedures (89.4%). Subjects in the random sample were asked to check three sources they had or would use if more information was needed; here the media (television and newspapers) were endorsed as current sources while state officials were most likely to be contacted if needed. The confirmatory sample indicated that the media was most helpful when they were making the decision to test and that the DEP was the source most frequently contacted for health information.

Factual radon knowledge was assessed by asking subjects to respond to a series of true/false questions. The monitoring sample made a significantly higher number of correct responses (86.8% as compared to 64.5%). Both groups appeared to have a basic understanding of what radon is, how it enters homes, and that high levels require immediate action. Although the monitoring subjects scored higher on health-related questions there was clear evidence that these issues were not well understood by either group. These findings were confirmed when subjects were asked to rate the seriousness of illness caused by radon exposure. Only 14.9% of the random sample believed it would be serious, while a surprisingly low 52% of the confirmatory group gave similar ratings. This is in direct contrast to a high percentage (75 and 98% respectively) correctly identifying lung cancer as the primary health risk associated with exposure. In addition, the monitoring sample generally described the problem as only slight to moderate (77.7%) despite all homes having levels of 4 pCi/l or above.

Monitoring intentions were also presumed to reflect the perceived seriousness of this threat. Within the random sample, 50.3% of the respondents indicated they had never considered testing while 24.8% had not made a decision. The apparent apathetic response among 75% of these homeowners has been demonstrated in studies examining other health and safety risks (Weinstein, 1988). Unrealistic optimism was expressed by a majority of the subjects ("my home is less likely to have radon") who gave 247 reasons why this would be the case. The confirmatory sample shared a similar bias in response to a set of questions comparing the dangers of radon to other health risks even though some of the hazards were substantially less harmful. Further evidence of this bias was shown when less than half of the subjects with readings of more than 20 pCi/l considered the problem serious.

Emotionally, people in both groups tended to be concerned and moderately worried rather than angry, helpless, or depressed about their situation. There were no significant differences between groups on these variables. Neither group tended to blame anyone for the radon problem and it appeared that increased involvement (testing, remediation) does not result in scapegoating. A sense of community concern and knowing others who had tested was positively correlated with monitoring intentions.

Conclusions drawn from these data are that most people are unrealistically optimistic about radon tending to underestimate exposure risks and health consequences. In the random sample few people, even in high risk areas, intended to test their homes. Data from the confirmatory monitoring sample indicated little if any relationship between high radon levels and: perceived seriousness of the threat; emotional distress; and, remedial action. Homeowners who had tested reported a lack of community concern and more specifically, disinterest or derision from friends and neighbors.

A follow-up study was conducted in 1988 to determine what remedial steps had been taken by the confirmatory monitoring sample (Weinstein, Sandman, & Roberts). Over 90% of subjects with readings of 20 pCi/l or more had made modifications to reduce the radon levels in their homes. Among participants with levels between 4 and 8 pCi/l 60% took mitigative action. Interestingly, nearly half of the homeowners with readings <u>under</u> 4 pCi/l also completed some modifications. Variables correlated with intent to monitor (Weinstein et al., 1987) were significant predictors of actions taken. Weinstein and colleagues (1988) estimated between 8 and 13 lives per household in this sample were saved due to mitigative efforts.

In summary, the New York (Smith et al., 1987) and New Jersey (Weinstein et al., 1987) studies demonstrated the effectiveness of campaigns in disseminating factual information to the public. Although people now know more than ever before, it does not appear increased knowledge leads to action. The optimistic bias prevalent in the New Jersey samples points toward an insufficiency in existing programs. People are not responding to this hazard as anticipated. The radioactive and carcinogenic properties of radon, its wide-spread occurrence, and lack of sensory indicators that a problem exists suggest that indoor radon would pose a significant threat. Research examining response to similar hazards provides a basis for understanding why radon poses a unique environmental challenge.

<u>Radon and other natural hazards</u>

In general natural disasters or hazards have an immediate and often transitory effect. A tornado, flood, or earthquake may devastate a community; however, recovery from such events usually occurs within a year with minimal post-traumatic symptoms. Most occur suddenly with little warning, are unpredictable, and usually viewed as uncontrollable (Fisher, Baum, & Bell, 1984). People may not experience personal injury or property damage but generally know friends or neighbors who have lost their homes or family members. Residents may be forced to evacuate their homes during the crisis and often have to relocate until dwellings can be repaired or rebuilt. The physical destruction caused by natural disasters often requires extensive reconstruction and in some cases permanently alters the environment.

Some catastrophes are caused by a combination of natural events and human mismanagement of environmental resources (Fisher et al., 1984). The collapse of a coal slag dam above Saunders, West Virginia is a case in point. The Buffalo Creek flood destroyed 15 communities, claimed 125 lives and left 4,000 people homeless (Titchner & Kapp, 1976). Heavy rains triggered the onset of this event, but ultimately the cause of the disaster was the inadequate design of the dam. In 1974 surviving families were awarded 13.5 million dollars in damages, with nearly half the amount allocated to cover psychological damages (Stern, 1976). Lifton and Olson (1976) described the human cause factor as one of the characteristics that contributed to the chronic stress symptoms observed in area residents two years after the 1972 flood.

The radon problem is similar to the Buffalo Creek disaster in that natural forces are in some degree precipitating factors. In some instances radon contamination may result from human error as in the case of improper disposal of industrial waste (Roessler, Roessler, & Bolch, 1983; Stranden, 1988; Weinstein, Klotz, & Sandman, in press).

Although radon is naturally-occurring gas, the threat it poses does not conform to accepted definitions of natural hazards. Families can be exposed to harmful levels for years without being aware of its presence. Homeowners who do test may find they have extremely high levels while their immediate neighbors tests confirm negligible amounts. Mortality associated with radon exposure results from long-term disease development, affects only portions of the community, and probably will not be diagnosed as radon induced. Although floods, earthquakes, and the like are seen as uncontrollable forces of nature there is a point where "the worst is over" and the reconstruction process can begin. While remedial steps can reduce indoor levels, they do not eliminate the source and may result in chronic preoccupation with the effects of what has occurred.

These issues have a direct bearing on the way individuals perceive this threat. The absence of visible physical damage may lead people to underestimate the consequences of exposure. Concentration variability particularly in high-risk areas may contribute to a sense of personal immunity. These factors most likely contributed to the optimistic bias reported by Weinstein and colleagues (1988) and are supported by the health belief model in the perceptions of susceptibility and severity influence the likelihood that a person will or will not take action to reduce a health threat (Wallston & Wallston, 1984). Other characteristics of the radon problem also share more in common with human-caused disasters.

<u>Radon and technological disasters</u>

Technological advancements have improved the quality of life and our ability to harness the unpredictable forces of nature. An integral part of scientific and industrial development are safeguards designed to prevent or minimize failure. When these systems malfunction confidence in the ability to prevent future mishaps is shaken. The public is suddenly confronted with the consequences of human error and an event that should not have happened. Technological disasters differ from natural catastrophes in that: they result in a loss rather than a lack of control; someone (or some organization) is responsible for the event; and, the threat generated by such events is not immediately resolved (Baum, Fleming, & Singer, 1983).

Radioactive contamination is generally seen as a technological problem as opposed to a naturally-occurring phenomena. The destruction produced by atomic weaponry during World War II and the proliferation of nuclear power facilities in the 1970's brought public attention to the risks inherent with this new technology. During the early phases of development and testing however, the long-term effects of radioactivity were still a matter of conjecture.

Over 250,000 U.S. military personnel participated in atmospheric nuclear tests between 1946 and 1962 (Vyner, 1982). In the 1970's the media began publicizing reports on the dangers of ionizing radiation, the Department of Defense was required to notify veterans who had participated in the atomic tests, and Congress began hearings on these veterans' disability claims.

A project was undertaken in the fall of 1979 to document anecdotal reports indicating that atomic veterans were developing psychological problems believed to be related to their nuclear testing experience (Vyner, 1982). The majority of these men left the military believing their participation in these tests had not affected their health. After several years all subjects in this study began to develop illnesses requiring extensive medical treatment. Four participants were diagnosed with cancer while the others evidenced various forms of stress-related diseases. The gradual realization that their nuclear test experiences could be responsible for their health problems triggered the onset of a syndrome characterized by a preoccupation with the consequences of radiation exposure accompanied by psychological and behavioral symptoms related to these beliefs. At the time of the study all subjects were chronically unemployed and had difficulty maintaining social relationships. Nine of these men evidenced organic disease prior to the onset of the syndrome and all subjects expressed a high degree of uncertainty regarding their ability to convince the government and physicians that their symptoms or illnesses were a result of radiation.

While the effects of radon are cumulative and do not approach the magnitude of radiation released by atomic blasts, the long-term cancer risks are comparable. Individuals exposed to high radon concentrations may attend more to bodily changes and encounter similar diagnostic problems exacerbated by stress-related symptoms. The social stigmatism associated with radiation is common to both groups. Friends and neighbors aware of radon contamination may refuse to enter the home. The president of Pennsylvanians Against Radon(PAR) has cautioned that advocacy on the part of affected individuals may alienate other community members (K. Jones, personal communication, November, 11, 1987). Veterans' efforts to convince legislators and physicians that their illnesses resulted from radiation exposure is a potential hurdle facing people living in high concentration areas.

The final group of studies describing the adverse effects of radiation exposure bear a closer resemblance to the problems associated with indoor radon. Research conducted with samples of people living near the Three Mile Island (TMI) nuclear power plant indicates that the events following a malfunction at the facility resulted in a chronic stress response among many area residents.

During the initial crisis in March, 1979 public information regarding the accident was sporadic and often contradictory. Local residents were advised by some authorities to evacuate and assured by other officials the incident did not pose a significant threat to the community. Decontamination procedures continued for several years and the restart of the undamaged reactor generated further concern. Studies indicate that area residents have continued to exhibit stress-related symptoms associated with the 1979 event (Baum, Gatchel & Schaeffer, 1983; Dew, Bromet, Schulberg, Dunn, & Parkinson, 1987; Gatchel, Schaeffer, & Baum, 1985; Schaeffer & Baum, 1984).

In a 1980 report to the U.S. Nuclear Regulatory Commission (NRC) Baum et al. reported that up to 70% of the local population viewed the crisis as a serious health threat with women and individuals with higher education levels reporting a greater degree of concern. This NRC report also documents a chronic stress response among residents nearly a year after the accident.

In 1983 Baum and colleagues reported the results of a field study examining response to the 1979 incident. Participants included 38 people living near the damaged TMI plant and the following three control groups: residents living at least 20 miles from any power facility, a group living near a coal-fired plant; and, a sample from a community within five miles of an undamaged nuclear power plant. Emotional, behavioral, and physiological response was assessed. Self-report of emotional distress was significantly higher among TMI subjects when compared to the control groups. Performance on two behavioral tasks indicated that the TMI group had more difficulty concentrating and were less motivated to attend to the tasks than controls. Analysis of urinary catecholamines revealed the TMI sample had significantly higher levels of epinephrine and norepinephrine. Elevated levels of these hormones are associated with the stress response (Baum, Grunberg, & Singer, 1982).

In 1984 Schaeffer and Baum examined adrenal cortical response to the TMI incident. Subjects included the four groups described previously. The purpose of this study was to confirm findings from previous investigations addressing the relationship between stress, emotional problems, and hormonal changes (Baum et al., 1982; Mason, 1975). Data indicated that elevated levels of cortisol were significantly correlated with the high somatic and emotional symptom reporting, poor task performance, and elevated urinary catecholamines evidenced by the TMI subjects. Both the 1983 and 1984 studies were based on data collected 17 months after the accident occurred and document persistent stress-related symptoms related to this technological disaster.

Results from two other studies confirm the evidence of emotional distress. A telephone survey conducted shortly after the incident indicated that residential proximity to the TMI plant increased self-reported feelings of threat and greater emotional upset particularly among pregnant women (Flynn, 1979). Houts, Miller, Tokuhata, and Ham (1980) found evidence of greater self-reported psychological distress among TMI community residents than in a comparable control group.

Fifteen months following the accident a decision was reached to vent the radioactive gas trapped in the containment building. The process involving controlled release of krypton-85 directly into the atmosphere again threatened nearby residents. In 1985 Gatchel, Baum and Schaeffer reported the results of a series of investigations examining response immediately prior to the venting, during and immediately following the release, and six weeks after the procedure had been completed. The control group consisted of subjects living near Frederick, MD who were at least 20 miles away from any power facility.

Participants in this study completed a number of self-report measures including: a multidimensional symptom checklist (Derogatis, 1977); a survey of attitudes about the 1979 incident, current, and future concerns about nuclear power; and, a socio-demographic questionnaire to insure both groups were comparable. Subjects also worked on two behavioral tasks and provided a urine sample for catecholamine analysis. Results indicated that the TMI group's performance on both behavioral tasks was significantly poorer than the control population across all time periods. Analysis of the self-report measures showed that the TMI subjects reported more symptoms than the Frederick group and that differences were greatest during the pre-venting phase. Response to the attitude survey indicated that TMI residents were significantly more threatened by the 1979 incident, venting procedures, and the likelihood of future accidents. Analyses of urinary catecholamines revealed that both epinephrine and norepinephrine levels were higher among TMI subjects across all times particularly during the pre-venting period. These data suggest people living near TMI were not only evidencing symptoms of chronic stress related to the 1979 mishap but also experienced an acute event that further taxed their abilities to effectively manage their lives.

Dew, Bromet, Schulberg, Dunn, & Parkinson (1987) examined the effects of the restart of the undamaged TMI-1 reactor in a sample taken in 1981 of 385 women living near TMI who had delivered a child during the fourteen months preceding the accident. Follow-up response in 1985 indicated an elevated pattern of self-reported symptoms including depression, anxiety, and hostility as compared to the subjects' responses four years earlier.

The evidence of chronic stress produced by the TMI accident is unmistakable. Self-report of stress-related symptomatology, behavioral deficits, and physiological dysfunction continued to persist more than five years after the event. Davidson, Baum, and Fleming (1982) found evidence of control-related problems among nearby residents supporting the notion that technological failure represents a loss of control over the environment.

Similarities between the TMI accident and the threat posed by indoor radon suggest the likelihood that exposure to high concentrations of radioactive gas will result in psychophysiological impairment. Concern regarding the health effects of radiation exposure are common to both groups. In both situations, the public had or has a limited knowledge of the consequences of the hazards due to conflicting or insufficient information from appropriate sources. Continued operation of the power facility and the on-going decay process releasing radon from the earth's crust contribute to these two sources of chronic stress.

Although most people are aware that radon gas is harmful and may be present in their homes few are capable of deciphering the scientific literature addressing this hazard. The latency between exposure and disease onset imposes a lengthy period during which people are unsure if they will develop cancer and may begin to believe that any physical symptom represents the beginning of some form of this disease. This is a particularly important issue for health-conscious individuals. Despite their attempts to reduce personal radiation exposure (i.e. fewer medical procedures using radioactivity) and adopting healthier life styles people may find themselves frustrated or angry at being subjected to yet another health-threatening substance. The few studies investigating psychological response to indoor radon partially address these issues but indicate that it does not appear to generate psychological deficits normally associated with either natural or technological hazards. Several factors have been identified as possible contributors to the seemingly apathetic response to this environmental threat.

The radon dilemma

Natural catastrophes are generally powerful, cause visible damage to the environment or property, affect the majority of community members, but have an identifiable point where the threat is over and a sense of normalcy returns (Baum et al., 1983). People do not perceive natural threats as something they can control nor is there anyone to blame for the devastation they inflict. Radon differs in that its effects are not visible, may only affect a minority within given communities, and the consequences of exposure are the result of long-term disease development. Since radon is a naturally-occurring gas people may assume there is nothing they can do to control exposure. Lack of sufficient information permitting the public to form appropriate risk perceptions is likely to inhibit preventative action.

It was hypothesized that the radioactive nature of this gas and its cancer-inducing properties would elicit a stress response similar to technological problems such as atomic testing and nuclear power mishaps. Evidence suggests that while the dangers associated with nuclear energy and weaponry evoke substantial public concern other equally potent sources of radiation do not (Slovic, Fischhoff, & Lichtenstein, 1981). Apparently the public views radon as a limited threat similar to the risks posed by medical treatments involving radioactive substances.

Toxic waste sites are another example of technological hazards that generate public concern due to the long-term health consequences of exposure. The situation that developed in the Love Canal section of Niagara Falls, NY in the late 1970's resulted in the formation of community-action groups, governmental intervention, and the eventual prosecution of the chemical company responsible for the toxic leakage (Levine, 1982). Response to this disaster was characterized by health concerns, a loss of control, and a sense that the community was no longer a safe environment (Levine & Stone, 1986). The shared beliefs of community residents that the disposal site represented a severe health threat, confirmation from authorities that the situation was indeed life threatening, and the court's decision that the Hooker Corporation was liable for damages contributed to the public's response to the situation.

Although the health threat posed by radon is as serious as living near a toxic disposal site factors influencing peoples' response to its dangers are absent. There is evidence that people exposed to high concentrations of radon do not experience a sense of losing control over their environment (O'Keeffe, Davidson, Weiss, & Baum, 1989). Since radon is a naturally-occurring gas no one can be held responsible for its presence. Even in high-risk areas some homes test at extremely low levels reducing the likelihood that community-based organizations will gain the support necessary to affect changes in government policy or public opinion regarding this issue.

Conclusions

Radon and its progeny are the primary source of natural radiation affecting a significant portion of the world's population. The literature on occupational exposure points to an increased risk of lung cancer among people exposed to high concentrations. Although this gas and its by-products have been studied for centuries, the health risks posed by indoor radon have only recently gained public attention. The ubiquitous nature of radon, limited public knowledge of this threat, and the health-impairing consequences of prolonged exposure contribute to its dangers.

The risk communication studies lend some insight into the problems surrounding the indoor radon issue. Primarily designed to find an effective means of communicating the dangers of this gas, this research revealed that the public tends to underestimate its risks and has adopted an optimistic attitude toward the personal threat of exposure.

Evidence also suggests a lack of relationship between actual test results and appropriate action (Weinstein et al., 1987). These data indicate the public may be misinterpreting exposure risks.

Despite the finding that people exposed to hazardous or toxic substances exhibit chronic stress, research suggests that individuals whose homes are contaminated by high concentrations of radon gas or who live in areas where the potential for exposure is great do not evidence the elevated symptoms generally associated with exposure to chronic environmental hazards (O'Keeffe et al., 1989).

It was hypothesized that the radioactive and cancer-inducing properties of radon were likely to result in chronic stress response similar to the observed among victims of other radiation hazards. Examination of the literature on natural and technological disasters revealed that several critical factors influencing psychological response to these events were absent in the case of indoor radon contamination.

Symptoms of chronic stress related to radon exposure may yet appear particularly among residents of high-risk areas such as the Reading Prong but undoubtedly will not be evidenced by the majority of homeowners confronted with this problem. In the future it may be feasible to examine the potential role of chronic stress in relation to this environmental threat but to date no evidence supports the notion that public response to radon compromises psychological well-being.

Federal and state agencies continue to improve and expand programs designed to provide the public with appropriate information and home testing is becoming more wide-spread as evidenced by the availability of test kits and an increasing number of companies offering testing and remediation services. Future research attention should be directed toward the development of programs designed to communicate the dangers of radon in a way that will encourage testing and appropriate remedial action without compromising the homeowners' sense of autonomy regarding these decisions. Psychological studies assessing response to this threat will enhance the process of determining what information formats are most successful and may suggest more effective ways to target high-risk communities.

Table 1

Conversion table for radon measurement units

(adopted from Nero, 1988)

Standard International Unit	Traditional Unit
Activity (Bq)	1 Ci = 3.7×10^{10} Bq 1 pCi = .037 Bq
Concentration (Bqm^{-3})	1 pCi/l = 37 Bqm^{-3}
$EEDC^{222*}$ (Bqm^{-3})	1 WL (PAEC) = 3740 Bqm^{-3}
Exposure Rate (Bqm^{-3})	1 WLM/year = 73.9 Bqm^{-3}

* Equilibrium-Equivalent Radon Decay Product

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