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Title: Work to Save Dose: Contrasting Effective Dose Rates from Radon Exposure in Workplaces and Residences Against the Backdrop of Public and Occupational Regulatory Limits

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Work to Save Dose: Contrasting Effective Dose Rates from Radon Exposure in Workplaces and Residences against the Backdrop of Public and Occupational Regulatory Limits

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Abstract

Office workers are exposed to radon while at work and at home. Though there has been a multitude of studies reporting the measurements of radon concentrations and potential lung and effective doses associated with radon and progeny exposure in homes, similar studies on the concentrations and subsequent effective dose rates in the non-mine workplaces are lacking. Additionally, there are few, if any, comparative analyses of radon exposures at more "typical" workplace with residential exposures within the same county. The purposes of this study were to measure radon concentrations in office and residential spaces in the same county and explore the radiation dose implications. Sixty-five track-etch detectors were deployed in office spaces and 47 were deployed in residences, all within Los Alamos County, New Mexico, USA. The sampling periods for these measurements were generally about three months. The measured concentrations were used to calculate and compare effective dose rates resulting from exposure while at work and at home. Results showed that full-time office workers receive on average about 8 times greater exposure at home than while in the office (2.3 mSv yr^{-1} versus 0.3 mSv yr^{-1}). The estimated effective dose rate for a more homebound person was about 3 mSv yr^{-1}. Estimating effective doses from background radon exposure in the same county as Los Alamos National Laboratory, with thousands of "radiological workers," highlights interesting contrasts in radiation protection standards that span public and occupational settings. For example, the effective dose rate from background radon exposure in unregulated office spaces ranged up to 1.1 mSv yr^{-1}, which is similar to the 1 mSv yr^{-1} threshold for regulation of a "radiological worker," as defined in the Department of Energy regulations for occupational exposure. Additionally, the estimated average effective dose total of > 3 mSv yr^{-1} from radon background exposure in homes stands in contrast to the 0.1 mSv yr^{-1} air pathway effective public dose limit regulated by the Environmental Protection Agency for radioactive air emissions.

Introduction

Background

Radon-222 is the gaseous decay product in the naturally-occurring uranium-238 decay series, and similarly radon-220 is the decay product of naturally occurring thorium-232. As a gas, radon can build up in concentration inside structures, with the concentrations dependent on numerous factors. Exposure to the decay progeny of radon can result in significant doses, especially to radiosensitive portions of the lung, and this exposure has been implicated as a potential contributor to lung cancer (NRC 1999; NCRP 1988, 1989; Pawel and Puskin 2004). Concentrations of radon, the subsequent radiation doses to the lung, and corresponding cancer risk to residents have been extensively studied and reported (NCRP 1988; NRC 1988, 1999; UNSCEAR 2000), but much fewer studies have included measurements in workplaces other than mines (Annanmäki et al. 1996; IAEA 2003). While the epidemiology has been argued, it is universally accepted that radiation doses from radon progeny are generally the highest contributor to a person's overall dose from background radiation sources (NRC 1999; UNSCEAR 2000).

The concentrations of radon and its progeny inside structures have been shown to depend on numerous factors (NCRP 1989). Some of the key factors include the amount of uranium and thorium in the surrounding soil and building materials, atmospheric conditions, construction type (i.e., slab, basement, crawl spaces, etc.), and porosity of building or ventilation rates. The large variability in the factors listed above results in a large range in radon concentrations in homes that spans several orders-of-magnitude. Numerous homes have radon concentrations that are sufficiently high to be a public health concern. In the United States, the Environmental Protection Agency (EPA) has

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put forth guidance to assist homeowners in decisions to mitigate the risks associated with radon gas in the homes (EPA 2007).

While radon levels and associated risks have been thoroughly studied and are regulated through a single government agency, less attention has been paid to the measurement and regulatory control of radon in workplaces other than mines (Chen 2005; Lewis 2008). In the United States, such exposure is controlled through the Occupational Safety and Health Agency (OSHA) through regulation 29 CFR 1910.1096, which references Nuclear Regulatory Commission (NRC) regulation 10 CFR 20 (OSHA 1970; Nuclear Regulatory Commission 1999) and set an acceptable radon concentration threshold in the workplace at one third of a Working Level (WL), which is about 1200 Bq m^{-3}. This limit is similar to that proposed in the international documents (IAEA 2003).

Purpose and scope of the radon measurements

The workforce in the United States was about 146 million workers in November of 2008 according to U.S. Department of Labor statistics (DOL 2008). This amounts to over 200 billion person-hours per year that people spend at work, of which a large fraction of time is spent in office-like spaces. Clearly, the large amount of time people spend at work justifies assessment of indoor air quality, for radiation protection or otherwise. However, radon concentrations in work spaces other than mines are rarely made with the possible exception of schools (EPA 1993).

A radon survey of office spaces was of interest to LANL for several reasons. First, exposure to natural radon in LANL office spaces has been considered to be outside

the regulatory reach of the federal regulations and Department of Energy (DOE) orders, and thus has not been studied as extensively as occupational exposure to other radionuclides. Second, a general survey of radon concentrations in LANL workspaces was of interest to management to ensure safe environments for workers and is in keeping with the intent of OSHA requirements. Though radon in LANL offices would not be derived from enhanced radioactive sources in the selected offices, radon exposure in general office spaces has the potential to significantly impact worker risk. Up to this point, very little was known about radon concentration in the offices or in local homes, and how these measurements would compare to the wide variety of radiation protection thresholds they intersect.

Purpose and Scope of Survey

The purpose of the radon survey is to measure and document indoor radon levels across a broad spectrum of office-type workspaces and neighboring homes. The measured concentrations are compared against those measured across the United States and across the world. The results are also compared against a wide variety of radiation protection thresholds such as: 1) the action levels of 148 Bq m^{-3} (the EPA action level for public housing, 2) the ~1200 Bq m^{-3} OSHA threshold for office spaces, 3) the effective dose threshold of 1 mSv threshold for defining a radiological worker, 4) the 50 mSv occupational effective dose limit, and for public exposures, 5) the 0.1 mSv and 1 mSv limits for public exposures from the air pathway and all pathways, respectively.

Methods

Selection of buildings

The buildings selected to be included in the survey are office spaces used by Los Alamos National Laboratory employees. Most of the spaces are owned by LANL, but there are a small number of offices in buildings that are leased from other property owners. In addition, numerous measurements were made in residences, mostly within the boundaries of Los Alamos County. This provided the opportunity to compare radon concentrations at office spaces with residential homes located within the same county.

The criteria for selecting a LANL office location to be monitored included 1) being an occupied office space or common area, 2) not in a radiologically-controlled area, and 3) having easy access to retrieve the monitor. Several office buildings were multistoried and detectors were placed in these on several floors, including basements, to look for effects of radon levels due to floor levels. Offices monitored were mostly on LANL property, but several off-site locations (in the neighboring towns of Los Alamos and White Rock) that are leased by LANL were also included. Residences were selected on a volunteer basis. In all, 65 detectors were placed in LANL offices (58 on LANL property and 7 leased in the surrounding towns) and 47 were placed in residential houses. Two to three detectors were placed at the same location in two office spaces and one home as a check for measurement precision.

If locations of high concern are identified during the screening of buildings, hourly measurements of the radon concentrations will be made over the course of a few days to provide immediate measurement of radon concentrations, and follow-up actions will be determined and recommended to management. For locations above the action

level of 148 Bq m^{-3}, recommendations may be either engineering actions to reduce the radon concentration or administrative actions to limit the exposure by limiting occupancy.

Alpha track measurement techniques

Measurements of radon were primarily made using alpha-track (AT) detectors using EPA protocol (EPA 1992). These are commercially available, inexpensive, and widely accepted as the best method to collect long-term (i.e., >3 days) time-averaged radon concentrations (Nero 1986; Yeager et al. 1994). The AT detectors were deployed and the integration time for the measurements was approximately 90 days, as prescribed by the commercial supplier.

Analysis of results

Representative averages, medians, and ranges were calculated categorized by type of building (office or residential), with a further categorization for offices of LANL owned or leased. A final categorization was made for office spaces based floor level. Statistical comparisons were made between residential and office buildings and across floors using the non parametric Mann-Whitney rank sum test (Mosteller and Rourke 1973). The residential and office concentrations were also compared to regional and national radon concentrations, and finally, the concentrations were compared against national and international safety standards.

Many of the residents in Los Alamos County not only reside but also work in the same county. Therefore it was worthwhile to calculate potential doses received by office

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workers while at work and then compare that value to potential doses received while at home. In addition, potential doses are calculated for the more homebound individuals who we assume spend 85% of their time at home. For these calculations several assumptions are made. Workers are at the offices 8 hours per day, 5 days per week, and 50 weeks per year. Assuming the workers are in the office the whole time while at work, they would be in the office about 2000 work hours per year. The time spent in the home is 0.85 (8760 hrs yr^{-1} − 2000 hrs yr^{-1}) = 5746 hrs yr^{-1}, assuming that 85% of a person's time outside work is spent in the home. We assumed the homebound individual spends 0.85 * 8760 = 7446 hrs yr^{-1} at home. The dose conversion factor of 9 nSv hr^{-1} (Bq $m^{-3})^{-1}$ published by UNSCEAR was used (UNSCEAR 2000; Chen 2005; Vanmarcke 2008). An equilibrium value of 0.4 is assumed and a seasonal correction factor of 1.5 is also used (based on residences- Denman et al. 2007), though the 1.5 correction factor will probably be conservative for office spaces due to year round ventilation. The general equation used to calculated effective doses is shown in eqn. (1).

$$H_E = DCF \cdot EF \cdot C_{Rn} \cdot S_w \cdot T_E \qquad (1)$$

where:

H_E = the annual effective dose in rem,

DCF = Dose conversion factor for radon progeny [9 nSv hr^{-1} (Bq $m^{-3})^{-1}$],

C_{Rn} = Average of measured concentrations in Bq m^{-3},

EF = Equilibrium Factor (0.4),

S_w = Seasonal correction factor of 1.5 (for a start time in July),

T_E = Time of exposure, 2000 hrs for occupational exposure alone, 5746 hrs for

office worker while at home, and 7446 hrs for 85% residential exposure,

Results

Summary

Table 1 provides the summary statistics for the radon concentration measurements and a comparison of concentrations between office and residential spaces in shown in Fig. 1. The distributions of the radon concentrations for the office spaces were skewed with a median value of 18.5 Bq m^{-3} and with minimum and maximum concentrations of 11.1 and 107.3 pCi L^{-1}, respectively. The office measurements were internally consistent, with the average range for detectors placed at the same locations of 2.6 Bq m^{-3}. In contrast, the average concentrations for residential structures were about 3 times those measured for the office building. The median radon concentration for residences was 55.5 Bq m^{-3}, with minimum and maximum concentrations being 22.2 and 233.1 Bq m^{-3}, respectively. The data in the residences were also self consistent with perfect correlation in measured radon concentrations among collocated detectors.

Data for radon concentrations in office spaces were further subdivided into two categories, LANL-owned or LANL-leased buildings, and both these were compared to the concentrations measured in residences. The distributions of the measurements are shown in Figure 2. The distributions appear shifted because several of the highest radon concentrations were measured in a leased building (107.3 Bq m^{-3}), the median concentration of the LANL operated buildings was equal to that measured for the leased buildings(18.5 Bq m^{-3}), The higher measurement in the leased buildings elevated the

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average concentration to 40.7 Bq m^{-3} as compared to the 22.2 Bq m^{-3} measured in the LANL owned offices. A non-parametric Mann Whitney rank sum test was not statistically significant at the 0.05 probability level between the LANL owned and leased buildings, and both these were significantly lower than the radon concentrations found in the residential homes (Fig. 1).

Fig. 3 shows radon concentrations in office spaces categorized by floor, including measurements in basements. No statistical differences were found in radon concentrations across floors. The concentrations for the basement floors ranged from 0.5 to 33.3 Bq m^{-3}, with a median of 24.1 Bq m^{-3}. For the first floor, the median concentration was 18.5 Bq m^{-3} and ranged from 11.1 to 107.3 Bq m^{-3}. The median concentration on the second floor was 18.5 Bq m^{-3} and ranged from 14.8 to 29.6 Bq m^{-3}, and finally, the concentrations on the third floor ranged from 14.8 to 18.5 Bq m^{-3}, with a median concentration of 14.8 Bq m^{-3}. In comparison to the office concentrations, the residential median concentration was 55.5 Bq m^{-3}, with a mean of 74 Bq m^{-3} and a range from 22.2 to 233.1 pCi L^{-1}.

The concentrations in the Los Alamos residences appear to be generally in the range and near central values for radon concentrations in the United States and neighboring countries (NCRP 1984; Cohen and Shah 1991; Marcinowski et al. 1994.) and are slightly, but not statistically significantly, above the world-wide geometric mean of 44.4 Bq m^{-3} (UNSCEAR 2000). There were only a few homes in the survey that exceeded the EPA recommended threshold of 148 Bq m^{-3}.

Potential dose implications

The calculated effective dose rates (whole body), based on eqn (1), are provided in Table 1. The effective dose rate was 0.3 mSv yr^{-1} for the average office worker while at work and 1.1 mSv yr^{-1} for the maximally exposed office worker. In contrast, the average effective dose rate for these workers while at home would be about 3 mSv yr^{-1} and 9.3 mSv yr^{-1} for the maximally exposed individual. Therefore, the average office worker who lives and works in Los Alamos county will receive about nine times on average more radiation dose from radon progeny at home than in the office with a total effective dose rate of about 3.3 mSv yr^{-1}. The effective dose rate for the average homebound individual, or non office worker, who spends 85% of the time in the home would be about 3 mSv yr^{-1} with the highest dose rate of 9.3 mSv yr^{-1}.

This higher effective dose received in homes is predominantly due to the higher concentrations in homes and because people spend relatively more time in the home. The average radiation dose of the office workers from exposure to radon progeny of about 0.3 mSv yr^{-1} and maximum dose of 1.1 mSv yr^{-1} can be compared to those regulated by the Department of Energy as "radiological workers" (DOE 2007). A radiological worker, whose job involves working with radioactive materials or working around radiation producing devices, is defined as a worker who has the likely potential of exceeding 1 mSv per year. This value, while on the upper end, is within the range of the estimated effective doses for workers in LANL offices (Fig. 4). The 0.3 mSv yr^{-1} average dose and the maximum office worker dose of 1.1 mSv yr^{-1} is much lower than the occupational limits for radiological workers of 50 mSv yr^{-1} and the recommended 5-year average of 20 mSv yr^{-1} (ICRP 1990), but is closer to the average occupational dose, not

including radon exposure, that radiation workers across LANL receive, which is much less than 5 mSv yr^{-1}.

Discussion and Conclusions

Radon concentrations were measured in office spaces across LANL and in residences in the same county. None of the office spaces was above the EPA residence threshold concentration of 148 Bq m^{-3}. These lower concentrations are likely due to higher ventilation rates in the office buildings. While ventilation engineers at LANL do not know the precise air exchange rates of the many buildings surveyed, typical offices have > 2 ACH to improve indoor air quality for everything from body odor, CO_2 levels, and temperature control (Awbi 1991). In contrast, the mean residence air exchange rate is about 0.6 ACH (EPA 1997). Increased ventilation rates have direct impacts on lowering the radon concentrations in buildings by bringing outdoor air with low radon concentrations inside and flushing out the higher, concentrated air out of the building (NCRP 1984, Awbi 1991).

The potential effective dose rate for the average office worker while at work was about 0.3 mSv yr^{-1} and ranged up to 1.1 mSv yr^{-1}. These are comparable to the 1 mSv yr^{-1} dose that DOE defines as a threshold for classifying a person as being a radiation worker, though the DOE has explicitly excluded radon exposure from regulatory control unless it is a product of anthropogenically enhanced uranium, which these office exposures are not. However, the fact that many office workers have the potential to exceed the threshold of 1 mSvr yr^{-1} defined for the radiation worker suggests the value of

measurements in the workplace, not only for consistency in regulation, but to identify problematic areas.

The greatest effective doses were those received at their residences. The dose to the average office worker while at home was about 9 times the effective dose received at work, primarily because of higher concentration in the home and from the likelihood of spending more time at home. A person who does not work in an office and spends up to 85% of their time at home would receive an average effective dose about 16% higher than the office worker and would receive total from work and home of about 3 mSv yr^{-1}.

The radon concentrations in the homes in Los Alamos County were within the range of concentrations measured nationally and internationally (Cohen and Shah 1991; UNSCEAR 2000). However, because of the number of homes measured in Los Alamos County was relatively small (n = 39), and because a number of concentrations were above the 148 Bq m^{-3} level, there is reasonable justification for additional measurements in residences in the county. The higher ventilation rates in office buildings relative to the typical home were sufficient to keep radon concentrations minimized in offices and additional radon measurements are probably not warranted unless the building has a compromised ventilation system or there are extenuating circumstances. The data additionally suggest that offices in basements do not have higher concentrations than office spaces on upper floors, again as long as the ventilation in the building is functioning well.

Contrasting Radon Effective Dose Rates and Risks with Regulatory Limits

The magnitude of the effective dose rates that result from exposure to radon and its progeny, both in the office and at home, present an interesting opportunity to contrast effective dose rates from radon exposure (at work and home) with regulatory limits, both public and occupational (Figure 4). In the public regulatory arena, the EPA regulates air emissions to levels that maintain effective doses less than 0.1 mSv yr^{-1} for maximally exposed individuals (MEI) and 1 mSv yr^{-1} for public dose from all exposure pathways,. These can be compared to the average annual effective dose rate measured in Los Alamos residences of about 3 mSv and a maximum of 9.3 mSv due to radon exposure, which are orders-of magnitude higher than the levels regulated for stack emissions and the calculated MEI dose of 6 x 10^{-3} mSv from LANL emissions in 2007 (LANL 2007). When one considers epidemiological evidence of elevated lung cancer risk down to 100 Bq m^{-3} for long-term exposures to radon and progeny (Darby et al. 2005, Krewski et al. 2005, Appleton 2007), this comparison argues for continued surveillance of radon in homes and effective mitigation at the 148 Bq m^{-3} level.

For comparison to occupational exposure, a reasonable likelihood of receiving 1.0 mSv in a year while at work is the threshold for identifying occupational "radiation workers." This definition is used to document and promote radiological controls to minimize dose for workers. This study shows that "typical" office workers receive annual effective doses that are similar to that specified in this definition. Though radon exposure is specifically exempt from occupational control unless it is artificially enhanced, OSHA appears to regulate radon exposure through a concentration limit of 1,110 Bq m^{-3}. Breathing radon and its progeny at this concentration for a 2000 hour work year could result in effective dose rates in the range of 8 mSv yr^{-1}. This is about two

times higher than the effective dose rate for a resident exposure with a radon concentration of 148 Bq m^{-3}, which translates to 4 mSv yr^{-1}. Though none of the office spaces in this study had concentrations exceeding 148 Bq m^{-3}, the OSHA regulations, for office exposure are high relative to EPA standards though they are in the range of international recommendations (ICRP 1993, IAEA 2003).

Finally, the Health Physics Society (HPS) issued a position statement on indoor radon exposure in 1990 (HPS 1990). Though this position paper encourages minimizing exposure to radon and its radioactive progeny, it goes on to suggest that the EPA should review its emphasis on using 148 Bq m^{-3} as an action level, and that the EPA should move toward prompt identification of indoor occupied areas with high radon concentrations "(i.e., tens of pCi/L and greater)" for prompt mitigation. Figure 4 shows that effective dose from tens of pCi/L (740 Bq m^{-3} (20 pCi/l) was in this example) would results in an effective dose rate of about 20 mSv yr^{-1}. This effective dose rate is about 5 times the current EPA recommendations at 148 Bq m^{-3}, and about 7 times higher than the reported levels (100 Bq m^{-3}) where epidemiological evidence of elevated lung cancer risk for long-term exposures to radon and progeny has been reported (Darby et al. 2005, Krewski et al. 2005, Appleton 2007). This analysis suggests the HPS recommendations are disproportionately high relative to national and international recommendations (EPA, ICRP 1993) and more recent epidemiological research.

The value and purpose of these comparisons are solely to elevate them into the discussion of regulations in context of the background radiation levels and to promote consistency. The data in Figure 4 illustrates that there radiation dose levels are not just based on radiation dose levels alone, but consider multifaceted factors, which combined

are used to determine radiation protection goals and regulatory limits. Clearly though, radon and its radioactive decay progeny contribute the greatest amount of our background radiation dose, both at home and in the office. As promoted, the health physicist's job is to manage the beneficial use of ionizing radiation while protecting workers and the public from potential hazards. Thus, concern for public health, if even partially based on doses from radiation, should focus a proportionate level of attention on radon exposure, both at home and in the office.

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List of Figures

Figure 1. A comparison of the distributions of radon concentrations between LANL office spaces and residential homes in Los Alamos County. The boxes represent 25%-75% of the values and whiskers represent the range of 95% of the values. Outliers are represented by the dots outside the range of 95%. Median concentrations are represented by the line inside the boxes.

Figure 2. Distributions of radon concentrations by building type and owner. The boxes represent 25%-75% of the values and whiskers represent the range of 95% of the values. Outliers are represented by the dots outside the range of 95%. Median concentrations are represented by the line inside the boxes. Not enough measurements were made for the LANL leased buildings to determine whiskers.

Figure 3. Distributions of radon concentrations in office building categorized by floor. The boxes represent 25%-75% of the values and whiskers represent the range of 95% of the values. Outliers are represented by the dots outside the range if 95%. Median concentrations are represented by the line inside the boxes. Not enough measurements were made for the basement, second and third floors to determine whiskers.

Figure 4. Annual effective dose rates for different radon concentrations and exposure scenarios contrasted against various radiation protection thresholds.

Table 1. Summary statistics for radon concentrations in the office spaces and homes are provided at the top of the table, and the associated effective dose rates are provided at the bottom of the table.

Radon Concentrations (Bq m^{-3})			
Location	Mean	Median	Maximum
Office Spaces	24.3	18.5	107.3
Homes	75.0	55.5	233.1

Effective Dose Rates (mSv yr^{-1})				
Exposure Scenario	Exposure time (hr)	Mean	Median	Maximum
Office work only	2000	0.3	0.2	1.1
Office worker while at home	5746	2.3	1.7	7.2
Homebound Individual	7446	3.0	2.2	9.3

Figure1. A comparison of the distributions of radon concentrations between all LANL
office spaces and residential homes in Los Alamos County. The boxes represent 25%-
75% of the values and whiskers represent the range of 95% of the values. Outliers are
represented by the dots outside the range if 95%. Median concentrations are represented
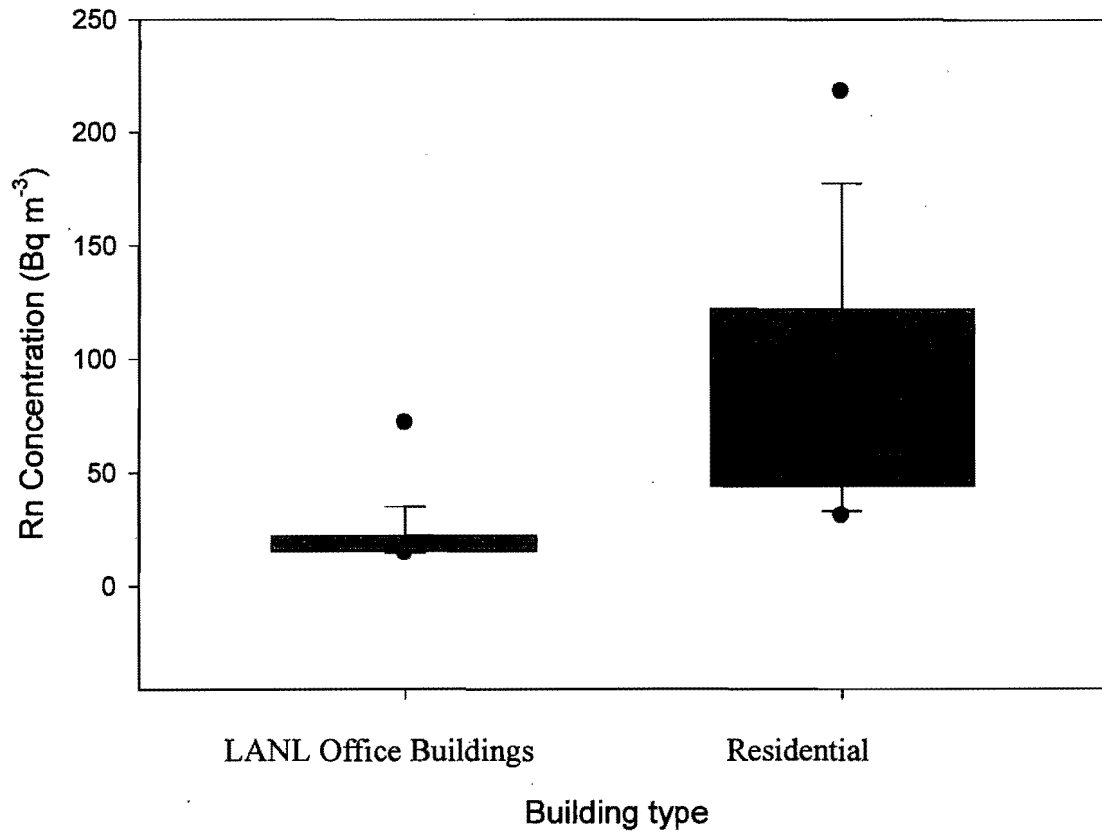by the line inside the boxes.

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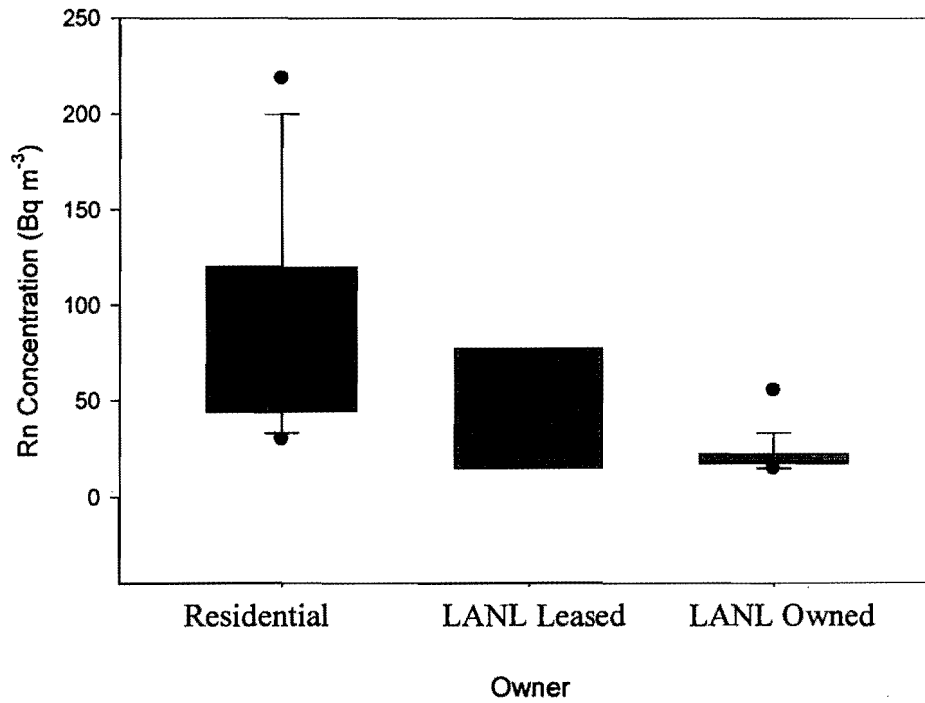
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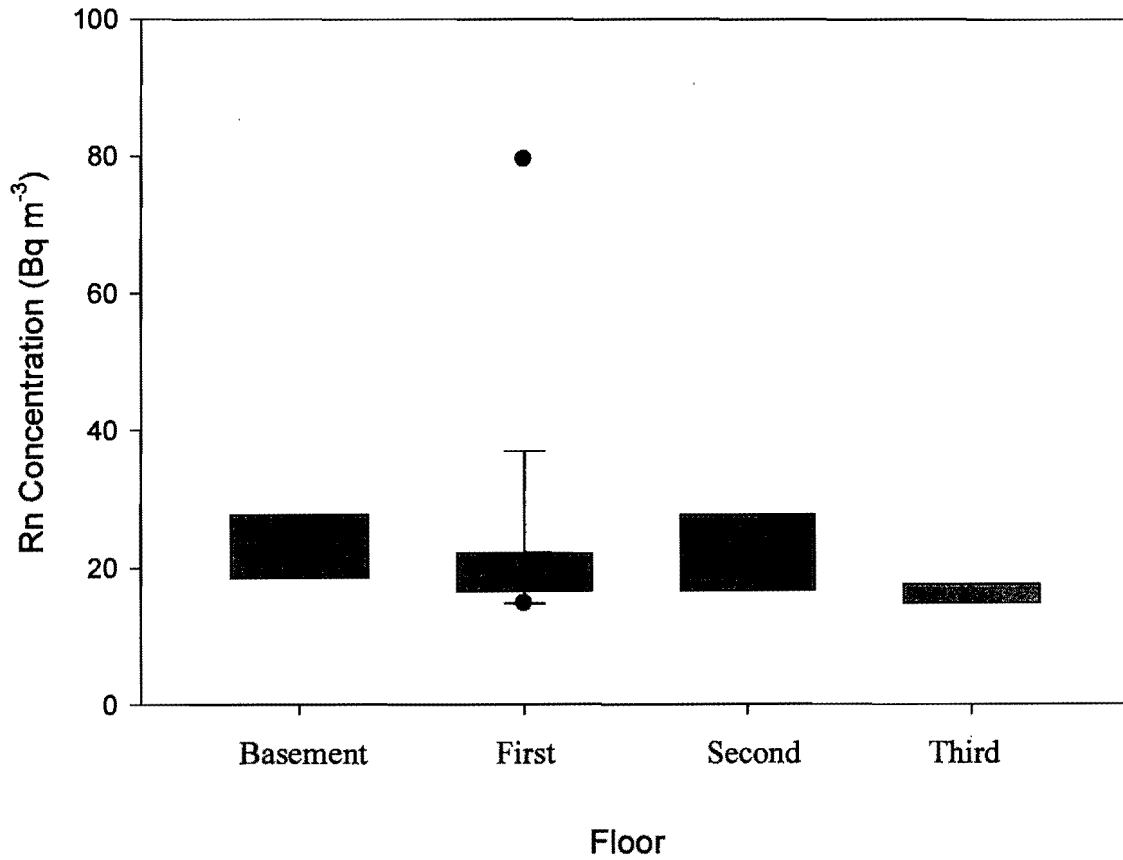
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