Radon in Institutional Buildings: The Impacts of Conservation Strategies

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The University of Minnesota has implemented fan scheduling as an energy conservation strategy for a building energy efficiency program affecting over 200 campus buildings. This paper describes increased radon levels in spaces where HVAC fan operation has been curtailed and presents mechanisms describing why this increase has occurred.

We have conducted a radon survey of institutional buildings on this campus having large earth contact footprints. While radon concentrations in Minnesota residences are commonly higher than the EPA guideline of 150 Bq/m^3 (4pCi/L), a three month deployment of etched-track detectors found no occupied spaces in the sampled set of buildings containing radon levels in excess of this EPA guideline. However, continuous radon measurements have indicated large changes in radon levels between occupied and unoccupied times when HVAC systems are cycled on and off in some of the mechanically ventilated and underground buildings.

Building pressure measurements indicate that pressurizing an interior space relative to the soil inhibits the transport of radon into the space. When an HVAC system is turned off, other HVAC systems (from neighboring air handling zones) and the natural stack effect become the dominant pressure sources in that air handling zone. This may create negative pressure differences across the building shell on the lower levels. The combination of increased radon infiltration and decreased dilution by ventilation has been observed to cause large increases in radon levels over short periods of time. Computer modelling of ventilation schemes in selected University buildings is currently being conducted to understand these processes more clearly.

Introduction

There has been extensive research regarding radon in residences and schools in recent years; however, there is still relatively little information regarding radon in large buildings (SC&A, Inc. 1990). The University of Minnesota Building Radon Study aims at understanding radon concentrations and dynamics in large institutional or commercial buildings. To understand radon behavior in buildings we must understand how radon concentrations vary in the same geographical region in different building types and study the impact of ventilation systems on radon and radon progeny concentrations. In this study we have (1) completed two radon concentration surveys in a sample of the 200 plus institutional buildings at the University of Minnesota; and have (2) compared radon dynamics in underground, mechanically ventilated, and naturally ventilated buildings chosen from the first radon concentration survey results.

For indoor radon concentrations to become high enough to be a problem, a radon source, an entry path, and a driving force are all required. A few recent large building studies have focussed on pressure driven processes (caused by HVAC systems and stack effects) and their effect on radon entry into buildings (Boyd, Inge, and MacWaters 1990; SC&A, Inc. 1990; Saum and Messing 1991). Recent air pressure distribution studies have shown that the impact of HVAC operation on radon entry processes in schools and other large buildings is important and can vary considerably within a building (Sinclair et al. 1990). Furthermore, diurnal variations in radon levels due to occupancy and HVAC systems are not the same for each building, and different types of HVAC systems have different effects. Turner et al. (1990) discuss different HVAC systems and their effects on radon entry into buildings. Potentially important measurements accompanying radon concentration measurements include: operational status of HVAC system, weather (outdoor temperature, precipitation, wind, barometric pressure, etc.), and occupied or unoccupied status (open or closed doors and windows) (Leovic 1990; Sinclair et al. 1990).

The highest indoor radon levels are usually found in ground contact areas. Radon levels in the upper levels of a building will be determined by the air handling systems, by diffusion, and by direct paths to the sub-slab environment such as telephone and electrical conduits (Boyd and Inge 1991). However, radon levels in buildings do not appear to be direct functions of radon levels in surrounding soil since research has not revealed a direct correlation between soil radon or radium concentrations and radon levels in large buildings (Llewellyn 1991).

University of Minnesota Building Radon Levels

The University of Minnesota is located in Hennepin County in the southeastern part of the state. The EPA considers Hennepin county a zone 1 county, having the highest risk of elevated indoor radon levels. Zone 1 counties have a predicted residential average indoor screening measurement level greater than 150 Bq/m^3 (4 pCi/L) (EPA 1993). The potential for high residential levels provided an impetus to measure radon concentrations in different types of institutional buildings on the University campus.

An initial long term radon measurement survey (phase I) was completed with 817 etched-track detectors covering approximately 130,000 square meters (1.4 million square feet) in 26 buildings (on a campus composed of 200 plus buildings). These measurements took place October 1992 through December 1992. We sampled a selection of University buildings from each of the following groups: (1) naturally ventilated buildings; (2) underground (mechanically ventilated) buildings; and (3) above grade mechanically ventilated buildings having large earth contact "footprints."

Analysis of the three-month etched-track measurement data has revealed no radon concentrations in occupied spaces above 150 Bq/m^3 (4 pCi/L). Figure 1 shows phase I data represented on a log-probability plot (if data can be represented by a log-normal distribution, they will fall on a straight line in this representation). Note: Three month etched-track radon measurement values below 1100 Bq/m^3 - days (30 pCi/L - days) are reported as 1100 Bq/m^3 - days (30 pCi/L - days) as this is the lower detection limit of these etched-track detectors. Due to exposure lengths of around 90 days for the first set of measurements, minimum values have been reported as 12 Bq/m^3 (0.3 pCi/L).

An analysis of the phase I measurement data reveals a geometric mean of 16 Bq/m^3 (0.44 pCi/L) with a geometric standard deviation of 2.9 for the entire sample set. Fewer than 4 percent of the measured values were above 150 Bq/m^3 (4 pCi/L). Locations where radon concentrations exceeded 150 Bq/m^3 (4 pCi/L) are either controlled access areas which are restricted due to the presence of asbestos or unoccupied rooms such as storage areas and mechanical spaces. A breakdown of the data into the three building types (Table 1) reveals naturally ventilated buildings with a geometric mean of 24 Bq/m^3 (0.65 pCi/L), mechanically ventilated buildings with a geometric

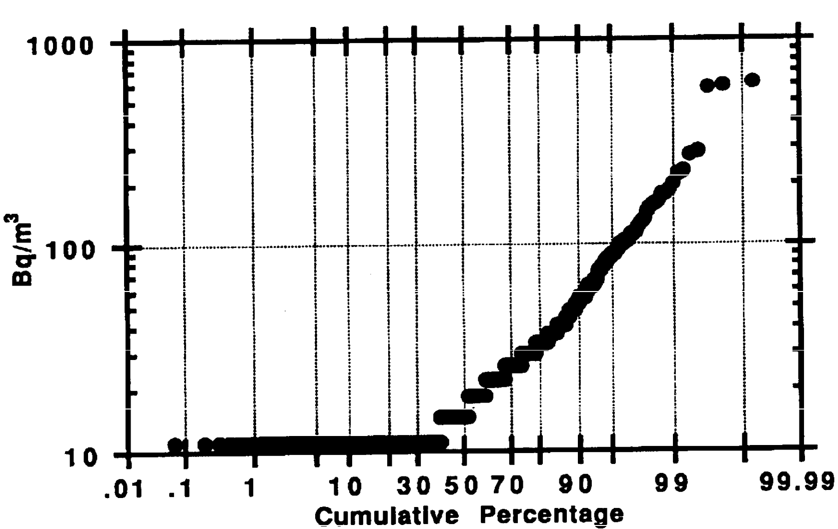

Figure 1. Phase I Etched-Track Screening Measurement Data (Note: lower detection limit of 12 Bq/m^3)

Table 1. Phase I Etched-Track Measurements

Phase 1	Geom. Mean Bq/m^3	Geom. Stand. Dev.	Number of Detectors
All	16.1	2.9	746
Natural	23.9	2.8	139
Mechanical	12.8	2.3	427
Underground	19.6	1.8	160

mean of 13 Bq/m^3 (0.35 pCi/L), and underground buildings with a geometric mean of 20 Bq/m^3 (0.53 pCi/L). In order to determine the geometric means and geometric standard deviations of the data sets, the authors assumed that the data collected that are below the detectable limit of the etched-track detectors are part of the same log-normal distribution as the remainder of the data (Travis and Land 1990).

Continuous radon measurements were made during the same time period as the phase I etched-track measurements in selected buildings. These continuous radon measurements have taken place in 51 different locations spanning 28 buildings (Grimsrud, Hadlich, and Krafthefer 1994). Further continuous measurements have been performed in buildings chosen from the phase I etched-track measurement sample results. Of particular interest are the continuous radon data sets from Wulling Hall, Biological Sciences, and Civil and Mineral Engineering buildings. These buildings represent naturally ventilated, mechanically ventilated and underground mechanically ventilated buildings, respectively. Continuous radon measurements conducted in these buildings (discussed herein) were made on levels below grade.

Commercially available radon monitors were used for the continuous radon measurements. These continuous radon monitors sample radon gas concentrations using a passive radon chamber design and solid state electronic detection. These monitors provide measurements averaged over a four hour interval. Additional building parameters which were measured include: building HVAC fan schedules, ventilation rates, weather data and building pressure measurements.

Building HVAC fan schedules have been put in place by the University Building Energy Efficiency Project (UBEEP) to improve the energy efficiency of campus buildings. HVAC systems are controlled by the Building Systems Automation Center (BSAC). HVAC fan operation schedules have been verified through BSAC and through independent monitoring of individual HVAC units. Weather data have been collected from the National Weather Service and the University of Minnesota, St. Paul campus weather stations. Pressure data have been collected with commercially available pressure monitors and data loggers (Grimsrud, Hadlich, and Krafthefer 1994).

The University Building Energy Efficiency Project Fan Schedule Policy

As an important energy saving and cost cutting measure, the University Building Energy Efficiency Project (UBEEP), together with Facilities Management and the Department of Environmental Health and Safety, started implementing a fan control policy during the winter of 1991. This policy conserves University resources by not operating the major air handling fans in Twin Cities Campus buildings when buildings are unoccupied.

To date fan schedules, which have been implemented in 48 buildings, save the University $920,000 annually (measured value). The impact of fan scheduling in a group of buildings can be seen in Figure 2. This figure shows the ratio of annual energy use after implementation of the fan policy to that before, stated in percent of the pre-scheduling value. Also shown is the energy use in a group of buildings, whose fans were not scheduled, that act as controls. The scheduled buildings show a total reduction in energy use of 18%; the control buildings show a 6% increase in energy use during the same time period.

Not all of the University's Twin Cities Campus buildings are good candidates for fan scheduling. Some older buildings have no mechanical ventilation systems, and some building mechanical systems are not part of the University's automation system that permits control of the buildings from a central location. Also, some buildings contain undersized fan units which need to run continuously for thermal control. Other buildings require twenty-four hour ventilation. Such buildings include those containing laboratories with fume hoods and those containing heat sources such as computer labs. Furthermore, since large buildings are broken up into multiple air handling zones, some buildings may be only partially served by time-of-day scheduled fans.

The Department of Environmental Health and Safety has been an important element in the fan scheduling program by helping to evaluate any health and safety problems for building occupants. The official fan scheduling policy is as follows:

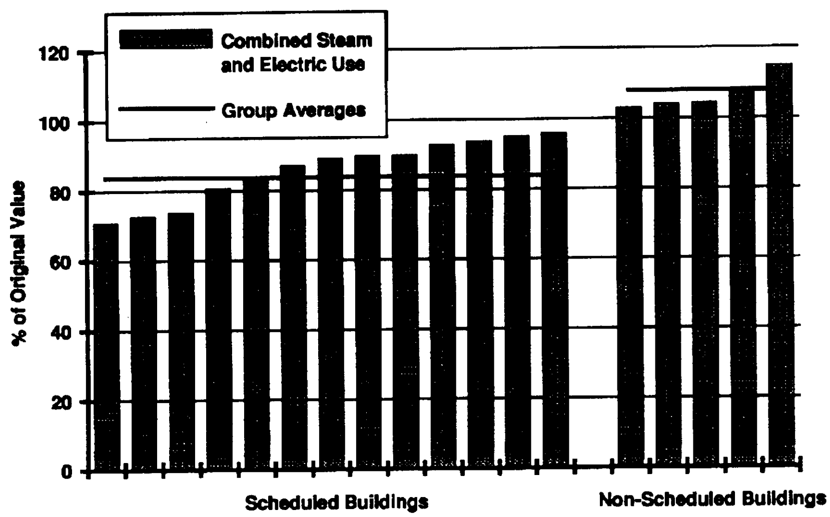

Figure 2. Comparison of Before-After Energy Use in Building Sample Due to HVAC Fan Scheduling

> The operation of major air handling fans in University buildings shall be determined on a building by building basis. The schedule for each fan shall be based on the occupancy profile and use of the area served by each particular fan.

Measured annual savings from this policy (from building meters) is $920,000. Engineering calculations predicted $930,000 in savings. If compliance with the policy were perfect, the measured savings would be $1,230,000 for the same time period (i.e. measured compliance with the policy was 76%).

The Effects of Fan Scheduling on Radon Levels

Continuous radon measurements have been concentrated in three buildings. These buildings encompass the three building types important to this study: naturally ventilated (Wulling Hall), mechanically ventilated (Biological Sciences), and underground (Civil and Mineral Engineering).

Wulling Hall is a four story (three above grade), 2,800 gross square meter (30,000 gross square feet), naturally ventilated building constructed in 1892. A continuous radon monitor has been collecting data in a basement mechanical room of Wulling Hall since October 1992. Radon levels are much higher during the cold winter months than during the warm summer months. The inverse relationship between outside air temperature and radon levels in this small, naturally ventilated building can be seen clearly in Figure 3.

The seasonal effects on indoor radon levels are much different from the daily/weekly cycles which we have seen in the larger mechanically ventilated buildings with time-of-day scheduled fan units. Data from Biological Sciences and Civil and Mineral Engineering buildings show the effects of daily fan scheduling on indoor radon levels (Grimsrud, Hadlich, and Krafthefer 1994). In this paper we will focus on Biological Sciences building. The effects of fan scheduling are similar in both of these large mechanically ventilated buildings.

Biological Sciences is a nine level (eight above grade), 19,000 gross square meter (200,000 gross square feet), mechanically ventilated building constructed in 1969. The basement is a 1,800 gross square meter (19,000 gross square foot) area whose occupied space is served entirely by HVAC fan unit S-17. This is the only space served by this fan unit. The only unoccupied basement rooms (mechanical rooms 32, 50, 74 and 76) are each served by their own supply and exhaust fan units which operate twenty-four hours per day. Figure 4 is the basement plan.

Fan unit S-17 is scheduled ON from 7:00 AM to 7:00 PM Monday through Friday, It is OFF the remainder of the time. In room 64, a classroom served directly by the scheduled fan S-17, there is a direct relationship between the times the fan is ON/OFF and the times radon levels are LOW/HIGH. Graphical representation of this data is shown in Figure 5, When the fan is ON, radon levels in room 64 decrease to near 0 Bq/m^3. When the fan is turned OFF at night, radon levels increase until the next morning. This effect is especially pronounced on weekends when the fan is OFF continuously for 60 hours. The three month etched-track detector result for room 64 was 81 Bq/m^3 (2.2 pCi/L).

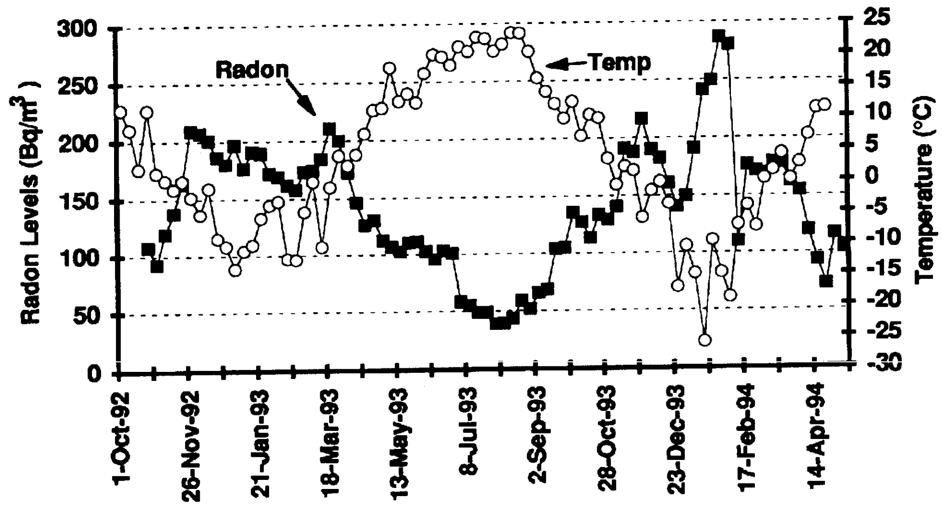

Figure 3. Average Weekly Radon Levels for Wulling Hall Room 25 and Outside Air Temperature

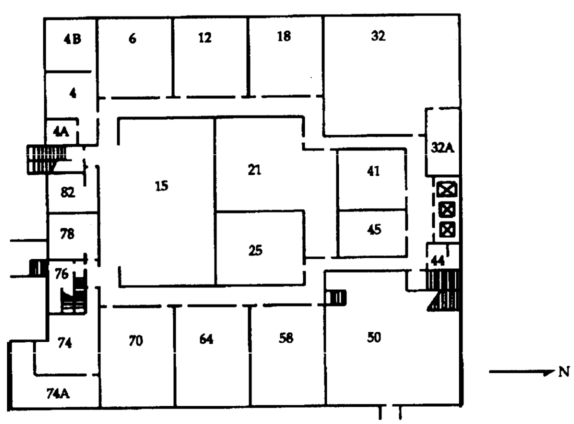

Figure 4. Floor Plan for Biological Sciences Building Basement

After observing both seasonal (Wulling Hall) and daily (Biological Sciences) variations in radon concentrations, a second set of long term etched-track measurements was undertaken. Measurements were made in a sample of sites showing the highest concentrations in the phase I survey. The second set of measurements (phase II measurements) were also planned for the coldest months of the year, so we expected that phase II measurements would show higher radon concentrations. We also chose sampling sites located in buildings in which fan schedules had been implemented to examine the impact that turning central HVAC systems off (during unoccupied hours) would have on average concentrations.

Phase II measurements were completed as a subset of the phase I measurements with 365 etched-track detectors covering 23,000 square meters (250,000 square feet) in 14 buildings. This set of measurements took place January 1994 through March 1994, the coldest months of the year in this climate, as opposed to the October 1992 through December 1992 deployment for the phase I measurement set. The geometric mean and geometric standard deviation from the second set of measurements can be seen in Table 2. Since the phase II measurements were a subset of the phase I measurements, only those measurement locations common to both sets are compared (the comparison phase I set is called phase I subset). The phase I subset data are included in Table 2 as well.

The results show a small increase in the geometric mean between the two data sets of 7 Bq/m^3 (0.2 pCi/L). The differences in geometric means between the phase I and phase II measurement sets are statistically significant at the 0.05 level when comparing both data sets (all), the measurements in mechanically ventilated buildings (mechanical) and the measurements in underground buildings (undergnd.) as shown in Table 2. The difference is not significant in naturally ventilated buildings. The increase in indoor radon concentrations could be due to two factors which had the greatest opportunities to affect the measurement sets, changes in stack effect strength due to varying outdoor air temperatures and fan scheduling changes in sampled buildings.

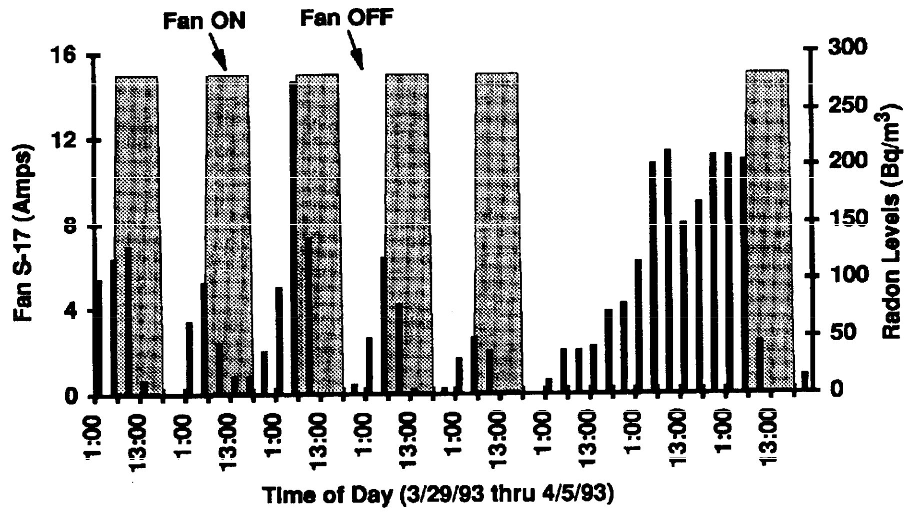

Figure 5. Biological Sciences Room 64 Radon Levels and HVAC Fan Unit S-17 Activity

Outdoor air temperatures varied between the phase I sample set and the phase II sample set. As can be verified in Figure 3, the average outdoor temperature from October 1 through December 31, 1992, during the first set of etched-track measurements, was 0.2°C (32. 3°F). The average outdoor temperature was only -7.9°C (17.7°F) from January 1, 1994 through March 31, 1994, during the second etched-track deployment. This temperature change affects stack effect pressures which could have changed radon entry in the measured ground contact spaces. The 8°C decrease in average temperature would increase the stack effect 0.35 Pascals per meter of building height in each building.

The second factor which may have affected indoor radon levels is changes in the fan schedules in measured buildings. Therefore, in Table 2 we have further analyzed both data sets and give the geometric means and geometric standard deviations for each of the three building types sampled in this study. As one would expect, radon levels are higher in naturally ventilated buildings due to smaller mixing and ventilation volumes in below grade, ground contact areas and pressurization of building volumes due to operation of the HVAC systems in mechanically ventilated buildings. Interestingly, the ground contact areas in mechanically ventilated above ground buildings showed mean values similar to the mechanically ventilated underground building. Three buildings had fan scheduling implemented between the times the two etched-track measurement surveys were performed. Data for these buildings are shown on Table 2 along with data for buildings scheduled during both measurement sets.

All of the geometric mean concentrations for individual buildings increased between the phase I and phase II measurements. The differences in geometric means are statistically significant for all but the Borlaug Hall tests. One expects a moderate increase in average concentrations because of the colder temperatures during the phase II measurements. One might expect, however, that the increases would be larger in buildings that also had fan schedules implemented between phases I and II. Qualitatively this does not appear to be the case.

Pressure Driven Changes in Radon Levels

The mechanism for radon entry into buildings (pressure driven flow) is well understood. Diffusion also contributes to radon entry, and can be detected in buildings with low concentrations. However, it is often difficult to unravel the various terms contributing to the pressures which dominate radon entry. In this set of buildings, one has wind and temperature differences contributing to weather driven pressures, plus a large contribution from HVAC operation.

Pressure measurements completed in Biological Sciences indicate large negative pressure differences between the basement and outside when HVAC fan unit S-17 (serving the occupied basement spaces) is cycled off at night. Figure 6 shows these pressure measurement data along with the radon concentrations taken in room 64.

Pressure data were taken between the basement hallway and outdoors (outside air). These measurements were made using a pressure monitor (a micro air flow sensor modified for pressure sensing) between the outside of the building and a below grade interior location and a

Table 2. Geometric Mean and Geometric Standard Deviation Table for Various Building Sample Sets

Group	Phase 2 (Subset)	Geom. Mean Bq/m^3 (pCi/L)	Geom. Stand. Dev.	Number of Detectors	Comparison Group	Significant Difference
1	All	18 (0.49)	2.5	281	5	yes
2	Natural	40 (1.080	2.4	68	6	no
3	Mechanical	14 (0.39)	2.2	129	7	yes
4	Undergnd.	16 (0.44)	2.1	84	8	yes
	Phase 2					
5	All	26 (0.69)	2.4	281	1	yes
6	Natural	37 (1.00)	2.3	68	2	no
7	Mechanical	22 (0.60)	2.3	129	3	yes
8	Undergnd.	16 (0.62)	2.1	84	4	yes
	Scheduled for Phase II					
9	CME Phase I	16 (0.43)	2.1	84	10	yes
10	CME Phase II	24 (0.64)	2.2	84	9	yes
11	OMWL I	15 (0.40)	1.6	54	12	yes
12	OMWL II	19 (0.51)	1.6	54	11	yes
13	Borlaug I	14 (0.37)	2.5	26	14	no
14	Borlaug II	19 (0.51)	2.4	26	13	no
	Scheduled for Phases I & II					
15	Rarig I	10 (0.26)	3.0	23	16	yes
16	Rarig II	26 (0.71)	2.1	23	15	yes
17	BioSci I	29 (0.80)	1.9	17	18	yes
18	BioSci II	63 (1.70)	1.6	17	17	yes

pressure monitor (a digital pressure sensing gauge) between the inside location and the building's basement hallway. We are inferring that the outdoor air pressure is related to the pressure in the soil since we are not able to make soil pressure measurements. The basement floor is approximately three meters (10 feet) below grade.

A negative measured pressure indicates the hallway at a lower pressure than outdoors. Room 64 is a classroom in the basement of the Biological Sciences building (Figure 4). It is important to note that while the fan is in operation, 7:00 AM to 7:00 PM, room 64 is at a higher pressure than the hallway. This pressure difference typically ranges between 4 and 5 Pascals. At night, when the fan is off, the pressure difference between room 64 and the hallway is negligible (0 to 0.2 Pascals).

Figure 6 suggests that when the fan unit is OFF, the large negative pressure in the basement draws radon rich soil gas inside through soil contact openings in the building's below grade shell. Conversely, when the fan unit is operating during occupied hours, the basement's positive pressure relative to outside inhibits radon gas from entering the basement; the fan unit also supplies some percentage of outside air, thus lowering indoor radon concentrations.

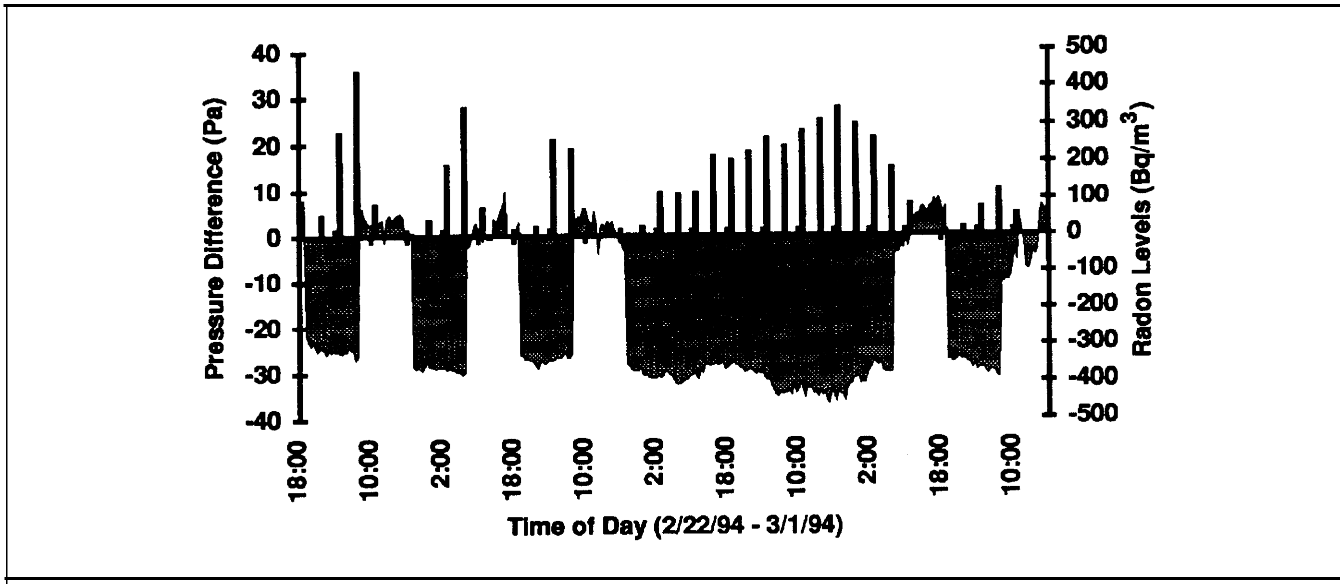

Figure 6. Biological Sciences Room 64 Radon Levels and Basement vs. Outside Pressure Difference

We believe the large pressure difference between the basement and the outdoors when fan unit S-17 is OFF is driven by the natural stack effect and neighboring HVAC systems operating 24 hours per day. Unlike Wulling Hall (a non-mechanical building whose pressure differences would be dominated by wind and the natural stack effect) the larger, mechanically ventilated Biological Sciences building will have pressure gradients driven by HVAC fan units. Recent pressure measurements indicate that the stack effect contributed about 20 Pascals to the negative pressures shown in Figure 6. Therefore, the neighboring HVAC systems, running 24 hours per day, contribute about 10 Pascals to the negative pressure.

Computer modeling of ventilation schemes in selected University buildings is currently being conducted to understand these processes more clearly. The building structure for selected zones of the Biological Sciences building and the Civil and Mineral Engineering building have been entered into the simulation package. The air flow conditions are currently being entered into the data base and preliminary runs using selected flow parameters are to be conducted.

Summary

Long term radon measurements conducted in University of Minnesota campus buildings have revealed low indoor levels. All measurements in occupied spaces on campus have resulted in long term average values lower than the EPA guideline of 150 Bq/m^3 (4 pCi/L). The geometric mean radon concentrations for naturally ventilated buildings are higher than those for mechanically ventilated and underground buildings. Mechanically ventilated and underground buildings show similar mean values.

Energy efficiency of the campus is improved if air handling systems are turned off when buildings are unoccupied. Thus, the University of Minnesota has implemented fan scheduling as an energy conservation measure in 48 buildings saving the University $920,000 annually. At this level of savings the incentive to retain the policy is strong.

Short term radon measurements show increases in radon levels when air handlers are off. These increases appear to track pressure changes that accompany changes in operation of the air handlers. Analysis of three-month etched-track samples in buildings when fan policies have been implemented show a small increase in average concentrations. However, even though these buildings have shown slightly higher geometric mean radon concentrations, etched-track measurements have revealed no long term radon concentrations above 150 Bq/m^3 (4 pCi/L) in occupied spaces.

Acknowledgments

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References

Boyd, M., T. Inge, and J. MacWaters. 1990. "Measuring Radon in the Workplace." The 1990 *International Symposium on Radon and Radon Reduction Technology*, Volume 4, Preprints, Paper D-IX-6. Environmental Protection Agency, Atlanta, GA.

Boyd, M. and T. Inge. 1991. "Radon in Federal Buildings." *Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology*, Volume 2, pp. 6-23 - 6-30. Environmental Protection Agency, Philadelphia, PA.

Environmental Protection Agency. 1993. *EPA Map of Radon Zones.* EPA-402-R-93-071, U.S. Environmental Protection Agency, Washington, D.C.

Grimsrud, D. T., D.E. Hadlich, B. Krafthefer. 1994. *University of Minnesota Radon Building Study: Quantifying the Effects of HVAC Ventilation Systems on Radon Concentrations: Final Report.* Final report to the Minnesota Department of Health, July 1994.

Leovic, K. W. 1990. *Summary of EPA's Radon Reduction Research in Schools During 1989-90.* EPA-60018-90-072. US-EPA Office of Research and Development Air and Energy Engineering Research Laboratory, Research Triangle Park, NC.

Llewellyn, R.A. 1991. "Radon in Large Buildings: Preconstruction Soil Radon Surveys." *Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology*, Volume 4, pp. P10-15 - P10-25. Environmental Protection Agency, Philadelphia, PA.

Saum, D., and M. Messing. 1991. "Radon Diagnosis in a Large Commercial Office Building." *Proceedings of the 1991 International Symposium on Radon and Radon Reduction Technology*, Volume 2, pp. 10-105- 10-115. Environmental Protection Agency, Philadelphia, PA.

SC&A, Inc. 1990. *Proceedings of the 1990 Forum on Radon Prevention in Large Buildings* - Draft. McLean, VA.

Sinclair, L. D., C.S. Dudney, D.L. Wilson, R.J. Saultz. 1990. "Air Pressure Distribution and Radon Entry Processes in East Tennessee Schools." *The 1990 International Symposium on Radon and Radon Reduction Technology:* Volume 5, Preprints, Paper IX-5. Environmental Protection Agency, Atlanta, GA.

Travis, C. C., M. L. Land. 1990. "Estimating the Mean of Data Sets with Nondetectable Values." *Environ. Sci. Technol.* 24 (7): 961-962.

Turner, W. A., K.W. Leovic, A.B. Craig. 1990. "The Effects of HVAC System Design and Operation on Radon Entry Into School Buildings." *The 1990 International Symposium on Radon and Radon Reduction Technology,* Volume 5, Preprints, Paper IX-3. Environmental Protection Agency, Atlanta, GA.