EXTENDED HEATING, VENTILATING AND AIR CONDITIONING DIAGNOSTICS IN SCHOOLS IN MAINE

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ABSTRACT

An extensive effort to assess the effects of HVAC system operation on the indoor radon levels was conducted. Many schools in the EPA School Evaluation Program have been found to have disabled or malfunctioning outside air on the ventilation system. The outside air in the Maine schools had been disabled. This condition was corrected using professional HVAC and control contractors. Measurements were made of radon levels, total and outside airflows, pressure differentials across the building shell and sub-slab radon levels. Exhaust ventilation, built up air handlers and unit ventilators were investigated. A heat recovery ventilator was added to a room that had leaky window sash as the outside air supply for a passive roof vent system. The passive vents have been blocked off.

16

INTRODUCTION

In August, 1990, extended radon diagnostics were performed in two Maine Schools. The purpose was to assess the effects of returning the heating, ventilation and air conditioning (HVAC) system to the original operating specifications would have on indoor radon levels. This effort was part of the 1990 School Evaluation Program[1]. Measurements of radon, air pressure differences across the building shell and carbon dioxide levels[2] were made to help judge the system changes. While a large amount of data was collected, these measurements were open to a number of interpretations because the radon levels found in the schoolrooms during the extended diagnostics week were much lower than were found by the screening measurements made in April, 1990.

In December of 1990, followup measurements were made at the Gray High School and Russell Elementary School in Gray, Maine. The purpose of these measurements was to provide a basis upon which to judge the effect of the HVAC improvements on radon levels, air pressure relationships and carbon dioxide concentrations in occupied rooms. December was a good time to make this assessment because it represented a worst case scenario. That is, the outside air dampers in the unit ventilators and built up air handlers were closed to minimum and the competing stack effect was at the maximum. Both conditions are the result of the low outdoor temperatures found in Maine at that time of year. The measurements were carried out by a team of people. The team included : Gene Fisher and Bob Thompson USEPA Office of Radiation Programs, Washington, D.C. ; Bruce Harris, USEPA, AEERL, Radon Branch, Research Triangle Park, NC; Bill Turner, Fred McKnight, H.L. Turner Group, Harrison, Maine; Terry Brennan, Camroden Associates, Oriskany, New York; and Gene Moreau, Bob Stillwell, Maine Department of Health Engineering, Augusta, Maine.

A special note of thanks is extended to the Maine Department of Health for their active participation in this evaluation.

PROCEDURE

The evaluation consisted of a visual inspection and measurement of key performance related variables in the Gray High School and the Russell Elementary School.

An extensive set of measurements were made in the High School. The following measurements were made :

continuous radon (pulse ionization and semi-conductor)
continuous air pressure differences (variable capacitance)
carbon dioxide survey (infrared spectrometer)

Continuous radon monitors were placed in rooms 2, 7, 17, 31, 32, 33, the Guidance Office and the Conference Room. The monitors used were eight Honeywell continuous radon monitors and two femto-Tech continuous radon monitors (room 33 and room 7). The Honeywell units provide mean radon levels for 4 hour intervals and the femto-Techs for 1 hour intervals. Air pressure differences were monitored across the floor slab in rooms, 33, 7, the Conference Room and the Guidance Office. Variable capacitance chambers manufactured by Setra were connected to a data logger provided by EPA to collect pressure difference data. Calibration curves were made for each sensor using a micromanometer. Ventilation rates, outside air fractions and ventilation effectiveness were estimated by making a survey of carbon dioxide levels in the occupied classrooms. These could then be compared to carbon dioxide measurements made in the same rooms at the end of the previous school year. Data was collected from 12/18/90 until 1/16/91. This afforded the opportunity to see the classrooms operated both normally and with school in recess for the Christmas Vacation.

Additionally, measurements of sub slab radon were made in the High School and the nearby Middle School. A carbon dioxide survey was also made in the Middle School. The Middle School is very close to the High School but does not seem to have nearly the elevated radon levels that the High School does. These measurements were made to determine whether the Middle School radon levels were lower due to lower source term, construction characteristics or HVAC operation and design. The radon levels under both schools were in the range of 2000 to 4000 pCi/L. There is no evidence that the source strength is the variable causing the large difference in the radon levels in the two schools.

RESULTS

Overview Of Results

The results of this investigation can be briefly summarized in a few lines. The evidence supporting these conclusions are then presented.

1) average radon levels that do not distinguish between occupied and unoccupied

conditions can be misleading

2) the operation of the air handlers, both outside air and exhaust only, has a definite reducing effect on the radon concentrations in the rooms

3) the decay rate of the radon after the air handler turns on is less than would be expected given the amount of outside air that is introduced because the radon is still entering due to negative building air pressure

4) repairing the outside air functions of the air handler made dramatic improvements in the carbon dioxide levels in the rooms where outside air was introduced.

5) while effective and reliable at solving radon problems, soil depressurization in rooms with inadequate ventilation leaves children sitting in high concentrations of CO_2 and other indoor air contaminants for which CO_2 levels are an indicator.

Effect Of Outside Air Improvements On Radon Levels And Dynamics

Introduction--

Continuous radon levels were monitored in eight rooms of the High School. Rooms 33 and 7 are going to be used to illustrate the effects of the air handler operation on radon levels in classrooms. The resolution of the femto-Tech units in these rooms allows one hour radon levels to be used in the analysis. These rooms are representative of the two different air handling systems - exhaust fans only and unit ventilators with passive relief. Room 33 is in the new wing of the high school, contains a unit ventilator and has repeatedly shown the highest average radon levels and spikes. Room 7 is in the old wing, which has exhaust only ventilation and has shown high radon levels. The only fan powered outside air that can potentially enter Room 7 is from the gym air handlers, when they are running. Otherwise, outside air to Room 7 consists of whatever is drawn in through leakage in the building shell, window wall and corridor.

The next two major sections will examine first Room 33, the unit ventilator room and then Room 7, the exhaust only room, in detail.

Room 33 - Unit Ventilator Ventilation--

The results of the continuous monitoring in Room 33 are shown in Figure 1. Notice that the "rain spike" in this room on Christmas eve rises from 8 to 90 pCi/L and

19

drops again to 16 pCi/L in a 24 hour period. This is far more severe than in other monitored rooms, indicating that a substantial amount of radon is available to enter this room. As in Room 7, the radon levels in this room drop quickly when the ventilation turns on. This can be seen at the points labeled "Air Handler On" in Figure 1. Notice that on Christmas eve during a rain storm there is large spike in the radon concentration. This spike is seen in every room monitored and is interpreted as a rain spike.

The dynamics of the drop in radon that occurs when the unit ventilator comes on is illustrated by Figure 2. This graph shows the 24 hour period of December 19, 1991. Between midnight and 6 AM the radon level hovers around 17 pCi/L. At 6 AM when the unit ventilator is turned on by a timeclock control, the radon level drops in an exponential decay until it reaches a minimum of around 2 pCi/L in the late afternoon. An exponential decay of contaminant level is expected when dilution air is introduced into the room. After the unit ventilator is turned off, the radon levels begin to climb until they reach a level of 7 pCi/L again at midnight. The mean radon concentration for this 24 hour period is 8.9 pCi/L and for the occupied time it is 6 pCi/L. However, for the lowest nine hour period the mean radon level is 3.8 pCi/L. This means that the dose delivered to the occupants could be reduced 37% by starting the unit ventilator three hours earlier.

NOTE : A correction for built up radon decay products in the continuous monitor is not required for the pulse ionization device used because the decay products are collected using an electric field without being counted. However, due to diffusion lag into and outof the sensitive volume, a one hour time delay is observed in the radon dynamic.

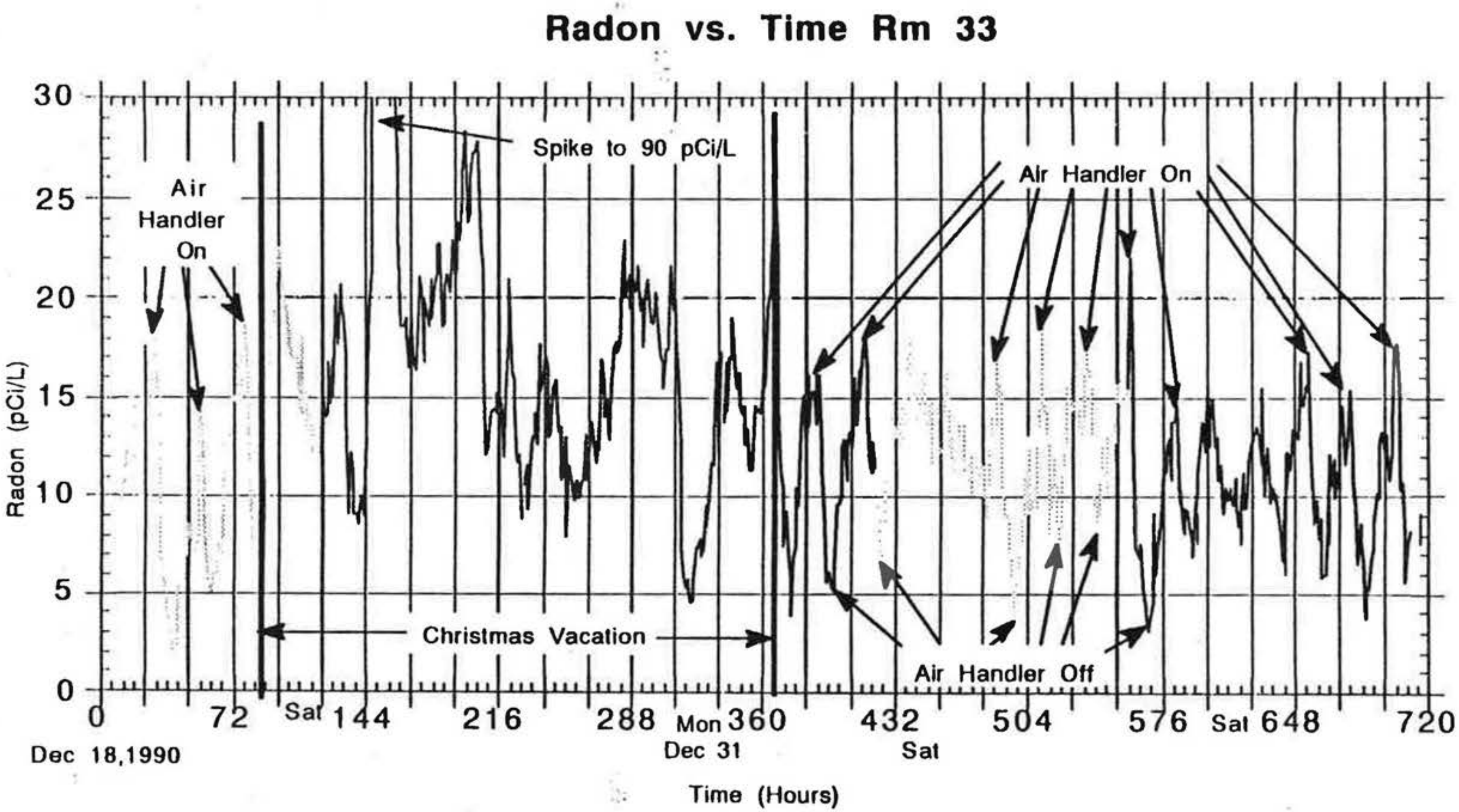
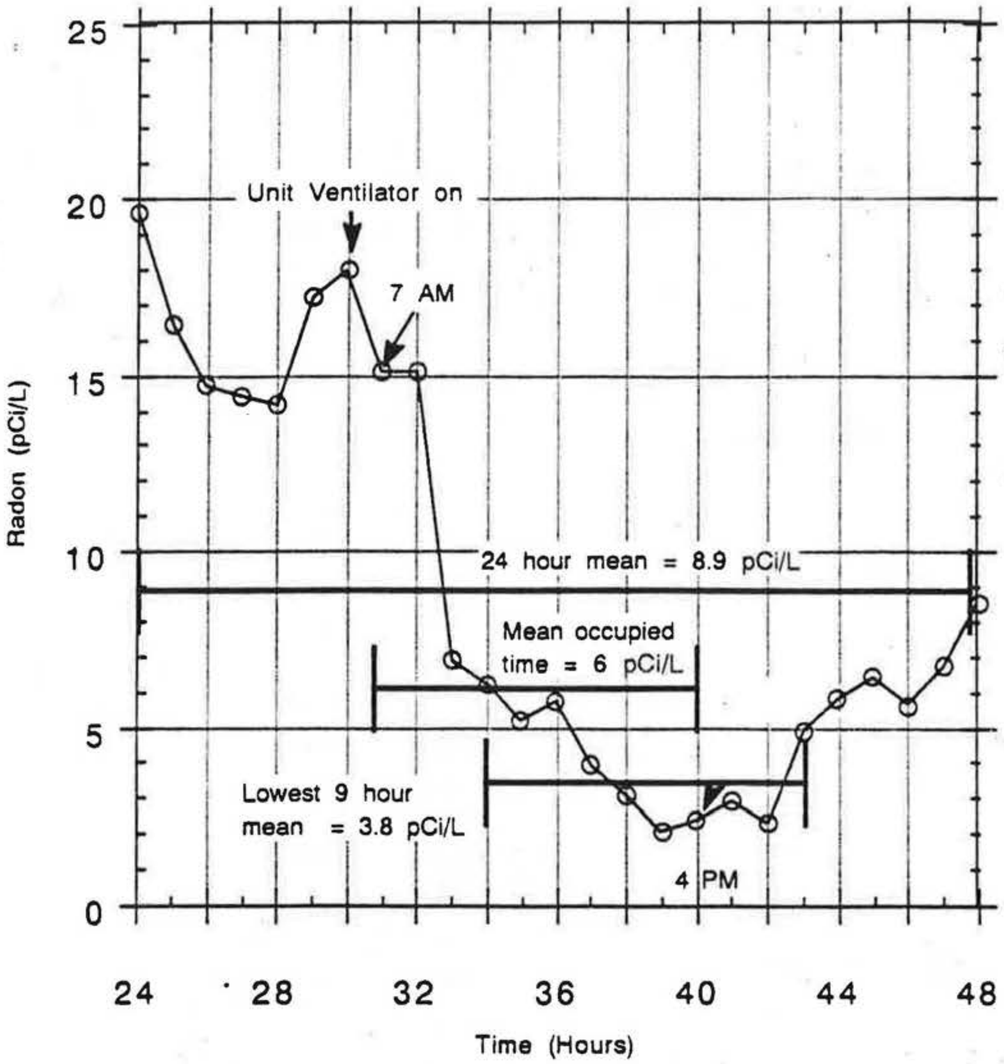


Figure 1 - Radon Levels in Room 33

Figure 2 - Radon Dynamics in Unit Ventilator Room 33



While for this one day, the 19th of December the mean radon level for the occupied time period was 6 pCi/L, it was not so for other occupied days. In fact, the average occupied time radon level for the entire monitored period shown in Figure 1 is a higher 7.8 pCi/L. This is still 28% lower than the 10.8 pCi/L mean for the entire time period.

Another approach to understanding this dynamic is to apply tracer decay theory. This has been done in the analysis shown in Figure 3. Figure 3 was created by taking the decay curves for all the occupied days during the monitoring period and plotting them on a single graph. The time scale has been changed from consecutive hours to hours after the unit ventilator turns on. The result is a scattergram that plots all the decay data for all the occupied days on top of each other.

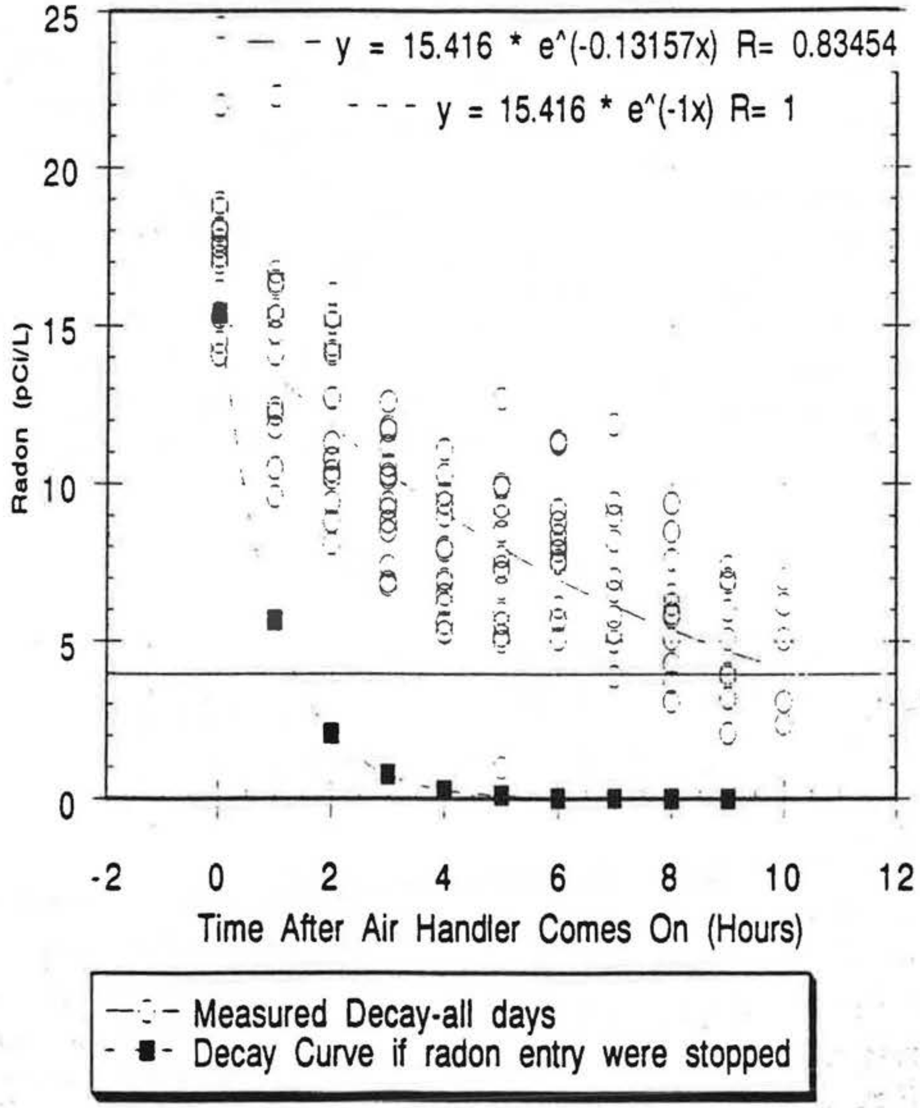
If a given amount of contaminant is released into a room and then allowed to be removed by dilution with ventilation air, it is expected that the concentration of the contaminant will decay exponentially with time[3]. The rate at which it decays is described by the solution to the continuity equation. This is given as the following :

1) $$C(t) = C(0) \times e^{Nt}$$

where : C(t) = concentration at time t
C(0) = concentration at the start of the decay
N = airchange rate in air changes per hour
t = time in hours

By fitting an exponential decay curve to the data in Figure 3, the decay rate and the air exchange rate for the average day during this monitoring period can be determined. It is obvious from this curve that if the radon level at the start of the day is greater than about 8 pCi/L, the mean level during the day would not get below 4 pCi/L. The curve fit yields an air exchange rate of 0.13 air changes per hour (ACH). By direct measurement of outside air, it is known that the air exchange rate in the room is 1 ACH. This discrepancy is explained in the following way. In order for equation 1) to describe radon concentrations, the entry rate of radon after the start of the decay must be zero. The introduction of outside air has not stopped radon from entering the room. This is easily verified by a glance at the air pressure difference between the room air and the sub slab air. The room air was at a lower pressure than the sub slab air during the entire monitoring period. When the unit ventilator turned on, this difference became smaller, but the room was still negative relative to the sub slab. The radon

Figure 3 - Reduction Rate of Radon in Room 33
Air Handler On - All Days Combined



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entry rate may have been reduced but it certainly was not stopped. If the room was pressurized by the unit ventilator then the radon concentration would have dropped according to the lower curve in Figure 3. The radon concentration would be below 4 pCi/L in a matter of an hour.

In fact, it is likely that this is the case in this room during the spring and fall when the outside temperature is warmer than in January. This is expected for two reasons. One, warmer outside air means a reduction in the air pressure differences induced by the stack effect. Two, when the outside air is warm enough gains from body heat will overheat the room and cause the outside air dampers to open more. This will increase the outside air volume and contribute to pressurizing the room.

Lastly, the room could potentially be pressurized even under the worst case condition represented by these test results. This could be accomplished by air sealing the room so that the minimum outside air flow rate would pressurize the room. Not only would this control the indoor radon but it also would result in energy savings by reducing air infiltration.

Room 7 - Exhaust Only Ventilation--

Figure 4 shows the continuous radon data in Room 7. The data begins on December 18, 1990. Christmas vacation began on December 20, 1990 and ended January 2, 1991. The radon levels in this room plummet whenever the rooftop exhaust fans turn on (see the points labeled "Air Handlers On" in Figure 1). This effect is repeatable. The radon levels drop in spite of the fact that operation of the exhaust fans drives the air pressure difference between room 7 air and the sub slab air 3 pascals lower. It is likely that the amount of radon entering the room increases when the fans turn on. Although more soil air is being drawn in by the operation of the fans, the dilution effect of the increased ventilation from above grade overwhelms the increased radon entry. Unfortunately, the increased entry is not overwhelmed enough so that the occupied radon levels are below 4 pCi/L, but are instead 7.1 pCi/L.

Figure 5 shows the agglomerated radon data for the occupied days in Room 7. This graph was generated in the same way that Figure 3 was for Room 33. The general trend of decreasing radon levels after the exhaust fan turns on is obvious. There is a great deal more scatter in this data than there was in the data from Room 33 (the unit ventilator room). The curve fit to this data shows an effective ventilation rate of only 0.065 ACH, while the measured exhaust rate informs us that there is actually 0.63 ACH (shown as the theoretical curve in Figure 5). The data from Figure 3 and Figure 5 are combined in a single graph in Figure 6. This figure highlights the similarities and differences between the dynamics of the two rooms. Notice that the theoretical curves for the two rooms almost coincide, even though the fan powered air exchange rates

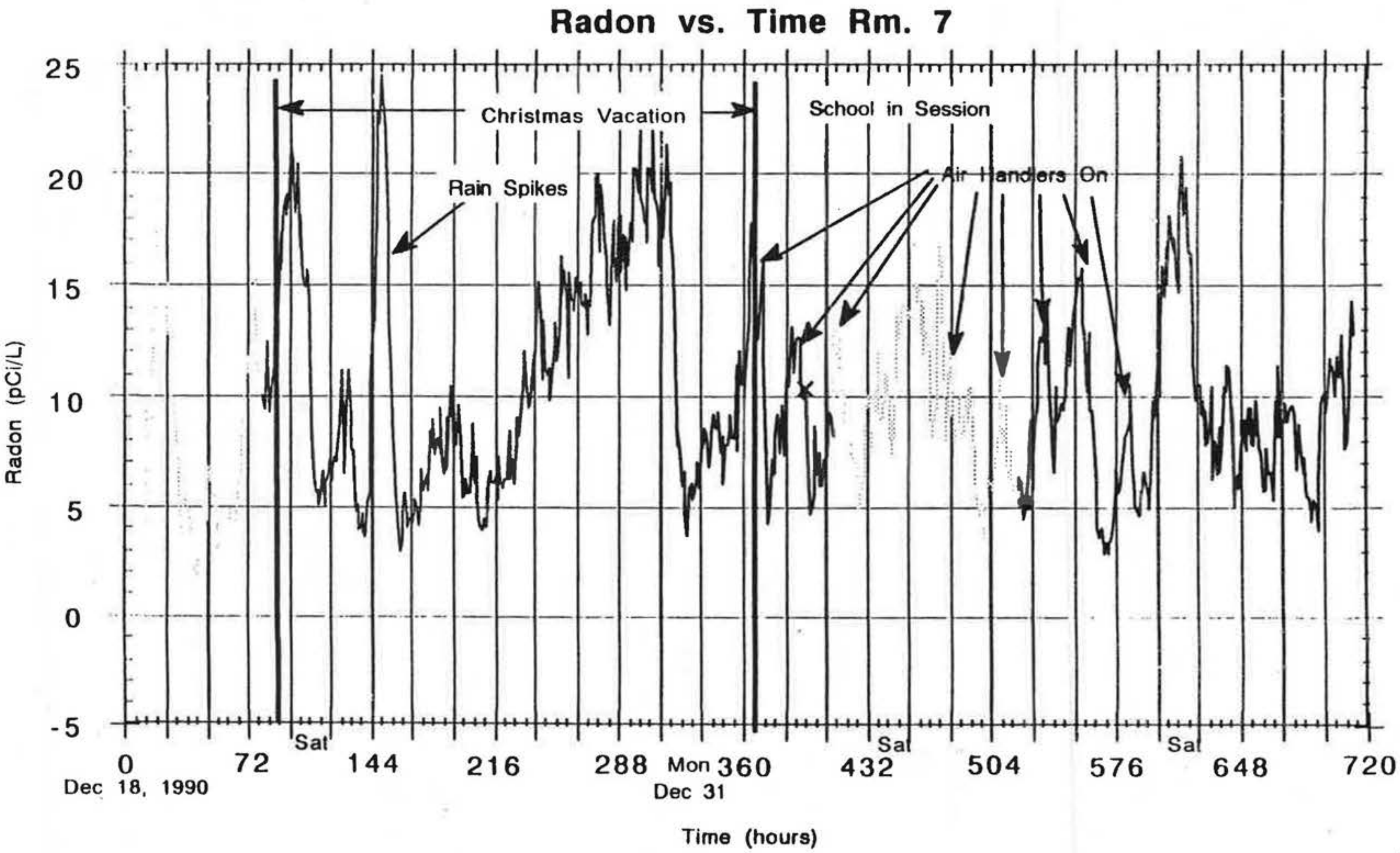
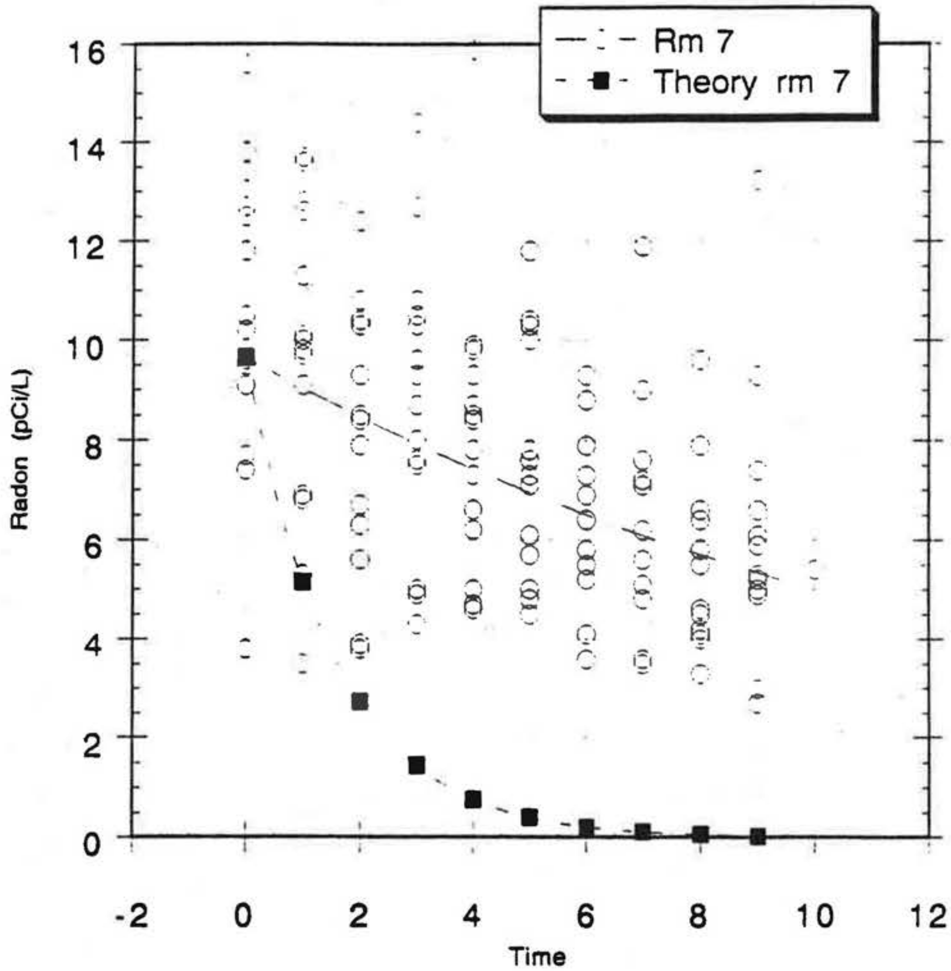


Figure 4 - Radon Levels in Room 7

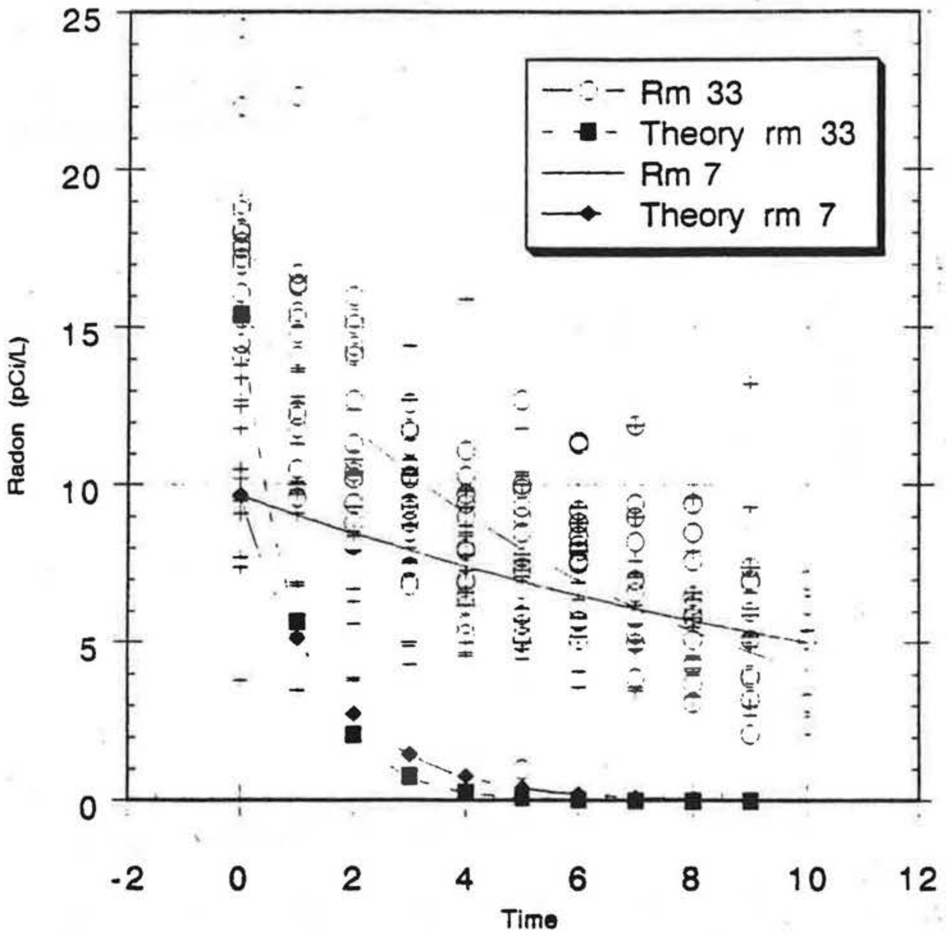
Figure 5 -Reduction Rate of Radon in Room 7
ExhaustFanOn-AllDays



— — y = 9.6569 * e^(-0.065616x) R= 0.4982

- - - y = 9.67 * e^(-0.63x) R= 1

Figure 6 - Reduction Rate of Radon
Air Handlers On - Rms. 7 & 33



— — y = 15.416 * e^(-0.13157x) R= 0.83454

- - - y = 15.416 * e^(-1x) R= 1

—— y = 9.6569 * e^(-0.065616x) R= 0.4982

—— y = 9.67 * e^(-0.63x) R= 1

28

are quite different (1 and 0.63 ACH). This is largely due to the difference in source terms. Room 7 begins the average occupied day at around 10 pCi/L while Room 33 begins the average occupied day at just over 15 pCi/L.

It is tempting to attribute the differences in radon dynamics in these two rooms to the difference between exhaust only and fan powered outside air ventilation. But, two rooms, no matter the depth of study provide anecdotal, not conclusive evidence. The results of these measurements do support the current model of radon entry and control as follows :

- entry is dominated by air pressure driven mechanisms
- exhaust ventilation can lower radon concentrations, but not as effectively as powered outside air ventilation

To these two basics we can add a further hypothesis :

- unless fan powered outside air ventilation stops radon entry, the reduction rate of radon will not be as great as expected from dilution alone

and a corollary :

- exhaust only ventilation will never lower radon concentrations as quickly as would be expected from dilution alone because it does not stop the entry of radon

It is important to understand that these two suggestions apply only to dynamic radon behavior and not to steady state conditions. This only applies to the rate at which radon levels change.

Effect Of Outside Air Improvements On Carbon Dioxide Measurements

Introduction--

The reason we breathe is to get oxygen to the cells in our bodies and to remove a number of the byproducts of respiration. Carbon dioxide and water vapor are the most plentiful products of respiration. Carbon dioxide levels in outgoing breath are several thousand parts per million. Carbon dioxide measurements made in occupied rooms can be used as a surrogate for levels of indoor air contaminants that are produced by the occupants themselves and routine activities of occupants. If a simplifying assumption is made about the generation rate of CO_2 being constant then they also can be used to estimate the outside air ventilation rate [4]. The ventilation guidelines of

15 cfm/person in the publication ASHRAE 62-1989 Ventilation for Acceptable Indoor Air Quality should result in a steady state 1000 ppm of carbon dioxide in an occupied classroom.

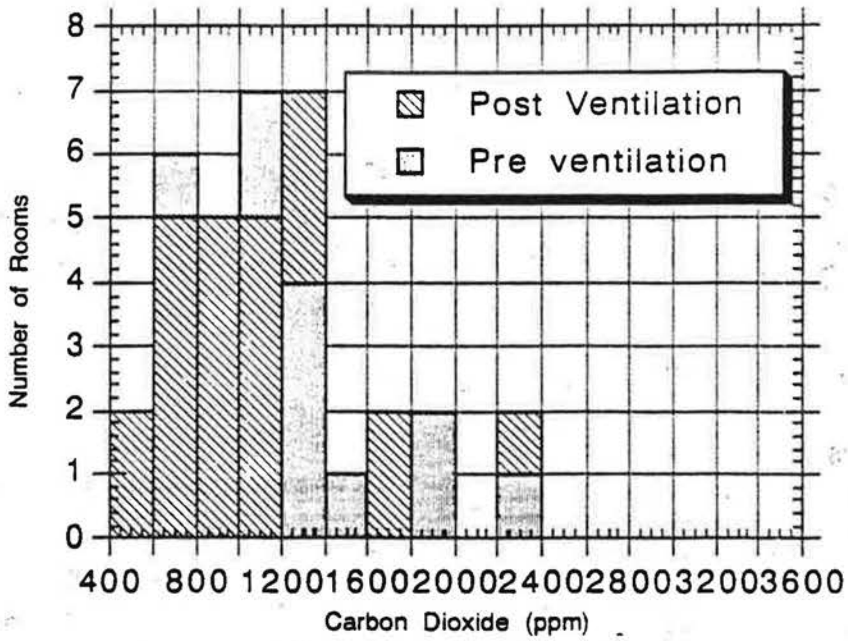
Carbon Dioxide Measurements--

Carbon dioxide measurements were made in the High School and the Russell School (pre and post radon control) and in the Middle School. The pre radon control measurements were made in early June of 1990 and the post measurements were made in December of 1990.

Carbon Dioxide Measurements in the High School--

A histogram is shown in Figure 7 that differentiates between the pre and post carbon dioxide measurements. Only measurements from occupied rooms with closed windows are shown. The distribution of CO_2 levels has been very clearly pushed to the lower levels by the repairs made to the ventilation system. The pre radon control CO_2 levels had a mean of 1402 ± 450 ppm and the post level mean was 1042 ± 394 ppm. This represents a 33% decrease in the mean. From a health, comfort and alertness perspective, this is a great improvement over the situation before the ventilation equipment was repaired. Although the mean is now nearly the level recommended in the ASHRAE guidelines[4], half the rooms in the post control sample would still be considered underventilated by the current guideline. Eight percent of them (2 rooms) are above 1700 ppm, which would reflect an outside air exchange rate of 5 cfmiperson. By contrast, all the rooms in the pre mitigation set of measurements were above the current guidelines (1000 ppm) and 27% of them (3 rooms) were above 1700 ppm.

Figure 7 - Pre and Post Control CO2 Histogram for High School

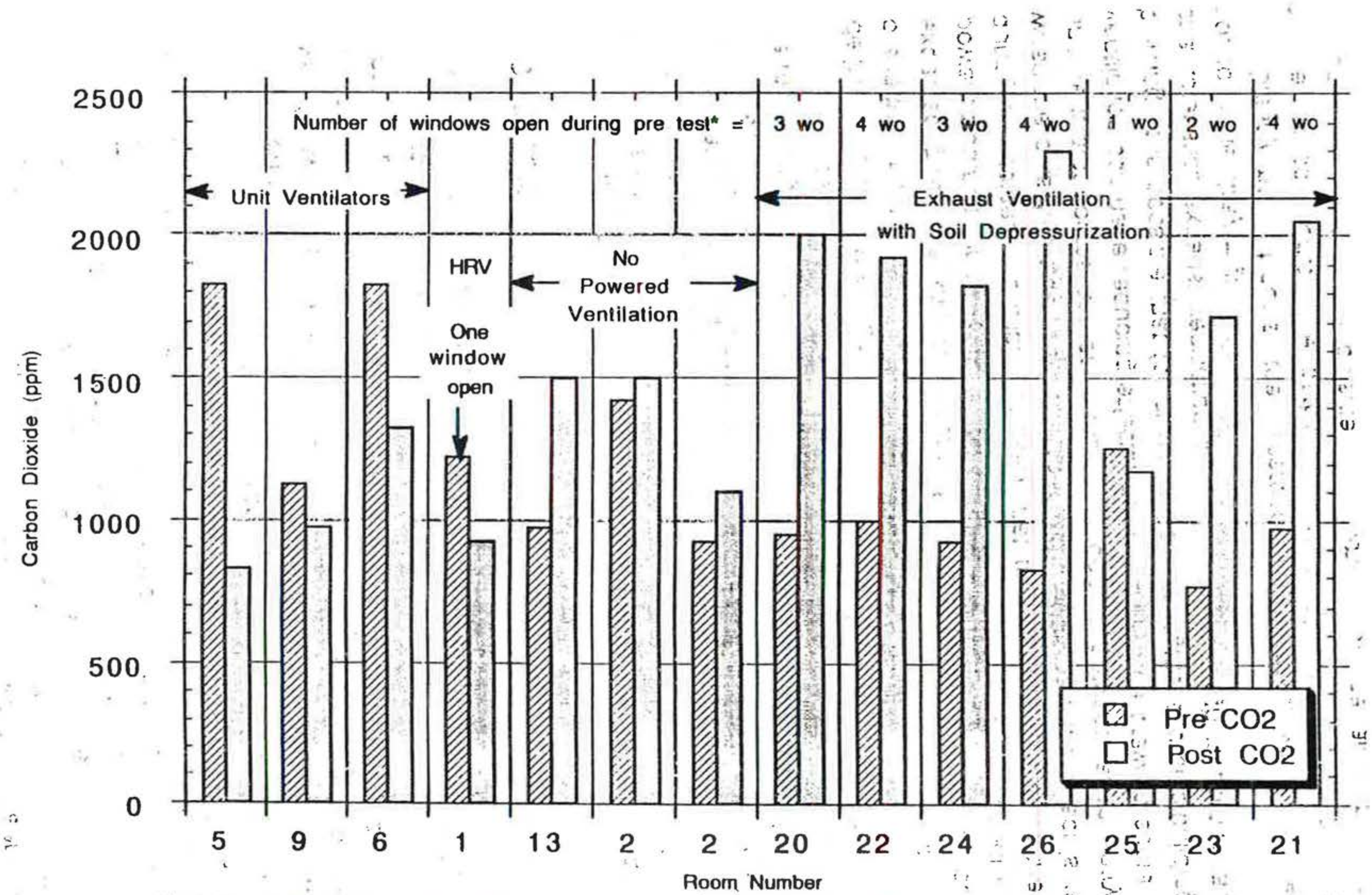


Carbon Dioxide Measurements in the Russell School--

A bar graph is shown in Figure 8 that differentiates between the pre and post carbon dioxide measurements and between ventilation and radon control type. Measurements are from occupied rooms with closed windows except the pre control measurements in the exhaust only ventilation - soil depressurization rooms. These rooms had open windows during the June measurements. The number of open windows is shown on the bar graph.

The CO2 levels have been very clearly lowered by the repairs made to the unit ventilators (rooms 5, 9, and 6) and by the installation of the heat recovery ventilator (located in room 1, with no powered ventilation). Pre control CO2 levels were not available for some rooms with unit ventilators (rooms 7, 8, 10 and 11) but post control measurements were. The mean post control CO2 levels for all the rooms in which unit ventilators were repaired (5, 6, 7, 8, 9, 10, and 11) was 1350 ± 408 ppm.

Rooms 1, 2a, 2b, 3 and 4 are in the oldest wing, where there is no fan powered ventilation. Rooms 2a and 2b show slight increases in CO2 levels, averaging 1500 ppm CO2, as compared to Room 1 which has dropped from over 1250 ppm to 925



*Note No windows were open in the Unit Ventilator rooms during the CO2 tests

Figure 8 - Carbon Dioxide Levels Pre and Post Radon Control at the Russell School

ppm. This is expected considering that no changes in the ventilation of rooms 2a and 2b have taken place, but a heat recovery ventilator has been added to Room 1.

Rooms 20, 21, 22, 23, 24, 25, and 26 are in the exhaust only wing, in which soil depressurization has been used to control the radon. The radon levels in these rooms (except for the library, which is around 7 pCi/L) are averaging between 1.4 and 3.5 pCi/L. The pre control CO2 levels in these rooms must be interpreted cautiously because at least one window was open in each room when these measurements were made. The post control CO2 levels had a mean of 1857 ± 376 ppm.

None of the exhaust only rooms meet the current ASHRAE guideline for ventilation rates. In fact, none of them meets the ASHRAE ventilation guideline for the year in which they were constructed. While it is clear that soil depressurization will control indoor radon, it is also clear that it has little impact on other indoor air contaminants.

Histograms of the CO2 data from the Russell School are not presented because there is so little pre control data that did not have windows open.

CONCLUSIONS

Conclusions for this work contribute to interpretation of radon measurements made in school rooms (and other non-residential settings) where a wide range of occupant activities and the operation of air handlers can have important effects on radon measurements. Radon measurements in the Maine Schools show that average radon levels that do not distinguish between occupied and unoccupied conditions can be misleading when the effect of air handlers is unknown.

The operation of both types of air handlers, outside air and exhaust only, has a definite reducing effect on the radon concentrations in the rooms. Unless radon is prevented from entering, the radon concentration does not drop as quickly as expected given the known amount of outside air that is being introduced. Only fan powered outside air has the chance of doing this. In the High School it is not doing so during the coldest months. It is likely that there are times during the spring and fall when the outside air dampers are open wider and the stack effect is reduced that the unit ventilator rooms are pressurized enough to prevent radon entry. Exhaust only ventilation can have reducing effects, but will always be drawing some soil air into the building. It is possible that for given source strengths and slab/building shell leakage characteristics exhaust ventilation could be good enough to control radon, but that is not so in the Gray High School.

Clearly many, if not all the classrooms investigated, were underventilated for the number of occupants. The carbon dioxide data gives plenty of evidence for this contention. Repairing the outside air functions of the air handler made dramatic improvements in the carbon dioxide levels in the rooms where outside air wa introduced. However, while effective and reliable at solving radon problems, sc depressurization in rooms with inadequate ventilation leaves children sitting in hig concentrations of CO_2 and other indoor air contaminants for which CO_2 levels are a indicator.

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4. ASHRAE, *62-89 Ventilation For Acceptable Air Quality.* 1989, American Society of Heating Refrigeration and Air Conditioning Engineers.