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FIELD EVALUATIONS OF A RADON RESISTANT CONSTRUCTION STANDARD PROPOSED FOR RESIDENTIAL STRUCTURES IN FLORIDA

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ABSTRACT

A set of eight houses were studied throughout their construction in north central Florida. Each house was built in compliance with a proposed radon resistant construction standard being developed by the Florida Department of Community Affairs. Post-construction monitoring was performed over a minimum six day period for each structure during which each house was operated in three different heating, ventilation and air conditioning (HVAC) system configurations. Continuous measurements of indoor radon concentrations, house ventilation rate, across slab differential pressures and interzone differential pressures provide time resolved radon entry rates and a performance index for passive radon barriers. The study demonstrates that; 1) passive radon barriers can provide acceptable indoor radon concentrations for slab-on-grade structures built over soils having soil gas radon concentrations as high as 3.1×10^5 Bq m^{-3} and 2) with an effective passive barrier, HVAC operational configurations have no detectable effect on indoor radon concentrations.

INTRODUCTION

The State of Florida has undertaken the development of radon resistant construction standards for newly constructed buildings in the state. This is a premier effort to develop a technically based building code for both residential and large/commercial buildings and focuses on the specific construction practices and environmental conditions found in this region of the country. The work presented here comprises an evaluation of the effectiveness of the radon resistant construction standards for residential construction which will enter the rule-making process later this year (Florida 1994). The radon resistant construction standards for large buildings are still under development and are about a year behind the residential standards.

This paper reports on the results for eight houses constructed according to the draft standards in 1993. This represents the latest in a series of new house evaluation projects that have contributed to the refinement of the draft standard through the evaluation of approximately 60 newly constructed houses. The eight houses reported on were constructed in the north central region of Florida (Alachua and Marion Counties) while a sister project conducted by the Southern Research Institute evaluated houses constructed in Central Florida (Polk County).

The project involved identifying new construction sites having elevated radon potential, working with builders to build these structures to the specifications of the draft radon resistant construction standard and subsequently monitoring the performance of the structures. Previous research projects have demonstrated the effectiveness of utilizing roughed in active soil depressurization systems (ASD) for these types of houses so the primary objectives of this project were to evaluate the effectiveness of passive barrier techniques and portions of the draft standard relevant to heating, ventilation, and air conditioning (HVAC) system design and installation.

Post-construction indoor radon concentrations are inadequate to provide quantitative information on these features since these measurements are highly dependent on building specific features such as the house ventilation rate, soil gas radon concentrations, and passive barrier effectiveness. We therefore used trace gas techniques to simultaneously measure the house ventilation rate and indoor radon concentrations, extracting the radon entry rate for the completed structures. Radon entry rate is the fundamental quantity that most radon barrier techniques attempt to reduce in order to maintain low indoor radon concentrations and was calculated for each house as a function of time.

METHODOLOGY

The radon resistant construction standard that was applied to the construction of residential structures in this study was developed over the preceding four years (Florida 1994). While some of the features for implementation of the standard are still being negotiated most of the technical features are well developed. The features of the standard that are relevant to this study includes specifications for; 1) passive barrier techniques, 2) ASD system rough-ins and 3) HVAC system design and installation. The standard is directed primarily towards slab-on-grade foundations since this includes the vast majority of the Florida housing stock, although features pertinent to other foundation techniques are included as well.

Passive barrier techniques include fill compaction, requirements for a continuous plastic membrane vapor barrier of good integrity below the slab, concrete slabs with minimum cracking, and sealing of cracks and plumbing penetrations through the foundation. ASD systems are specified for operation in the sandy fills nearly always used in Florida. Specifications are provided for the rough-in of either pit-type systems or extended suction systems using either drainage mat or gravel. According to the draft standard HVAC systems are to be designed with minimal duct leakage, must not have ducts running below the slab, and must have provisions to prevent pressure imbalances between various portions of the living space. This listing, while not all inclusive, illustrates the major features of the draft standards that were implemented and evaluated in this study.

The ultimate implementation of the standard is still being debated, but it is expected that an increased number of radon resistant construction features would be used for areas having increased radon potential. For example, areas defined as low radon potential areas would not be required to incorporate any of the code features, areas defined as moderate radon potential areas would be required to incorporate the passive radon resistant features of the standard and areas defined a elevated radon potential areas would be required to include active features of the standard. In order to perform this evaluation candidate sites and builders were selected from the local area. Site evaluation consisted primarily of soil gas concentrations measured at a depth of 1 m on the foundation site prior to any excavation. Sites were required to have at least 37,000 Bq m^{-3} soil gas radon concentrations in order to be included in the study. Local builders were also solicited for participation in the study and an incentive of approximately $2000 per house was allotted to offset the builder's additional costs and time to install the features specified by the draft standard. This was paid in increments for tasks successfully accomplished and resulted in the structures successfully incorporating the features of the draft standard.

Throughout the construction period the research team worked very closely with the builders. One individual from the research team was in daily contact with the site supervisor for each structure and houses were generally visited on a daily basis during the early construction period and less frequently after the foundation and superstructure were completed. The close proximity of the researchers to the building sites was a major advantage since construction schedules are very flexible and a quick response was frequently required to ensure that particular features were installed as desired. Following the completion of the house a six-day measurement period was provided to the researchers before the house was occupied.

Measurements made over the six day period were made for the three different sets of house conditions, summarized in table 1. Continuous measurements were logged by a Campbell Scientific 21X data logging system which could be remotely downloaded when necessary. Parameters that were measured continuously throughout the experimental period included indoor radon concentration, house ventilation rate, differential pressure across the foundation slab, differential pressures between indoor air zones, and barometric pressure. In addition, independent measurements were made over each two day period for sub-slab radon concentrations using grab sampling techniques with scintillation cells, and indoor radon concentrations using E-PERM electrets. The continuous radon measurements were made over ten minute intervals using a Pylon AB-5 and a PRD scintillation cell and pressure measurements were made using Setra Model 264 Pressure Transducers (25 Pa full range). Other continuously measured parameters (pressures and trace gas concentrations) were similarly measured over ten minute intervals throughout the experimental periods. The trace gas system used was a repetitive pulsed technique. The system consisted of an automatic timer and release mechanism that was constructed to release a pulse of SF_6 trace gas into the house where it was well dispersed by low speed mixing fans. The decay of the gas was monitored by a Miran Model 203 Specific Vapor Analyzer over the subsequent time interval and fit to a decaying exponential to extract the mean ventilation rate over that time period. While not as elegant as continuous injection techniques, this technique was necessitated by the limited amount of experimental set-up time that was available in each of these houses and the possibility that the ventilation rates could vary significantly between different structures.

Table 1. Three different house conditions were sampled for a minimum period of two days per condition.

House Condition	HVAC Operation	Interior Door Position	Rationale
1	Off	Open	Evaluates natural, environmental driving forces
2	On	Open	Evaluates effects of mechanically created pressure differences and airflows while minimizing pressure differentials between indoor air zones.
3	On	Closed	Creates maximum differential pressures between indoor air zones and across the foundation slab.

RESULTS AND DISCUSSION

The continuous data collected for each of these newly constructed houses had similar behavior. Because of limited space only the results for House # 8 are illustrated in the accompanying figures 1 through 4. These results are, however, qualitatively representative of the behavior exhibited by each of the eight structures studied. The quantitative values that reflect the performance of the individual houses are illustrated in Table 2.
Figure 1 illustrates that indoor radon concentrations remained low and also demonstrate the commonly observed diurnal (24 hour) cycle. The house ventilation rates are illustrated in figure 2 with the variation of indoor radon concentrations superimposed using the same time averaged blocks for comparison. The whole house ventilation rates also exhibit a strong diurnal cycle, which contributes to the diurnal variations of the indoor radon concentrations. Throughout this measurement period the HVAC system of each structure was operated under three different configurations; 1)HVAC off, single air zone, 2)HVAC on, single air zone and 3)HVAC on, multiple air zones. Figure 1 indicates that the radon concentration was relatively constant throughout the measurement period, regardless of the HVAC operating configuration. This demonstrates that the HVAC did not adversely affect indoor radon concentrations even when operated under the worst case configuration (i.e. multiple zones with one zone being significantly depressurized and where large interzone differential pressures exist.

The diurnal variation of the radon concentrations in each of these structures, typically about +/- 37 Bq m^{-3} about the mean radon concentration. This diurnal variation is observed for each of the structures studied, all having about the same pattern with radon concentrations peaking in the early morning hours and at their smallest values in the late afternoon. The observed variation of indoor radon concentrations can qualitatively be attributed to changes of house ventilation rates that may be expected to occur throughout the day. It might be expected that surface winds, gusts, and atmospheric instability, in general, are all at their maximum in late afternoons in Florida, particularly throughout the summer season when most of these measurements were performed. These wind effects on the house shell increase the pressure differentials across the shell and produce the resulting increase of house ventilation rate. As the house ventilation rate increases, the indoor radon concentrations would be expected to decrease, assuming that the radon entry rate remains constant.

Similarly, the atmosphere is in its most stable state and winds are calmest during night time hours. Any wind induced differential pressures and the associated ventilation rate are consequently at their minimum permitting indoor radon concentrations to increase, again assuming that the radon entry rate remains approximately constant. The indoor radon concentrations will continue to increase under these conditions until surface winds begin to pick-up and increase the ventilation rate of the house. The highest radon concentrations are usually observed in the early morning hours around dawn. This qualitative process describes the type of behavior observed in each of the houses in this study. In nearly all cases the general trends between indoor radon and house ventilation rates are in opposite directions. Decreasing ventilation rates routinely produce increasing radon concentrations and the radon concentrations can be observed to decrease as the house ventilation rate increases as illustrated in Figure 2.

Since both indoor radon concentration, C, and the ventilation rate, λ_v, are known as a function of time, the radon entry rate, R, can be determined from the governing differential equation:

$$dC/dt = [R/V - \lambda_v C] - \lambda C$$

where , V is the house volume, λ the radioactive decay constant of ^{222}Rn. In this case the equation was rearranged and used in its discrete form as

$$R(t) = [(C(t+\Delta t)-C(t)/\Delta t) + \lambda C(t) + \lambda_v C(t)] V$$

in order to extract the radon entry rate. Using this solution technique radon entry rates were calculated as a function of time for each of the houses studies. The radon entry rates calculated for House 8 are illustrate in figure 3.

The calculated radon entry rates are relatively constant throughout the measurement period, with most of the houses exhibiting variations between the maximum and minimum entry rate not much larger than a factor of two. No significant variations of radon entry rate corresponding to changes of the HVAC operation configuration are observed. This is, of course, expected since neither the indoor radon concentrations or house ventilation rates changed detectably with different HVAC operating scenarios. These results do, however, provide evidence that the operating configuration of HVAC systems do not affect the radon entry rate in these structures, even in configurations that we be expected to provide the largest amount of indoor depressurization.

The average radon entry rates across the measurement periods for each of these houses are illustrated in Table 2. Average radon entry rates are typically around 5 Bq s^{-1}, with the smallest being 2.8 Bq s^{-1} and the largest 9.5 Bq s^{-1}. The data from Table 1 demonstrates that all of the houses have similar small entry rates, regardless of the presence of indoor depressurization or pressurization. This indicates that the passive radon barriers installed in all of these structures do a good job of limiting radon entry into the structure interior.

Since the across slab differential pressures were also measured for each of these houses throughout the measurement period, it is also interesting to consider whether these variations correlate with time variations of the radon entry rate. These differential pressure measurements are illustrated for House 8 in Figure 4. Each of the houses studied exhibits this semi-diurnal periodicity of across slab differential pressure that has generally been observed for a number of houses across Florida. The twelve hour periodicity arises from naturally occurring

Table 2: House Performance Summary. Values listed for each house represent the time average throughout the test period of the respective parameter.

House Number	Indoor Rn ($Bq\ m^{-3}$)	Air Change Rate (h^{-1})	Radon Entry Rate ($Bq\ s^{-1}$)	Radon Entry Flux ($Bq\ m^{-2}s^{-1}$)
1	85	0.49	8.6	0.046
2	111	0.33	9.5	0.044
3	81	0.34	4.1	0.017
4	100	0.27	4.9	0.034
5	93	0.31	5.2	0.024
6	155	0.26	5.9	0.032
8	100	0.38	6.9	0.032
11	104	0.21	2.8	0.025

variations of the atmospheric pressure (Hintenlang and Al-Ahmady 1992), which has been observed across the entire state of Florida. Other barometric pressure changes that are associated with fronts and meteorological changes may be superimposed on this cyclic behavior to produce significant across slab differential pressures. Note, however, that there is no evidence to suggest that the radon entry rate correlates with the across slab differential pressures for any of these structures. Since these differential pressures would be expected to be the major driving force for the convective entry of soil gas radon, yet no correlation is observed, it is believed that the presence of the radon resistant barriers implemented in these structures reduce the convective entry of radon. If the radon barrier was not effective we would expect to see the radon entry rate track the across slab differential pressures for these structures.

Evaluation of the radon entry rate alone does not, however, permit a direct comparison between the relative performance of the passive radon barriers installed in each of these houses. In order to compare the effectiveness between different structures it is also necessary to include some structural features. As an initial performance index we normalize each of the radon entry rates to the slab area to obtain the radon entry rate per unit area, or radon entry flux. These values of radon entry flux are tabulated in Table 1, and account for the variation in the slab sizes of these structures.

The effectiveness of the passive barrier can also be examined as a function of some of the important physical characteristics of these structures. This includes the types and number of cracks that are present in the structures as well as other slab penetrations. Slab edge cracks may be found in stemwall types of foundations. The stemwall houses in this study (houses # 6 and #8) have radon entry fluxes of 0.032 $Bq\ m^{-2}s^{-1}$, at the mean of the entry flux for the entire group of houses studied (0.032 $Bq\ m^{-2}s^{-1}$). It consequently appears that the passive barriers for stemwall foundations are just as effective as those for monolithic foundations.

Many of the houses examined in this study did not exhibit any slab cracking and the cracks that did occur, including control joints, were sealed. A summary of the amount of unplanned cracking, average radon entry rate and averaged entry fluxes are provided in Tables 1 and 2. Comparison of the houses containing cracks and those that did not exhibit any cracking shows that no significant different between these two populations of foundations. The average radon entry flux for each group is essentially indistinguishable, 0.032 $\pm$ 0.009 $Bq\ m^{-2}s^{-1}$ for the uncracked foundations, 0.031 $\pm$ 0.01 $Bq\ m^{-2}s^{-1}$ for the cracked foundations, and an overall average for all of the study houses of 0.032 $\pm$ 0.009 $Bq\ m^{-2}s^{-1}$. This demonstrates that the cracks present in these structures did not contribute significantly to the entry of radon into the structures. This is can be attributed to ensuring that a vapor barrier of good integrity is installed below the foundation slab.

Table 3: House Characteristics Summary

House Number	Slab Area (ft^2)	Foundation Type	Degree of Cracking	Sub-slab radon (Bq m^{-3})
1	2012	Monolithic	None	27,010
2	2320	Monolithic	2	35,890
3	2510	Monolithic	Extensive	18,060
4	1550	Monolithic	None	29,930
5	2320	Monolithic	None	45,250
6	2000	Stemwall	1	277,020
8	2320	Stemwall	3	10,690
11	2100	Monolithic	None	313,830

Plumbing penetrations have been suggested as more dominant entry routes than slab cracks for both slab-in-stemwall and monolithic slab foundations by several previous studies (Pugh et al 1992, Revzan etal 1992). If plumbing penetrations provide the dominant radon entry route then we may expect the radon entry rate to scale in proportion to the number of plumbing penetrations through the structure's foundation. Unfortunately, even though the houses in this study had varying numbers and configurations of baths, and utility areas, they all coincidentally have the same number of slab penetrations (22) with one exception, House #3 which had 30 penetrations. This makes it difficult to see any correlations with entry flux except for House #3, which had the lowest entry flux observed, indicating that these penetrations were successfully sealed at least for this structure.

One of the houses studied did have average indoor radon concentrations above 148 Bq m^{-3} during the test period. As observed from Table 1, House #6 had an average indoor radon concentration of 155 Bq m^{-3}. The active soil depressurization system (gravel filled pit type) that was roughed-in during construction was activated in this house and promptly reduced the indoor concentrations to 55 Bq m^{-3}. This demonstrates the continued success of ASD systems designed by the draft construction standard in reducing elevated indoor radon concentrations. The more interesting question concerning this house is why was the passive barrier system alone not able to maintain indoor concentrations below 148 Bq m^{-3}? An examination of Tables 1 and 2 reveals some notable features; a) this structure utilized a stemwall style of foundation construction, b) it has relatively high sub-slab radon concentrations, approximately 277,000 Bq m^{-3}, and c) it has a relatively small ventilation rate. In previous new house evaluation project studies the stemwall foundation and high sub-slab radon concentrations would probably have been identified as the major contributing factors to the elevated indoor radon concentrations. An examination of the radon entry rates and radon entry fluxes from Table 1, however, show that the radon entry flux for this house is extremely close to the mean of all of the other houses 0.032 Bq m^{-2} s^{-1}. Significantly this house does exhibit a low ventilation rate (0.26 ACH), the second lowest value observed in these houses and well below the mean of 0.32 ACH.

Another important factor is illustrated by a comparison with the performance of House #4, which has a similar entry flux and ventilation rate while having acceptable indoor concentrations of 100 Bq m^{-3}. The difference between these two structures is the magnitude of the indoor air volume. House #4 is a two-story structure and while having a similar normalized entry rate has approximately twice the air volume with which to dilute the entering radon. Without the additional air volume provided by the second story, this structure would also be likely to have average indoor radon concentrations above 148 Bq m^{-3}. We therefore conclude that the major factor contributing to the elevated indoor radon concentrations in House #6 is the combination of a moderate entry flux and a low ventilation rate. We do not believe that the elevated radon concentrations that resulted in this house can be attributed to a failure of the passive barrier features of the draft radon resistant construction standard since the radon entry flux is typical of the successful houses in this study even though it has higher sub-slab radon concentrations than all but one of the other structures. It is important that the radon resistant construction standards provide provisions for maintaining some minimal air exchange rate in residences to help dissipate the radon that is bound to enter these structures even with good passive barriers in place.

CONCLUSIONS

Simultaneous measurements of indoor radon concentrations, driving force pressures for radon entry and house ventilation rates were made in eight newly constructed houses to evaluate radon resistant construction methods. Each of these houses was built over high radon potential soils and were constructed implementing the draft radon resistant construction standards being developed by the Florida Department of Community Affairs.

Radon entry rates were calculated from the measured parameters. The resulting radon entry rates were relatively constant throughout the measurement periods and for different house operating conditions, with variations of indoor radon concentrations being driven predominantly by the house ventilation rate. Normal cycling in the barometric pressure produced a semi-diurnal cycle in the across slab differential pressures in all of the houses studied. These differential pressures did not, however, correlate with observed changes of the radon entry rate, indicating that pressure driven flow is not providing a major contribution to the radon entry. These results imply that the passive radon barrier effectively reduces a large fraction of the convective driven entry. Similarly, averaged radon entry rates and entry fluxes were not correlated to the foundation slab cracking present in these structures. Although measures were taken to reduce the amount of slab cracking, half of the slabs studied exhibited some unplanned slab cracks.

A general figure of merit, the entry rate per unit slab area, or radon entry flux is useful and suggests that residences built using the radon resistant construction standard should be able to have entry fluxes less than about 4.5×10^{-2} Bq m^{-2} s^{-1}. It does not appear that sub-slab radon concentrations high enough to overcome the effectiveness of passive barriers reached in this study. The passive barriers have demonstrated their effectiveness at maintaining radon entry fluxes at less than approximately 4.5×10^{-2} Bq m^{-2} s^{-1} for sub-slab radon concentrations as high as 314,000 Bq m^{-3}. If passive barrier techniques become ineffective at some concentration of sub-slab soil gas radon, it is probably greater than 370,000 Bq m^{-3}. In fact, we observed excellent performance for House #11 at 314,000 Bq m^{-3}, which had quite a low radon entry flux.

This research provides support for and suggests some changes to the current draft of the radon resistant construction standards in several areas. Overall the study demonstrates that the implementation of passive barriers can be practically incorporated in foundations during new house construction and that when implemented as prescribed by the draft standards can successfully prevent indoor radon concentrations from exceeding the 148 Bq m^{-3} guidelines in the majority of houses.

The study results also demonstrate that the operation of well designed and constructed HVAC systems (i.e. those built to current building code standards) does not significantly affect indoor radon concentrations, regardless of the pressures that may be induced between interior air zones. There should, therefore, be no requirement for the radon resistant construction standards to include provisions to transfer air between different air zones within a structure such as transfer grills, door undercuts, etc. A more important subject with which HVAC systems do interact is the overall house ventilation rate. It appears to be prudent to ensure an average house ventilation rate equal to, or greater than 0.25 ACH in order to prevent the accumulation of elevated radon concentrations since passive barriers do not block 100% of the radon from entering.

The radon resistant construction standards developed for residential construction by the Florida Department of Community Affairs have been demonstrated to be technically feasible and can be implemented on a practical basis. Passive barrier techniques can provide houses constructed over sandy fills and high soil gas radon concentrations with acceptable indoor radon concentrations as long as house ventilation rates are not permitted to be too low, and ASD continues to be an inexpensive and very effective back-up to passive barriers.

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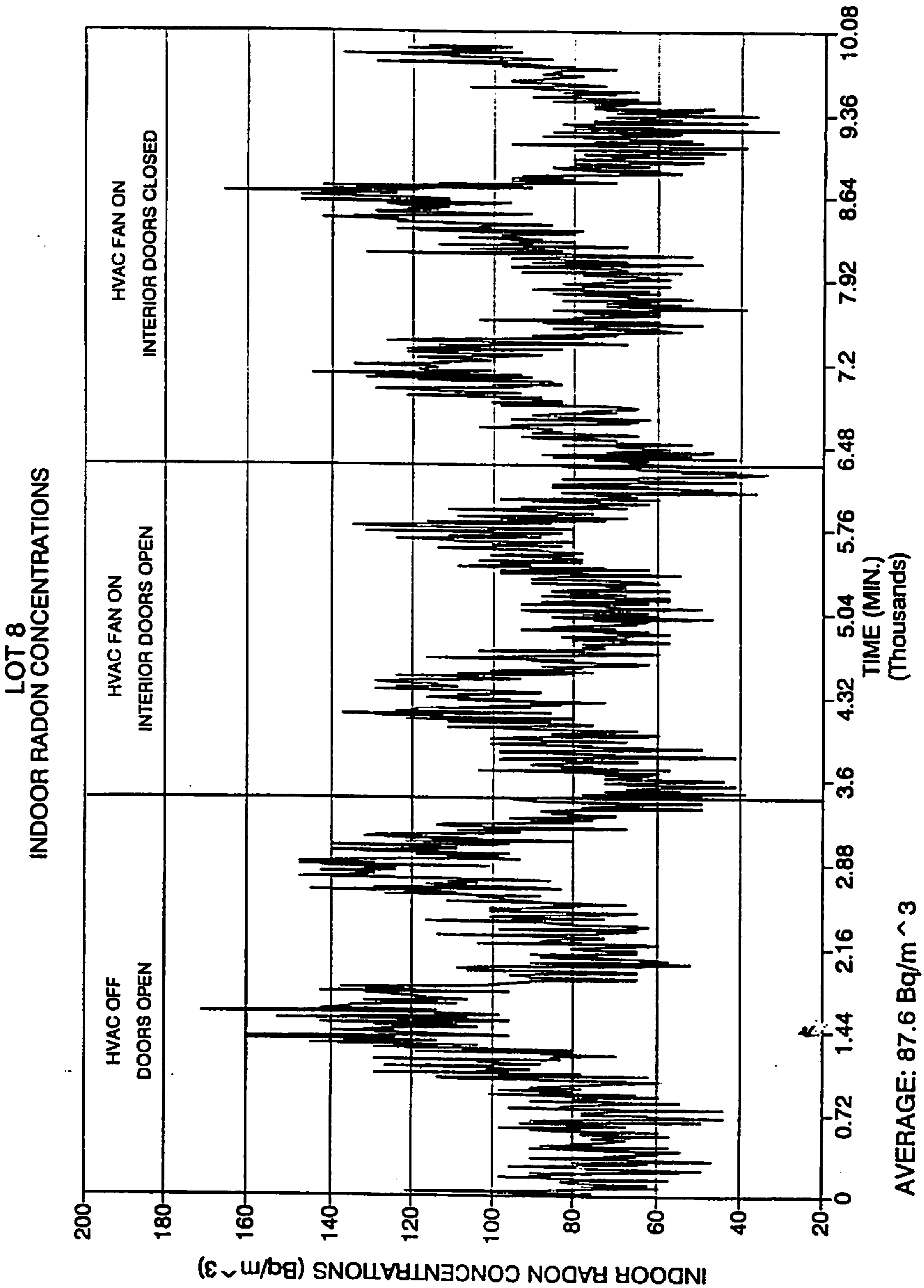
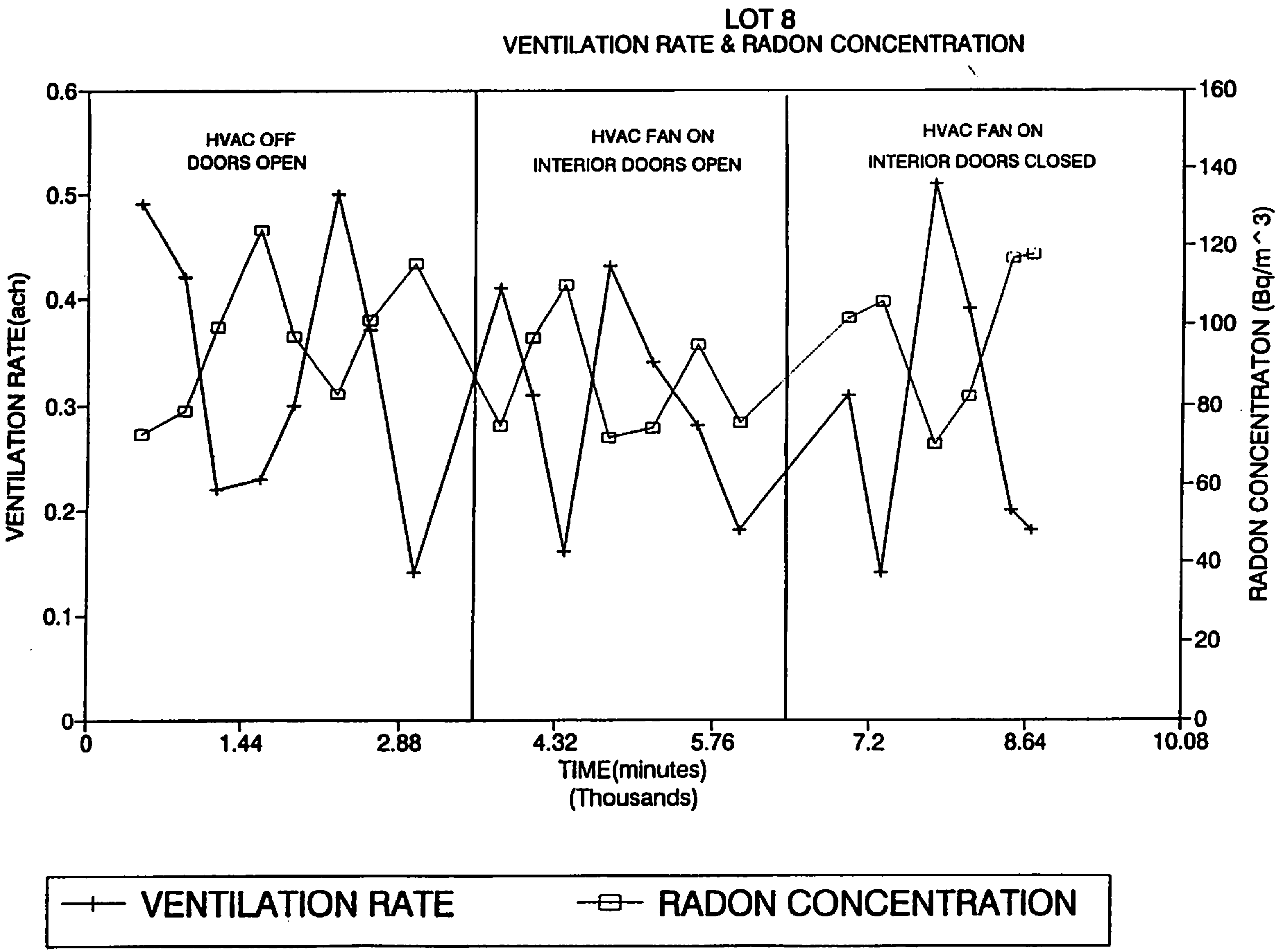
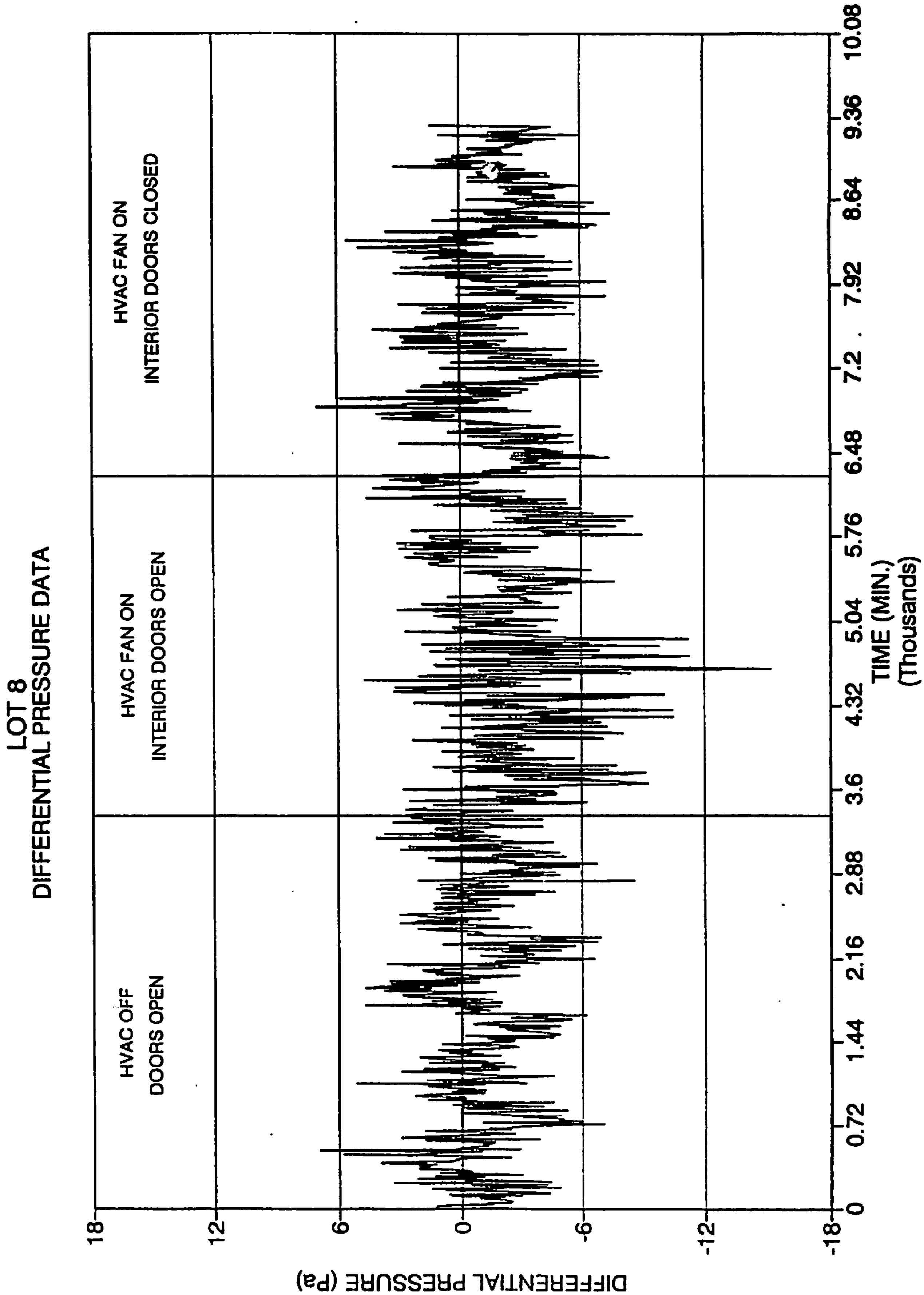


LOT 8
INDOOR RADON CONCENTRATIONS
HVAC OFF
DOORS OPEN
HVAC FAN ON
INTERIOR DOORS OPEN
HVAC FAN ON
INTERIOR DOORS CLOSED
INDOOR RADON CONCENTRATIONS (Bq/m^3)
200
180
160
140
120
100
80
60
40
20
0
0.72
1.44
2.16
2.88
3.6
4.32
5.04
5.76
6.48
7.2
7.92
8.64
9.36
10.08
TIME (MIN.)
(Thousands)
AVERAGE: 87.6 Bq/m^3



LOT 8
VENTILATION RATE & RADON CONCENTRATION
HVAC OFF
DOORS OPEN
HVAC FAN ON
INTERIOR DOORS OPEN
HVAC FAN ON
INTERIOR DOORS CLOSED
VENTILATION RATE(ach)
RADON CONCENTRATON (Bq/m^3)
0.6
0.5
0.4
0.3
0.2
0.1
0
160
140
120
100
80
60
40
20
0
0
1.44
2.88
4.32
5.76
7.2
8.64
10.08
TIME(minutes)
(Thousands)
VENTILATION RATE
RADON CONCENTRATION



LOT 8
DIFFERENTIAL PRESSURE DATA
HVAC OFF
DOORS OPEN
HVAC FAN ON
INTERIOR DOORS OPEN
HVAC FAN ON
INTERIOR DOORS CLOSED
DIFFERENTIAL PRESSURE (Pa)
18
12
6
0
-6
-12
-18
TIME (MIN.)
(Thousands)
0
0.72
1.44
2.16
2.88
3.6
4.32
5.04
5.76
6.48
7.2
7.92
8.64
9.36
10.08