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THE IMPACT OF GAS FURNACE OPERATION ON RADON CONCENTRATIONS IN RESIDENCES: A LITERATURE SURVEY

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The Impact of Gas Furnace Operation on Radon Concentrations in Residences: A Literature Survey

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THE IMPACT OF GAS FURNACE OPERATION ON RADON CONCENTRATIONS IN RESIDENCES

A LITERATURE SURVEY

PREPARED FOR

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Abstract

Radon entry into residences is dominated by the pressure-driven flow of radon-bearing soil gas into the building substructure. The pressure difference driving this flow is caused by the wind, the indoor-outdoor temperature difference, and the operation of ventilation systems that exhaust indoor air to the outside. Combustion-fired furnaces are physical analogs of exhaust ventilation systems and therefore might be expected to cause an increase in the radon entry rate. This survey summarizes the information in the literature that relates furnace activity to indoor radon concentrations. Little direct experimental evidence links the two. The survey then examines literature that relates furnace activity to related parts of the problem. Based on the results of this search and current models of radon entry we conclude that at the present time it is not possible to predict if furnace activity would cause an increase or decrease in radon concentrations in a house.

Introduction

The pressure-driven flow of radon-bearing soil gas into buildings has been identified as a significant, if not predominant source of radon in houses (Nero and Nazaroff, 1984; Nazaroff *et al.*, 1985; Nazaroff *et al.*, 1986; Nazaroff *et al.*, 1987; Akerblom *et al.*, 1984; Sextro, 1987; DSMA, 1983). This convective flow is driven by a pressure gradient established in the soil and across the building substructure. One potential source of the pressure gradient, and thus of an increased radon entry rate, is the operation of furnace systems which draws indoor air for combustion and exhausts the combustion products to the outside through a stack or chimney. The effects of the operation of forced-air combustion furnaces within a house on radon entry and indoor radon concentrations is the topic of this literature review.

Radon in buildings

Radon gas, the decay product of radium 226 that is found in trace amounts in all soils of the earth, has come to be recognized as a major indoor air pollutant. An excellent review of the current status of radon research is presented in the recent book edited by William Nazaroff and Anthony Nero, *Radon and Its Decay Products in Indoor Air* (1988). As the editors note, It is now widely understood that the most important component of radiation exposure to the public is due to the inhalation of radon decay products indoors. Even more important is that the estimated level of health risk associated with average indoor radon levels is much higher than that due to other environmental carcinogens. Furthermore, and perhaps most importantly, radon concentrations ten or even a hundred or more times the average are observed with startling frequency, even in buildings that are otherwise quite ordinary. Long-term exposure to these higher concentrations leads to individual risks of lung cancer that are so high as to be unacceptable by almost any standard (Nazaroff and Nero, 1988).

Furnace activity and radon concentrations

Furnace activity causes several effects in houses that will change radon concentrations. These include:

- An increase or decrease in the pressure difference across the barrier separating the living space from the soil. This will increase or decrease the radon entry rate into the house.
- An increase or decrease in the infiltration rate of the house. This changes the major removal mechanism of radon in the house.
- Mixing air from regions of high radon concentrations (e.g., basements) throughout the living space, therefore increasing concentrations in the living space.

The initial part of the literature survey will examine the influence of furnace activity on radon concentrations. Before beginning, however, we must define terms that will be used in the report.

Furnace operation refers to the combustion driven air flow from the indoors to the outdoors. When the furnace is operating, indoor air is used for combustion (unless the house contains an explicit outdoor air supply) and dilution of the exhaust products of combustion as they move up the stack. This indoor-to-outdoor flow, driven by the buoyancy of the hot air-exhaust product mixture, will generally cause both a small increase in the substructure pressure difference, which is responsible for soil gas entry, and a small increase in the ventilation rate.

Blower operation refers to the distribution of conditioned room air throughout the house. This is an efficient mixing mechanism that tends to equalize pollutant concentrations throughout a house. The operation of the blower can also influence (increase or decrease) the pressure difference across the shell, if there are leaks between the supply or return ductwork and the substructure space (e.g., a basement or crawl space). Once again, the building's ventilation may also be affected.

Furnace activity refers to the entire process in which combustion occurs and blower operation distributes combustion air throughout a house.

Radon Concentrations in Houses with Forced Air Furnaces

There are no studies in the literature that directly examine the effects of gas furnace activity on radon concentrations. Several large, detailed monitoring projects have examined radon entry and the reduction of radon concentrations in houses where levels are excessive (Turk *et al.*, 1987; Turk *et al.*, 1988). Some of the houses in these studies contained combustion furnaces with forced-air distribution systems. However, the studies were not designed to examine the impact of furnace activity on radon concentrations and therefore, only suggestive information can be extracted from these data sets. For example, while the combustion process may have a small effect on radon entry, subsequent blower operation appears to produce much larger pressure effects (both positive and negative in different houses) and swamps the effects of combustion (Turk, 1988).

The data set from one of the houses in which the blower activity does not mask the effect on pressures caused by combustion is the subject of the modeling paper of Revzan *et al.* (1988). Revzan and colleagues extend previous work modeling radon entry to demonstrate dependence of radon concentrations on environmental variables and extent of furnace use. Statistical methods are used to find the best values of the parameters in the models.

Figure 1 displays measured and predicted values of the basement-subslab pressure difference ΔP_{bs}, the fraction of the period during which the furnace was operating A_f, the basement-outdoor temperature difference ΔT_{bo}, and the difference between the basement temperature and the temperature of the soil at a depth of 100 cm ΔT_{bs}. Regression analyses demonstrate that the basement-subslab pressure difference can best be explained by the variations in basement-soil temperature differences and furnace activity.

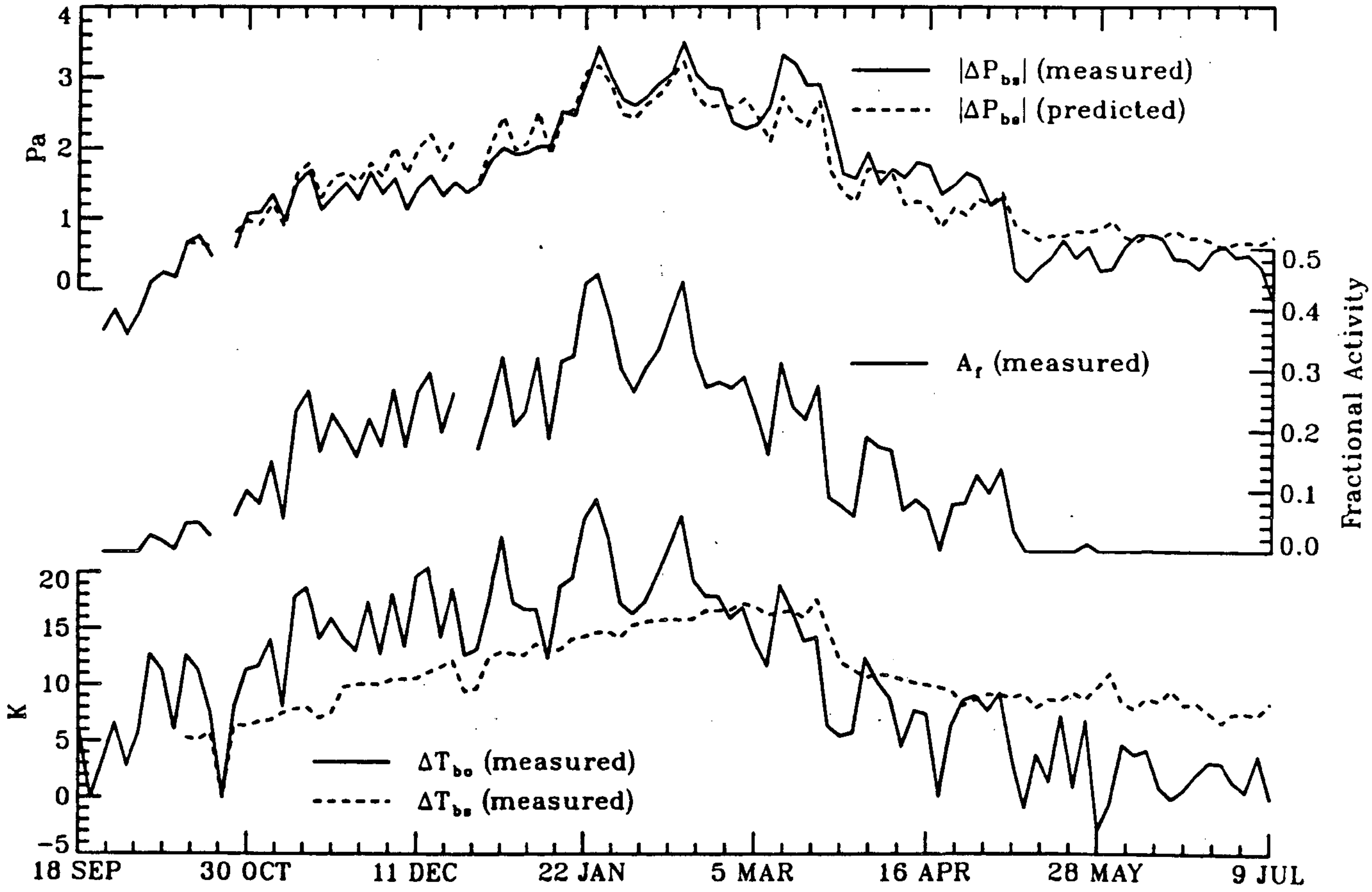

FIGURE 1. Figure 1 displays measured and predicted values of the basement-subslab pressure difference ΔP_{bs}, the fraction of the period during which the furnace was operating A_f, the basement-outdoor temperature difference ΔT_{bo}, and the difference between the basement temperature and the temperature of the soil at a depth of 100 cm ΔT_{bs}. From Revsan et al. (1988).

Similar fits show the importance of furnace activity in explaining time variations in radon concentrations in the basement and living spaces. The incremental effect of furnace activity on radon concentrations in the living area are shown in Figure 2. This result demonstrates the mixing effects of the furnace on radon concentrations within the house. Note that this result will be present in any forced air heating system, i.e., electric or gas. The approximate two-to-one ratio between basement and living space concentrations during non-heating months changes to approximately equal concentrations during the heating season due to the mixing afforded by blower operation.

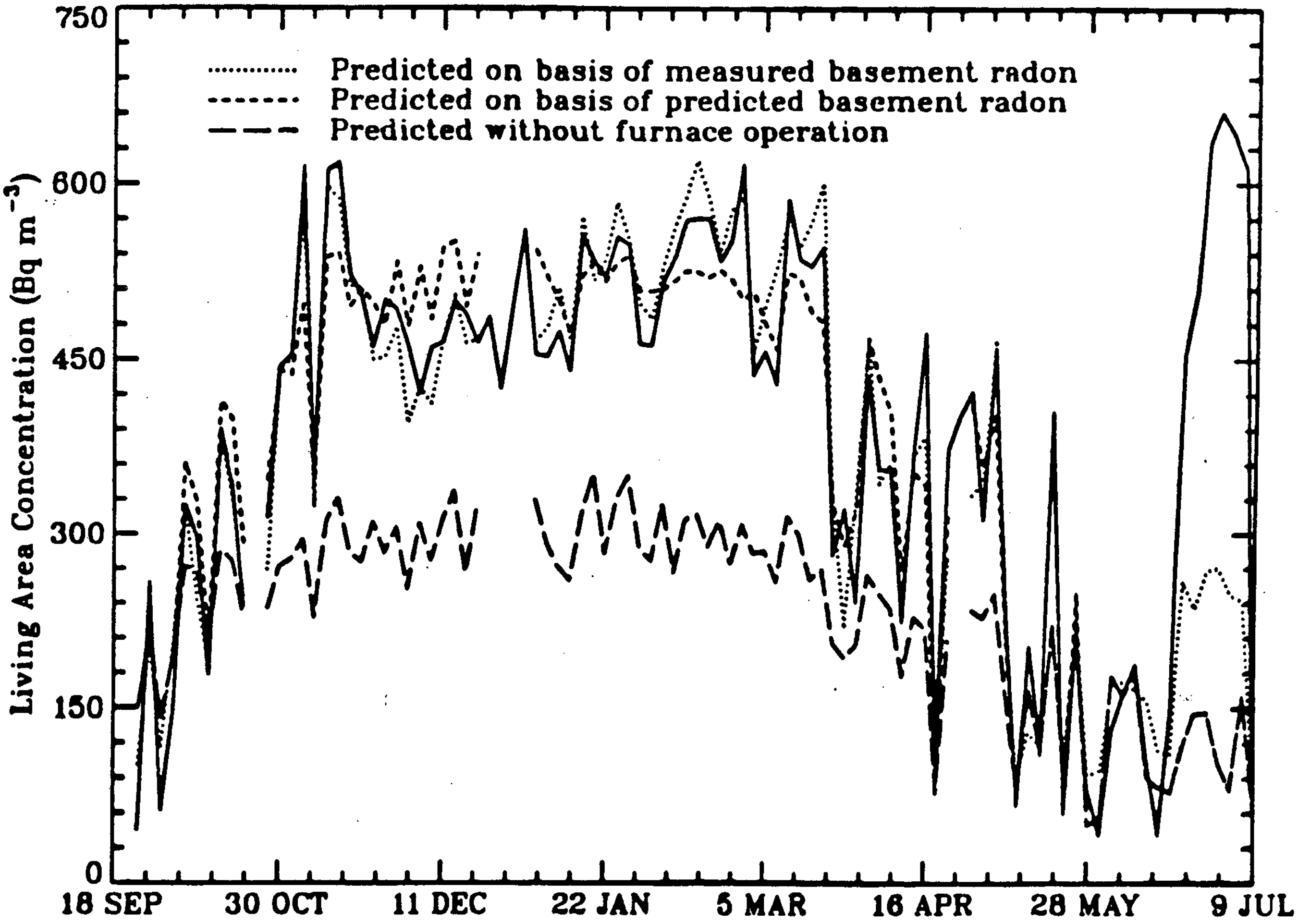

FIGURE 2. Figure 2 shows the predicted radon concentration in the living space based on the modeling of continuous measurements in a single-family house in New Jersey. One pCi/L is equal to 37 Bq/m^3. The substantial difference in predicted radon concentration in the living space of the house is the result of mixing due to furnace blower operation, not increased radon entry due to furnace activity. From Revzan et al. (1988).

A study of a different kind has been conducted in the state of New York. Here 2000 houses were selected randomly and radon concentrations monitored. Included in the information collected about each house was a description of the type of heating system in place. It is tempting to investigate the relationship between the concentrations observed and the types of heating systems present using data collected in this study. However attractive this might be, the analysis would be flawed because different heating system types tend to be clustered in different geographical regions. Since houses with strong radon sources are known to be clustered in particular geographical regions it is impossible to separate the effects of source differences from the effects of heating system types in analyzing the data. If one could find a study population that contained equal numbers of houses with similar characteristics in the same geological regions having electric and gas combustion heating systems, then one might be able to extract useful information. We have not had access to the data set yet to see if this might be done.

An earlier study in New York illustrates these problems. Nitschke *et al.* (1985) reported measurements of ventilation rates and indoor air quality in 60 homes located in upstate New York. Included in the study were six-month integrated alpha-track measurements of radon concentrations in the homes. Fifteen homes had forced-air gas or propane furnaces, five had forced-air electric heating systems, and six had forced-air oil heat. The median concentrations observed in the electric, gas, and oil heated homes, each with forced-air distribution systems, were 1.7, 1.0, and 1.0 pCi - L^{-1}, respectively. Box plots of the distributions for the three heating types are shown in Figure 3.

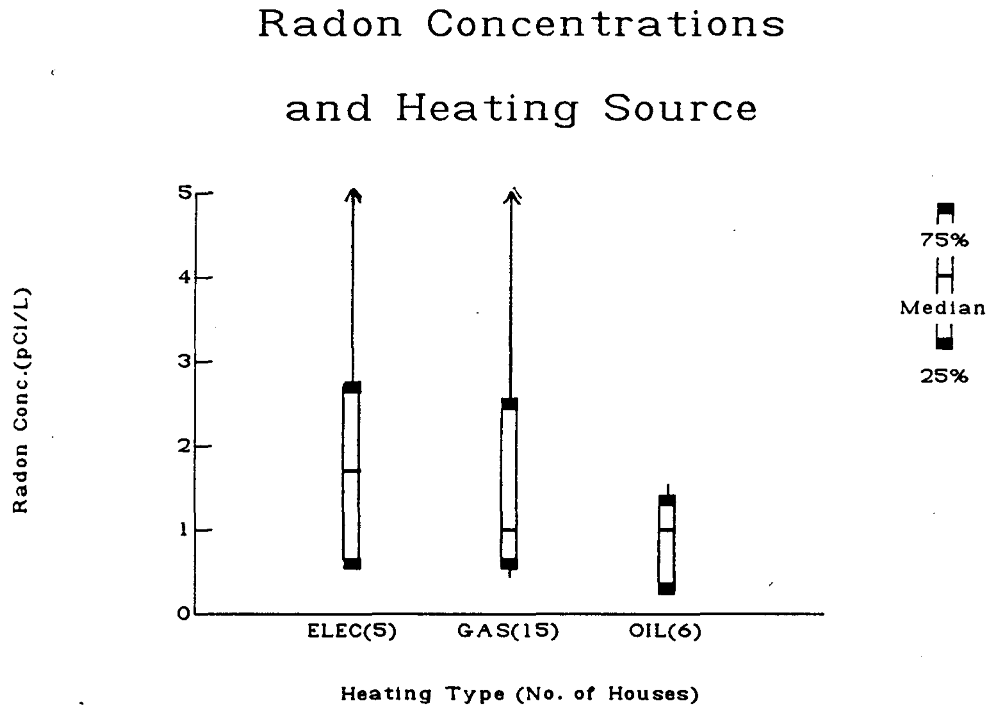

FIGURE 3. A box plot showing the median, 25- and 75-percentile, and extreme points of the distribution of measurements of radon concentrations (six-month averages) in the living spaces of houses in the state of New York. The data are from Nitschke et al. (1985). All heating systems used forced-air distribution systems.

It is not correct to conclude from these distributions that radon concentrations are higher in homes having forced-air electric furnaces than in homes having forced-air gas furnaces. Information about the radon source must be known before such a conclusion is drawn.

Riley *et al.* (1986) reported results of a study investigating ventilation rates and indoor air quality in 300 homes in Canada built to R-2000 energy efficiency standards and compared the results with those obtained from a sample of conventionally-built new homes. Sixty percent of the R-2000 homes and 42% of the conventional homes were heated with electricity; the others with natural gas. Small differences were seen in air infiltration rates between homes heated electrically and gas heated homes but the differences are not statistically significant. Radon concentration differences were not examined between homes heated with the two systems.

Nazaroff *et al.* (1985) observed the effect of the operation of a fireplace on radon concentration and air exchange rate. On five separate occasions over a five-month period of continuous monitoring of a house near Chicago the fireplace was used. On each occasion the air exchange rate increased significantly. During two of the fireplace burns the radon concentration increased substantially; during the other three events, little change in radon concentration was observed. Fireplace operation must have increased the radon entry rate as much as, and in two cases, more than the ventilation rate.

We were not able to find other studies in the literature that examined the impact of furnace activity on indoor radon concentrations directly. We shall therefore examine individual parts of the problem. The remainder of the survey will examine the impacts of furnace and blower operation on building pressures.

Initially we assume that radon entry is dominated by pressure-driven flow of soil-gas into a house. In an elegant series of experiments Nazaroff and colleagues addressed the issue of the importance of diffusive entry from the soil and showed that pressure-driven flow of radon-bearing soil gas is the dominant entry mechanism for radon from the soil, particularly in houses with elevated radon concentrations (Nazaroff *et al.*, 1985; Nazaroff and Doyle, 1985; Nazaroff *et al.*,1987).

Each of the papers above yield results that are consistent with the hypothesis that pressure-driven flow of radon from soil gas into a house is an important entry mechanism for radon. The experiments do not show that diffusive transport does not exist; indeed, it will always exist in the presence of a concentration gradient. However, each experiment adds to our information about the parameters that must be known to calculate the importance of the diffusive term. As that information comes available it becomes clear that the diffusive component of the source term is too small to account for the concentrations seen in houses, particularly those with elevated concentrations. For this reason, mitigation strategies for homes with elevated concentrations have been developed with the pressure-driven flow model in mind.

Furnace Activity and Building Pressures

There are several physical phenomena associated with gas furnace operation that may influence indoor radon concentrations.

- Combustion air is drawn from indoors and exhausted outdoors increasing the indoor-outdoor pressure difference.
- Dilution air is drawn into the draft hood of the furnace during combustion increasing the indoor-outdoor pressure difference.
- The flue/draft hood combination raises the neutral pressure level even when the furnace does not operate, increasing the pressure difference at the base of the building and the ventilation rate.
- Air leakage in the supply or return ducts located outside the conditioned space (e.g., in the attic or crawl space) can increase or decrease the indoor-outdoor pressure difference and present a direct entry path for radon (from the crawl space).
- Blower operation can increase the transport of air between radon and living zones of a building.
- Unequal supply and return flows to a region of a house (e.g., a basement) can increase or decrease the pressure difference that causes radon entry and also change the ventilation rate.

These factors are not independent. The chimney or stack of the furnace will increase the pressure difference across the building substructure that drives radon entry. However, the presence of the stack will also increase the building's infiltration rate -- a factor that will reduce indoor radon concentrations. When the furnace is operating, indoor air is used for combustion (unless the house contains an explicit outdoor air supply) and dilution of the exhaust products of combustion as they move up the stack. This indoor-to-outdoor flow, driven by the buoyancy of the hot-air/exhaust-product mixture, will generally cause both a small increase in the substructure pressure difference, which is responsible for soil gas entry, and a small increase in the ventilation rate. The operation of the furnace system's blower can also influence (increase or decrease) this substructure pressure difference, especially if there are leaks between the supply or return ductwork and the substructure space (e.g., a basement or crawl space). Once again, the building's ventilation may also be affected.

Combustion and building pressures

The impact of gas furnace operation on building pressures has received modest attention in the literature. The dominant theme of these papers has been the investigation of the impact of furnace activity on infiltration, another pressure-driven flow problem.

Elkins and Wensman (1971) examined the effects of weather factors and family activities on the infiltration rates of two identically constructed houses, one gas-heated and the other all-electric, both with forced air heating and cooling. The chimney was blocked in the all-electric house. The two houses ("Living Difference Homes"), located in Ohio, were occupied by families carrying out normal activities. Computerized data recording systems monitored appliance energy consumption, weather data, and activities such as window and door opening and fan operation. The authors report that air infiltration in the gas-fueled house was considerably greater than in the all-electric house, even when gas appliances were not in operation, and displayed a greater sensitivity to wind forces, presumably due to chimney flow. Infiltration rates ranged from 0.24 to 0.83 ACH in the gas home and 0.13 to 0.42 ACH in the electric home. Although the homes were described to be identical, no measurements were reported of their leakage areas.

Nicholas Malik (1978) examined the determinants of air infiltration in a study of two Twin Rivers (NJ) townhouses during the winter. The townhouses were identical in construction, each with a gas furnace located in the basement and with two walls exposed to the outside. Variables examined included indoor-outdoor temperature difference, wind velocity, wind direction, rate of furnace gas consumption, and door openings. Regression analyses of large data sets yielded the result that continuous furnace operation increased the infiltration rate in the structure by 0.24 ± 0.05 ACH. Malik computes the supply of air required for stoichiometric combustion when the furnace fires continuously to be one-third (0.08 ACH) of this (13 cfm). He attributes the remainder (26 cfm) to air entrained with the exhaust gases exiting the flue. Air flow into the basement, either directly from the outside or through the living space, must balance the air lost in combustion and in flow up the chimney.

Joel Peterson (1979) reviewed work examining the impacts of wind, stack effect, furnace operation on air infiltration to produce a simple algorithm for estimating infiltration. He cites studies from the U.S. and Canada demonstrating additional air change rates of 0.19 to 0.40 ACH resulting from continuous furnace operation. Comparisons in houses with gas or electric heating have shown increases of 12 to 50% in the infiltration rates when gas furnaces are used. In addition to the effects of the environmental variables, he suggests adding an additional an average value of 0.1 ACH when estimating infiltration rates in a house containing a gas-fired or oil-fired furnace.

Elkins *et al.* (1979) developed an infiltration model based on indoor-outdoor pressure and temperature difference, wind speed and direction, gas furnace/vent fan operation, and the presence of a chimney. They conducted intensive air infiltration tests in three houses, all with forced-air, gas-fired heating. They report that the presence and operation of a gas furnace significantly contributes to a house's infiltration rate. They estimate that chimney exfiltration during furnace operation is 39 cfm. The existence of a chimney generates additional buoyancy forces, induces a slight whole-house negative pressure, and raises the neutral pressure level. Maximum infiltration rates of 0.26 ACH with chimney open and 0.12 ACH with chimney closed were found for conditions with no wind or temperature driving forces but with the blower operating. Furnace operation tends to decrease the indoor pressure further and raise the neutral pressure level. In a two-storey house 18 feet in height, the neutral level rose from 9 feet with the chimney blocked to 12 feet with it open and the furnace operating.

Shaw and Brown (1982) examined the effect of gas burner and chimney operation on the air leakage characteristics of an unoccupied, two-storey house in Ottawa heated by a forced-air electric or gas furnace located side-by-side in the basement. The chimney was capped during operation of the electric furnace. In a series of tests they reported that a switch from an electric furnace to a gas furnace results in a 50% increase in air infiltration for a test house with wind speeds less than 3.5 m/s and that approximately 60% of the exfiltration was through the chimney. Furthermore, the stack operation reinforced by the exhaust air through the chimney remained the dominant driving mechanism for infiltration with wind speeds up to 7 m/s and indoor-outdoor temperature differences greater than 20K. Flows through the chimney averaged 51 cfm when the furnace was operating continuously and 44 cfm when off. Air infiltration rates when the chimney was capped were 23 cfm smaller than when uncapped. The infiltration rates with the gas burner cycling under thermostatic control were nearly identical to those with it off. A higher inside-outside temperature difference resulted in less difference between the infiltration rates with the burner on and off. Shaw and Brown also found that under calm conditions and a temperature difference of 28K, the operation of the gas furnace produced an additional pressure difference across the building shell of approximately 1.5 Pa and raised the neutral pressure level by 1.2 m (33%).

Several papers (Swinton *et al.*, 1985; Scanada Sheltair Consortium, 1987; and Dumortier and Modera, 1987) examine the related topics of backdrafting, the flow of air and combustion products down the flue and out the dilution device, and spillage, the flow of combustion products out the dilution device when flue flow is upward but not sufficient, in the furnace flues of houses. While important, these deal with the impact of the house on the furnace system rather than the converse; They will therefore not be considered further in this survey.

Blower operation and building pressures

There has been some note in the literature of the impact of leakage in the distribution system of a forced air furnace on infiltration rates. Little attention has been given to duct leakage as a potential entry pathway for pollutants.

Peterson (1979) noted that appliance fans may also contribute to a pressure drop across the building shell and change the air infiltration. Peterson reports that operation of a shower fan, kitchen fan, and/or clothes dryer may add 0.47 to 1.01 ACH to a house's infiltration rate, a surprisingly large number. The operation of a furnace blower may have a similar effect, particularly when leaks are present in the system.

Elkins *et al.* (1979) observed that in test houses, furnace blower operation induced a slight negative pressure in the houses and increased infiltration, especially into the crawl space and attic. During blower operation, tracer gas that was injected into the house to measure infiltration rate built up in the crawl space (and sometimes in the attic). Most air leakage into the attic was directly from the crawl space, with the blower operating and a small (positive or negative) indoor-outdoor temperature difference. Convective transfer through the wall stud spaces was the predominant mechanism of leakage from the crawl space into the attic. With low driving forces (calm wind conditions and little indoor-outdoor temperature difference) the living space air exchange rate averaged 0.22 ACH with the furnace blower on and 0.07 ACH with it off. A negative whole-house pressure of 0.5 to 0.8 Pa was observed for continuous blower operation. A significant portion of blower-induced infiltration is the result of supply and return duct leakage. In one case, while the furnace room door was kept closed and the blower operated continuously, basement air was drawn into the return ducts and discharged into the living space. In another case, house infiltration was almost entirely due to supply duct leakage.

Hawthorne, Gammage, and Dudney (1986) investigated the indoor air quality and air exchange rates of 40 homes in eastern Tennessee over a one year period. Operation of a heating, ventilation, and air conditioning central air circulation fan was identified as the factor having the greatest impact on air exchange. Pilot studies conducted before the main study revealed a considerable increase in air exchange rate while the HVAC fan was on. Fan operation increased the overall infiltration from a mean value of 0.53 ACH in houses without a central air circulation system or with the fan off to a mean value of 0.86 ACH with the fan operating. The large difference in air exchange rates with and without the circulating fan operating was attributed to duct air leaks. Reduced pressure going to the fan and increased pressure after the fan lead to air exchange with garages and crawl spaces. The researchers recorded cases of gasoline vapors and automobile exhaust pollutants entering a duct system under negative pressure from an attached garage and being distributed throughout the living space by the HVAC system. We note that similar effects are likely if leaky ductwork passes through crawl spaces containing radon gas.

Cummings (1988) reported measurements of infiltration rates in nine residences in Florida. Tests were performed with the air conditioner blower on and off. Infiltration rates average 0.62 ACH when the blower was on and 0.22 ACH when off. Cummings was not able to determine if this increased infiltration was a result of duct leakage in the attic or a change in the pressure distribution in the living space.

Discussion

There is no conclusive experimental evidence in the published literature that furnace operation changes the average radon concentration in the living space of a residence due to increased radon entry. However, the results of Revzan *et al.* (1988) shows dramatically that blower operation changes the radon concentration in the living space of a house with a furnace in a basement. We note that this result electric or gas-fired forced air heating systems.

Many researchers have noted the increase in infiltration associated with the operation of a gas furnace. Shaw and Brown were able to quantify the pressure change on the building envelope associated with furnace operation. They were also able to demonstrate the rise in the neutral pressure level of the house with the presence of the chimney.

A final complication in this discussion is the impact of blower operation on radon concentrations. The literature review shows that blower operation combined with duct leakage can increase infiltration substantially (and therefore should increase radon entry) and also provides an entry pathway for pollutants from outside the conditioned envelope. No evidence was reported that it reduces infiltration although one would expect that effect to occur in some houses as well. We note that the issues associated with blower operation will be common to all forced-air heating systems regardless of their heat source. Electric heat-pump forced air systems (and, as Cummings showed, central air conditioning systems) should also display these effects.

Nazaroff *et al.* (1988) present a discussion of the impacts of pressure changes due to unbalanced ventilation modes (a physical analog of gas furnace operation) on infiltration and radon entry. Making simplifying assumptions the authors argue that radon concentrations in a house will vary with changes in the pressure difference across the building envelope raised to a power that ranges between -0.5 and +0.33. The range of the exponent of the pressure difference depends on the flow characteristics of the leakage in the building shell and the properties of the soil surrounding the house. This result indicates that an increase in the pressure difference caused by the furnace operation could either increase or decrease the radon concentration in the house depending on structural characteristics and soil conditions.

Discussion

Mowris and Fisk (1988) have explored a physically similar problem theoretically using both an analytic approach and a two-dimensional finite difference numerical simulation to model the impact of exhaust fan ventilation on radon entry and radon concentrations in houses. Both the simplified theoretical treatment of Nazaroff *et al.* (1988), noted above, and the treatment of Mowris and Fisk offer the possibility of producing results that will help identify the key variables in the problem that must be explored through experiment.

Experimental studies designed to examine the question of the impact of forced air combustion furnaces on radon concentrations in houses should be designed carefully, should use real-time instrumentation, and should examine the question in several climate regions of the United States so that regional variations in housing styles and climates are adequately represented.

Acknowledgments

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