IMPACT OF INFILTRATION-REDUCING ENERGY CONSERVATON MEASURES ON INDOOR AIR QUALITY

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ABSTRACT

This paper reviews both the theoretical and actual impacts of energy conservation measures on indoor air quality in residential structures. Though it is widely believed that energy conservation measures either cause or contribute to indoor air pollution and possible health effects, the relationship is far more complex than is normally assumed. The impact of energy conservation measures on indoor air quality depends in considerable measure on the nature of a given contaminant, its sources, and responses to changes in infiltration and ventilation conditions. For specific contaminants the effect of energy conservation measures which reduce infiltration may be, in some cases, significant, and in other cases minimal or of little consequence. The effect of infiltration-reducing measures on indoor radon and moisture levels are discussed. The primary cause of indoor air pollution is strong sources. Although energy conservation measures may, in some cases, exacerbate an indoor air pollution problem, the assurance of good indoor air quality is best accomplished by source control.

INTRODUCTION

Significant attention has been given to reducing energy usage in both new construction and existing residential dwellings in the past two decades. This emphasis on energy conservation has resulted from the escalating costs of home space heating that began in the middle 1970s. Attempts to reduce residential energy usage have focused on measures to control conductive and convective losses. Increased use of insulation has been prescribed to decrease conductive loses; tight, lower-infiltration construction practices and sealing leakage areas in existing dwellings for decreasing convective losses.

When infiltration is reduced, a concomitant decrease in air exchange rates with the outdoor environment is expected. Reductions in building air exchange rates as a result of energy conservation practices are widely believed to either cause or contribute to indoor air pollution. Because energy conservation practices which reduce infiltration-induced air exchange in dwellings are widely promoted by governmental agencies in North American and northern Europe, as well as by public and private power producers, concern has been expressed that such measures may increase contaminant concentrations sufficient to affect human health (Everett and Dreher 1982).

INFILTRATION REDUCTION

In new construction, significant reductions in infiltration-related energy losses can be achieved by "tightening" the [redacted] [redacted]

building envelope. Such tight construction practices reduce leakage area available for infiltration-induced air exchange and energy losses. Such houses are, therefore, more efficient with significantly lower air exchange rates than previous generations of housing (Grimsrud et al, 1983). On a more limited scale, super-efficient houses have been constructed with air exchange rates as low as 0.10 air changes per hour (Nazaroff et al 1981).

In existing houses, which represent the largest portion of the housing population, efforts have been made by homeowners, public agencies, and power producers to reduce energy losses through the implementation of weatherization practices and programs. The focus of weatherization efforts has been to reduce building leakage areas by caulking and sealing, as well as installing storm windows and doors. Such weatherization measures have had varying success in reducing building leakage area and, by implication, building air exchange rates.

In a study of 60 houses in upstate New York, standard weatherization practices were observed to reduce average leakage area by 17%, with greater effectiveness in houses constructed before 1940 (Sheldon et al 1987). Grimsrud et al (1987) observed that standard weatherization practices reduced leakage areas by about 15%, with reductions of 50% when more intensive weatherization measures were implemented. Studies conducted by the Bonneville Power Administration (Turiel et al 1983; Bonneville Power Administration 1984) indicated that the sum of a variety of weatherization practices (caulking and sealing leakage areas, installing storm windows and doors, sealing air ducts, and blow-in insulation) reduced leakage area by an average of 20-30%, with a range of 0-60%.

GENERAL DILUTION THEORY AND CONTAMINANT CONCENTRATIONS

Concern that reduced outdoor air exchange rates will result in increased indoor contaminant concentrations is based on considerations of general dilution theory (Billings and Vanderslice 1982). By doubling the volume of air available for dilution under static conditions of contaminant generation, the concentration of a contaminant will be reduced by 50%. If the air volume is doubled a second time, the concentration will be halved to 25% of its original value. The converse is also true. By reducing the air volume available for dilution, the concentration is correspondingly increased. If similar dilution phenomena were to occur in buildings, one would expect a significant increase in contaminant concentrations with reduced air exchange rates putatively associated with very tight or moderately tight new housing construction and, to a lesser extent, with the application of weatherization measures in existing dwellings.

Applicability of General Dilution Theory

Is general dilution theory an appropriate means of predicting the effect of reduced air exchange rates on indoor contaminant levels? The answer, of course, is not a simple one. One would expect it to adequately predict the effect of air exchange on contaminants generated episodically (e.g. emissions from gas cooking and tobacco smoking) or where source emissions are constant or fairly so (e.g. human bioeffluents, unvented space heaters, etc.)

Formaldehyde and VOCs. In cases where emissions of contaminants such as formaldehyde and VOCs (volatile organic compounds) from building materials, furnishings and other sources vary in response to changes in environmental parameters such as temperature, relative humidity and ventilation rates themselves, general dilution theory does not apply. In the latter case, increased ventilation results in changes in vapor pressure gradients around the emission source. In response to these changes, emission rates increase. This phenomenon has been reported for sources of formaldehyde and VOCs (Matthews et al 1983; Tichenor and Guo 1991; Hodgson and Girman 1989). In general, a six-fold increase in ventilation will result in a two-fold increase in source strength. Such increases in emission rates offset in part the effect of increased air exchange on contaminant concentrations. These have been observed to compromise the effectiveness of mechanical ventilation systems used in controlling formaldehyde levels in residential structures (Jewell 1984; Matthews et al 1986; Godish and Rouch 1988). This phenomenon diminishes somewhat the effect of tight building envelope construction and weatherization measures on indoor air quality. The effectiveness of general ventilation for continuously-emitted contaminants such as formaldehyde and VOCs is diminished because of emission rate increases associated with increased air exchange.

Radon. General dilution theory can not explain the effect of infiltration and air exchange on indoor radon levels. Indeed, radon entry into dwellings is coupled with building infiltration conditions, that is, indoor radon levels increase with increasing infiltration rates (Arvela and Winqvest 1987).

Several studies which have attempted to determine the effect of energy conservation measures on radon levels in dwellings have reported increased radon levels associated with putatively lower air exchange conditions. Fleisher and Turner (1984), in studies of upstate New York houses, reported that radon levels in 21 energy-efficient houses were 1.5-1.7 times higher than a comparison population of 14 conventional houses. Burkhart et al (1984) observed 1.5-2-fold higher levels in weatherized houses compared to matched houses which were not. In addition, the studies of Nazaroff et al (1981) have demonstrated that elevated radon levels observed in low-infiltration energy-efficient houses could be dramatically reduced by increased building air exchange rates by using balanced ventilation. These studies suggest that decreased air exchange associated with energy conservation measures significantly increase radon levels in houses, albeit far less than would be predicted from general dilution theory.

Significantly different results have been reported from other investigations. Nero et al (1983), for example, observed no significant relationship between air exchange rates and radon levels in 17 energy-efficient and 29 conventional houses in San Francisco and 53 conventional houses in Maryland. Though Grimsrud et al (1987) observed a slight, but not significant, increase in radon levels associated with weatherization measures that reduced specific leakage areas by 15%, they observed a 75% reduction in radon levels in five houses when specific leakage areas were reduced by 50%. Desrochers and Scott (1986) observed no differences in summertime radon levels in a population of seven Canadian houses at an average air exchange of 0.08 ACH compared to a wintertime average of 0.34 ACH. In this last case, Desrochers and Scott (1986) concluded that similar radon levels observed under different air exchange conditions were a result of the counterbalancing effects of stack and wind effects on convective radon soil gas flows and dilution resulting from increased air exchange rates.

The mixed results from the studies reported above may be due to a variety of factors. These differences, which range from increases in radon levels to no net change, to decreases, may reflect differences in study methodologies, source strength, and environmental conditions. Because of the large variation in radon source strengths observed in houses (Nero et al 1983), comparisons between energy efficient and conventional houses using small study populations are not likely to produce reliable results. Balanced ventilation studies may also yield erroneous conclusions. The effect of balanced ventilation is to equalize pressure differences in a building. These pressure differences are the major force responsible for drawing radon-laden soil gas into buildings.

Infiltration has two opposing effects on radon levels. On one hand, it induces convective flows of radon out of the ground and into buildings. On the other hand, increased air exchange rates associated with infiltration would be expected to dilute radon and other contaminants. It is not unrealistic or even inconsistent to observe infiltration-related effects which range from increasing radon levels with infiltration increases, to no net increase as reported by Desrochers and Scott (1986) to decreases in radon levels. The theoretical basis for these observations would be an interplay between radon supply and dilution processes. Under normal conditions it appears that radon levels increase with increasing infiltration rates (Arvela and Winqvist 1987). However, under high soil gas demand infiltration conditions, one can anticipate a depletion or local exhaustion of radon supplies with the dilution effect dominating.

AVERAGE vs PEAK LEVELS

Infiltration inflows of outdoor air into dwellings is affected by two environmental factors, the indoor/outdoor temperature difference (the so-called stack effect) and the wind speed. Infiltration rates increase with increasing wind speed and ΔT, the difference between the indoor and outdoor temperature. When wind speed and ΔT are at minimum values, infiltration potential is low regardless of the "tightness" or "leakiness" of a particular structure. Under such conditions peak contaminant levels (with the exception of radon) would be expected in both energy- and non-energy-efficient buildings. As a consequence, little difference in peak levels would be expected in low, moderate, or high infiltration-potential housing. However, reduced air exchange associated with infiltration-reducing measures would be expected to increase average contaminant levels and exposures. Associated with this phenomenon would be an anticipated increase in contaminant half-life, the period of time that contaminant emissions and indoor levels decrease to 50% of their initial levels. Increases in half-lives associated with low air exchange rates have been observed for formaldehyde sources (Godish 1990).

WEATHERIZATION AND INDOOR CONTAMINANT LEVELS

Studies conducted to evaluate the effectiveness of standard weatherization practices indicate that they reduce effective leakage areas in residential buildings by approximately 15%; with more intensive measures, by 20-30% or more. If one assumes a one-to-one relationship between leakage area and infiltration-induced air exchange, such reductions in air exchange could be described as being low to moderate, with , at worst, a similar impact on indoor contaminant levels.

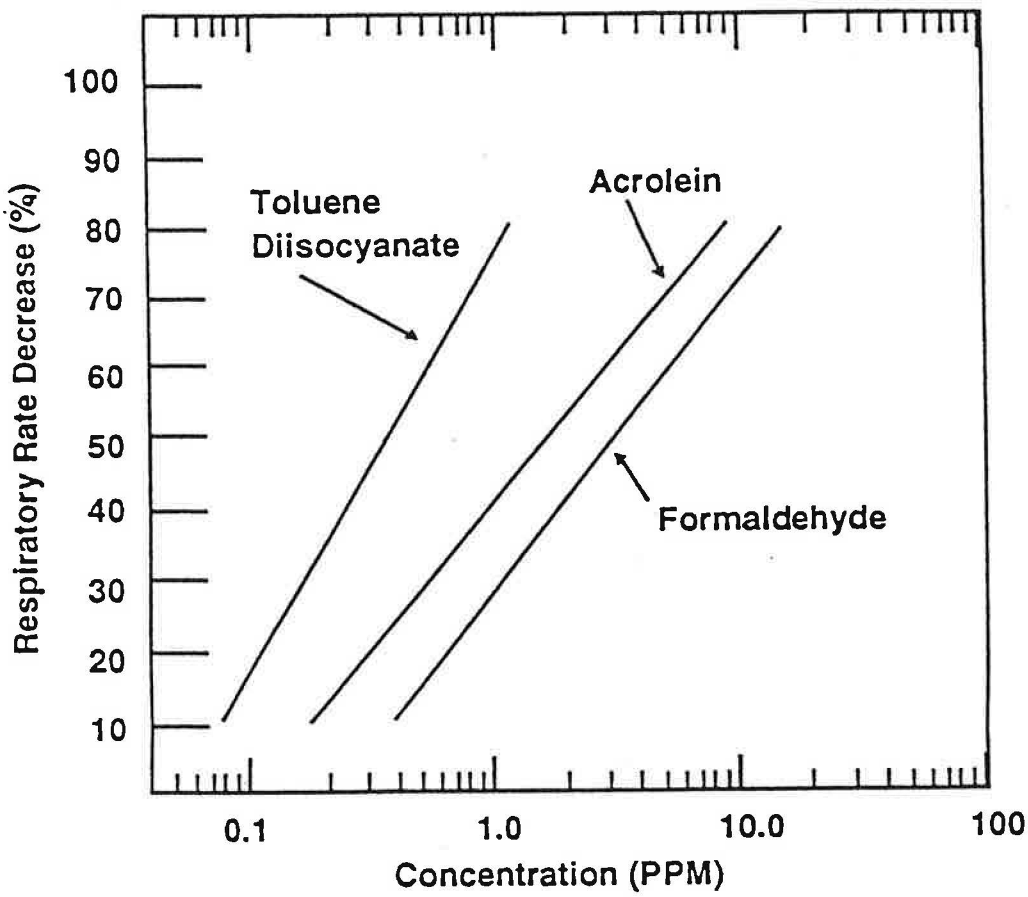
The assumption of an equivalent relationship between leakage area and infiltration-induced air exchange appears not to be valid. Wilcox et al (1990), in a study of 40 California houses, observed no apparent relationship between leakage area and house air exchange rates. There appear to be several factors that confound the relationship between leakage and air exchange rates. In their studies, Wilcox et al (1990) observed differences in leakage area associated with "normal" and taped ducts. The importantce of the "leaky" ducts is that they can result in significant air exchange when heating/cooling system fans are operating, particularly during high heating/cooling demand periods.

In addition to "leaky ducts", caulking and sealing leakage areas around windows and doors in the region of the neutral pressure plane can be expected to have a minimal impact on air exchange since little infiltration occurs where pressure differences are limited.

CONTAMINANT EXPOSURE AND IRRITANT RESPONSE

Further confounding the relationship between infiltration-reducing energy conservation measures and indoor air quality is the relationship that exists between the concentration of irritant chemicals and biological response. In the studies of Alarie (1981) and Anderson (1991), the irritant effects of formaldehyde and other VOCs in mouse bioassays have been observed to be log-linear (Figure 1), that is, about a ten-fold increase in concentration is required to double the irritant response. Conversely, a decrease in concentration of about 90% is required to reduce the irritant response by 50%. This log-linear dose-response relationship of irritant chemicals would suggest that relatively large (order of magnitude) reductions in infiltration-induced air exchange rates would be required to have a significant effect on human responses to irritant chemicals.

Figure 1. Respiratory Response to Irritant Chemical Exposures



THE SPECIAL CASE OF MOISTURE

Though not generally considered to be an indoor contaminant, excessive building moisture levels can nevertheless pose significant indoor air quality and structural problems. These may manifest themselves as condensation on indoor surfaces and in wall cavities. Such condensation may result in physical damage and mold-induced rotting. Mold growth may result in significant mold spore contamination of indoor air. High indoor relative humidities can also promote the growth of mold on indoor surfaces in the absence of condensation and provide a favorable environment for dust mites. Allergens produced by molds and dust mites are major risk factors for inhalant allergies and asthma (Anderson and Korsgaard 1984). Exposure to such biogenic allergens appears to be the single major cause of illness associated with residential buildings. Any change in construction practices or implementation of energy conservation measures that increase indoor moisture levels would be expected to have potentially significant untoward effects on indoor air quality and the health and well-being of occupants.

It is widely assumed that construction or weatherization measures which reduce infiltration-induced air exchange rates will also increase indoor moisture levels. As with other indoor air quality concerns the relationship between indoor moisture levels and infiltration-induced air exchange is far more complex than what initially appears to be the case.

Effect of Infiltration Reduction

A number of investigators have attempted to determine the effect of either tight house construction practices or infiltration-reducing weatherization measures on indoor humidity levels. In a study of the effect of mechanical ventilation on contaminant levels in nine low infiltration houses in upstate New York, Offerman et al (1982) observed that on average a doubling of air exchange rates reduced indoor relative humidity by 5%. In studies of Pacific Northwest houses, Grimsrud et al (1987) observed no increases in water vapor concentrations when conventional infiltration-reduction measures were employed (reduction in specific leakage area of approximately 15%). However, when more intensive measures were implemented (achieving a 50% reduction in leakage area), a 29% increase in water vapor concentration was observed. Harving et al (1992) studied the relationship between air exchange rates and indoor moisture levels in 115 Danish dwellings. Though they observed no significant association between air exchange rates and relative humidity, a significant inverse correlation with absolute humidity or water vapor concentration (n= -0.26) was observed. This relationship accounted for about 7% of the variation between the two variables. The studies described above suggest that infiltration-reducing construction and weatherization measures appear to have a small, or in some cases significant, effect on indoor moisture levels.

Problems in Energy-efficient Houses

In a different type of study, Tsongas (1991) conducted an inspection of 86 relatively new, energy-efficient houses equipped with air-air heat exchange ventilation systems. One-third of these houses had mold and mildew problems on indoor surfaces such as walls, one third on window frames and/or sills, almost three-quarters had condensation on window glass and frames and one quarter had window sill damage as a result of condensation.

These houses had been characterized as having a variety of ventilation problems. Ventilation systems including local exhaust fans and air-air heat exchangers were ~~being~~ not being operated in one-third of the houses inspected, with no kitchen ventilation in two-thirds of the houses and no bathroom ventilation in half the houses.

Studies conducted by Tsongas (1991) have documented serious moisture and mildew problems in a large percentage of the energy-efficient, low-infiltration houses inspected. Differences in the operation and use of local exhaust and whole-house mechanical ventilation systems appeared to be, at least in part, responsible for the problems observed. Results of his study suggest that the installation of mechanical ventilation systems in low-infiltration housing did not provide (for various reasons) the benefits for which they were intended. These observations seriously challenge the assumption that undesirable effects of low-infiltration housing can be relatively easily solved by the installation of mechanical ventilation systems. Though his studies are suggestive of a relationship between energy-efficient houses and low air exchange, definitive conclusions can not be drawn because comparisons were not made with an equal population of less energy-efficient houses.

Household Sources and Indoor Levels

On a theoretical basis one can expect that where there are significant household sources of moisture (such as that associated with bathing, cooking, and people), inadequate ventilation will result in elevated moisture levels near sources of generation and on a whole-house basis. Indeed, in the Danish dwelling study of Harving et al (1992) a significant correlation was observed between absolute humidity and the number of individuals per floor surface area.

In the absence of local exhaust ventilation in high water generation areas such as bathrooms, mold and mildew problems can be expected regardless of a dwelling's infiltration characteristics. In low-infiltration housing such problems may be less localized. Increased air exchange would, however, provide little or no moisture control when outdoor moisture levels are high as is common in some coastal areas. Since significant vapor pressure gradients are required to remove moisture, the absence of such a gradient even at high building air exchange rates would result in little or no reduction in building moisture levels.

Soil Moisture and Indoor Levels

It has been reported that soil moisture is in many cases the dominant source of water vapor in the air of dwellings (Ricketts 1980; Quirotte 1984; Schaub 1985). Soil moisture flows from the ground in a crawlspace may be as high as 50-80L/day in a $130m^2$ house. Although some portion of soil moisture entering living spaces of dwellings may occur from surface evaporation, it is likely that convective flows similar to those that transport radon are a major source of building moisture levels. These convective flows, as previously described for radon, are coupled with infiltration rates. Thus increased infiltration rates would be expected to increase the flux of moisture into a dwelling and decreased infiltration would be expected to result in decreased convective moisture flows. Unlike radon where higher levels are associated with permeable soils (Tanner 1986), moisture is associated with poorly drained soils. The nature of convective soil gas flows from such soils is not known.

Factors Affecting Moisture Problems in Residences

Whether or not a dwelling is going to have a problem with excessive moisture levels will depend on a number of variables. These include the relative magnitude of sources, climate, removal processes, indoor temperature, the presence of cold surfaces, etc. Air exchange as a removal process represents only one of a number of important factors that determine whether a building structure will have moisture and mold problems. The source factor is particularly important. A dwelling constructed on moist ground will likely have moisture and mold problems irrespective of building air exchange conditions. This was evident in the studies of Godish et al (1993) conducted in the Latrobe Valley of Australia. Despite the fact that most of the houses included in the study had no insulation or caulking around windows and doors, they nevertheless had high indoor moisture levels, significant airborne mold concentrations, and respiratory problems among occupants. These problems were likely due, in part, to the relatively cool winter-time indoor temperatures maintained by dwelling occupants during the austral winter and to poor drainage conditions observed on many home sites.

CONCLUSIONS

Infiltration-reducing energy conservation measures employed in new house construction and in weatherization programs are widely believed to cause or contribute to indoor air pollution. In both theoretical and actual terms the relationship among infiltration-reduced building air exchange, contaminant and moisture levels and human health effects is relatively complex. These complexities involve departures from general dilution theory by contaminants such as formaldehyde, VOCS and radon, the coupling effect between infiltration and soil gas flows of radon and water vapor, effects of infiltration on peak versus average contaminant levels and contaminant half-lives, the relatively limited effect of weatherization measures in reducing building air exchange rates, and the log-linear relationships between concentrations of irritant chemicals and human responses. Moisture levels in indoor spaces associated with infiltration-reducing energy conservation measures represent a special concern because of their potential indirect effects on indoor air quality. The complex relationships among reduced building air exchange rates associated with infiltration-reducing energy conservation measures, contaminant and moisture levels, and potential health effects controverts the relatively simplistic views commonly expressed about these relationships. These complexities make a strong case for the use of source control in maintaining good air quality in residential environments.

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