# ASSESSMENT AND CONTROL OF INDOOR AIR QUALITY IN A SUPER-INSULATED, RETROFIT HOUSE

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## Introduction

To demonstrate the effectiveness of energy retrofits, a single family residence in St. Paul MN, originally constructed in 1957, was retrofit in June 1983. Two hundred mm of glass fiber insulation was added to the walls, 300 mm of cellulose insulation was added to the ceiling, and 70 mm of extruded polystyrene insulation was added to the below-grade foundation to a depth of 1.2 m. Triple pane windows, a contiguously sealed 1.5 mm polyethylene vapor barrier, and an air to air heat exchanger were also added. These modifications resulted in approximately 50% reduction in annual heating consumption compared to the average consumption used during the previous three years, but complaints of poor air quality were registered by the occupants.

In this paper, an assessment of the resultant indoor air quality is reported. Also reported are additional modifications that have been made to the HVAC system to improve the indoor air quality without compromising the energy savings achieved through the energy retrofit.

## Assessment of Energy Retrofit

Physical characteristics of the house and occupancy patterns of the family were determined by completion of a survey form, a questionnaire, and a daily log. Zonal air exchange rates, including infiltration, and concentrations of indoor contaminants were determined by real-time measurements during a 42-hour period.

### Existing Conditions

The family is comprised of a working father and mother, three teen-age children and one child of grade school age. The mother, father and two of the teen-agers smoke cigarettes. The youngest child is asthmatic. Occupancy patterns are seldom routine as the father works days, the mother works evenings, and two of the teen-agers have graduated from high school. A schematic of the HVAC system, as it existed after the energy retrofit, is shown in Fig. 1. The central forced air system had a gas-fired furnace and an electrically-driven refrigeration system with an air-cooled condenser which was located near the outdoor air intake and exhaust grilles. An electronic air cleaner had been previously installed. The kitchen range was electric, but the range hood had been deactivated when the ceiling was insulated and the vapor barrier was installed. The vents from the gas-fired water heater and clothes dryer were connected to the air-to-air heat exchanger, as shown, including a diversion damper that allowed the vent from the clothes dryer to be directly coupled to the system return air. The capacity of the furnace had been reduced by deactivating one burner, but the supply air flow rate was maintained.

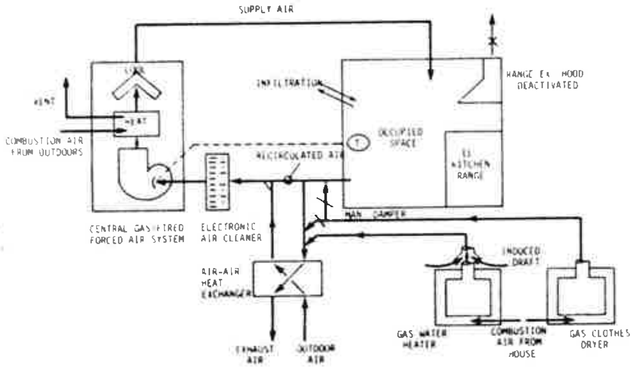


Fig. 1. Schematic of existing (before IAQ modifications)

## Air Quality Measurements

Continuous measurements of $CO_2$, CO, $NO_2$, HCHO, dry-bulb temperature, and relative humidity were obtained in the upstairs kitchen, a downstairs bedroom, and outdoors. The tracer gas, $CH_4$, was also measured at these locations. A manifold was constructed to draw the air samples through instrumentation and discharge it back to the sampling locations. Radon and particulate measurements were obtained in the downstairs den. Measurements were obtained over a 42-hour period in July 1984. Integrated samples of $NO_2$ were also made with Palmes-tube type devices during a one week period following the test. During the test, the HVAC system was cycled by the room thermostat. The electronic air cleaner was energized with the system, but the air-to-air heat exchanger ran continuously.

Results indicated that the air exchange rates in the kitchen and bedroom were approximately 0.14 and 0.24 ACH during the initial and latter parts of the test, respectively. This change was found to correlate well with weather conditions, as half-way through the test the wind became gusty and the direction shifted about 180 degrees. The kitchen temperature was 5$^{o}$C warmer and the relative humidity was 20% lower than the downstairs bedroom; thus, enthalpies in the two zones were nearly equal. Concentrations of $CO_2$ in the two rooms indoors were not significantly different, but increased to about 1200 ppm during the first half of the test, as opposed to 600 ppm during the latter half. These concentrations also correlated well with the change in wind patterns. Differences between indoor and outdoor concentrations of HCHO and $NO_2$ were negligible during the test; CO differences were also small most of the time, but spikes were detected which appeared to correlate with the parking of automobiles near



the outdoor air intakes. Peaks in particulate measurements to more than 500 ug/m$^3$ appeared to correlate with periods of relatively high smoking. The average concentration during the test was 113 ug/m$^3$. To verify the apparent relationship with smoking, particulate concentrations in two ranges were examined: 0.3-0.4 and >3 um. As tobacco smoke usually has an upper size of 1-2 um, larger particulates may have been related to vacuum cleaning or other activities. Differences in the larger particulate size were not detected except for two events. Measurements of radon decay products in the downstairs den indicated that levels were less than 0.002 WL.

## System Modifications

### Description of Modifications

Based on results of the air quality assessment, and comupter simulations of the system performance, modifications, shown schematically in Fig. 2, were made: 1) replacement of the air-air heat exchanger with a dilution control packake that provides adiabatic mixing of outdoor air and return air for thermal and air quality control; 2) redistribution of supply air to the downstairs bedrooms and den; 3) installation of return air grille and ductwork in the child's upstairs bedroom; 4) replacement of kitchen range and deactivated exhaust hood with a unit containing gaseous feedback control for exhaust or recirculation through an electronic air cleaner; 5) relocation of the outdoor air intake to the opposite side of the house from the exhaust grilles to minimize self-contamination of the ventilation air; and 6) revision of control strategies to improve dehumidification in winter by dilution and in summer by refrigeration.

### Control Strategies

To provide improved air quality with little or no impact to the annual energy consumption, the control system has been modified to function in six psychrometric regions, as shown in Fig. 3.

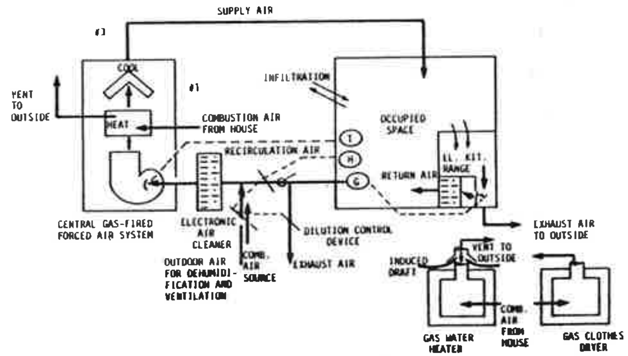


Fig. 2. Schematic of system after IAQ modifications.

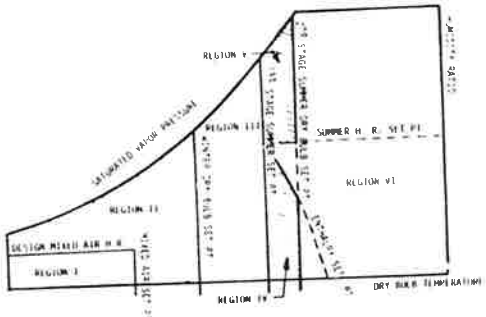


Fig. 3. Psychrometric regions for energy efficient IAQ control stratgies.

Region I: cold-dry outdoor conditions. When the thermostat calls for heating, the furnace is energized; the electronic air cleaner is energized with the supply fan. If the room humidity is below set point, the outdoor damper in the dilution control package remains in the minimally open position for combustion air, the exhaust damper closes and the return damper opens to recirculate the air. If the room humidity is above set point, the outdoor and exhaust air dampers open and the return air damper closes to maintain a mixed air temperature at 12.8 °C and humidity ratio of 0.0036 $kg_w/kg_a$, or less (i.e. mixed air relative humidity not more than 40% at winter design conditions). If the room humidity is above set point and the thermostat has the furnace de-energized, the supply fan is energized by the humidistat; if recirculation is not sufficient to lower the humidity below the set point in 15 minutes, the dampers modulate to provide mixed air at 12.8°C at RH $\leq$ 40%.

Region II: cool-humid outdoor conditions. Thermostatic control is the same as for Region I. If the humidity ratio of the outdoor air exceeds 0.0036 $kg_w/kg_a$, the minimum amount of dehumidification available through this strategy is limited by the humidity ratio and temperature of the outdoor air. For example, 45% outdoor air (e.g., 125 l/s) is required to maintain a mixed air temperature of 12.8 °C if the return and outdoor air temperatures are 21.8 and 1.7 °C, respectively. If the outdoor air is saturated with water vapor, the minimum dehumidification available is 0.37 kg/hr; for colder outdoor temperatures, the difference in humidity ratios increases thus increasing the dehumidification capability although the percentage of outdoor air decreases; for warmer outdoor temperatures, the percentage of outdoor air increases thus increasing the dehumidification rate assuming the outdoor air humidity ratio remains constant. When the humidity ratio of the outdoor exceeds that corresponding to the set point of the humidistat, dehumidification cannot be achieved by dilution.

Region III: isothermal conditions. When the outdoor temperature is above the winter and below the summer set points of the thermostat, the furnace and the refrigeration system are de-energized. However, if set point of the humidistat is set above the humidity of the oudoor air, removal and dilution control with outdoor air is provided.



Region IV: warm-dry outdoor conditions. When the room air temperature exceeds the first-stage summer set point, the humidity is below the set point of the humidistat, and the enthalpy of the outdoor air is below the loci of set points of the economizer control, sensible cooling is provided by dilution control with outdoor air supplied at low fan speed.

Region V: warm-humid outdoor conditions. When the room air temperature exceeds the first-stage summer set point and the humidity is above the set point of the humidistat, the dampers in the dilution package are de-energized (i.e., minimum outdoor air provided), the refrigeration system is energized, and air is supplied at low fan speed to decrease the sensible heat ratio for improved dehumidification and energy efficiency.

Region VI: hot outdoor conditions. When the room air temperature exceeds the second-stage summer set point, the dampers remain de-energized and air is supplied at high fan speed to increase the sensible heat ratio required for sensible and latent cooling at summer design conditions.

## Re-evaluation

The modified system was re-evaluated in February 1985. Preliminary results indicate that room air humidity control at 30% RH was achieved at the room air temperature of 21.8 °C, compared to humidities which often exceeded 50%, previously, and resulted in condensation formation on the windows. Concentrations of $CO_2$ did not exceed 600 ppm during the first week of the re-evaluation, except when thermostatic night set-back was employed. During night set-back, the furnace remained de-energized throughout the night. Temperatures upstairs and downstairs dropped less than 2 and 3 °C, respectively, although outdoor temperatures dropped to below -12 °C. Because the humidity remained below set point, the supply air fan was not energized during night set-back and stratification between rooms became apparent. For example, the $CO_2$ concentration in the downstairs bedroom increased to approximately 1100 ppm when cigarette smoking occurred and the door was closed, while the $CO_2$ concentration in the upstairs kitchen remained at approximately 600 ppm.

## Conclusions

This study provides evidence that if the environmental impact of energy retrofits is not controlled, potential energy savings may not be realized because of the health risks perceived by the homeowners and occupants. Also evident is that $CO_2$ concentrations in residences may be sufficiently high for concern, that periods of maximum exposure to indoor contaminants do not necessarily occur at times of maximum heating or cooling requirements, and that air to air heat exchangers may not provide sufficient dilution during moderating seasons. Thus, if the potential for energy savings is to be maximized, control strategies that are also responsive environmental acceptability are required.

SUMMARY

J.E. Woods, B.C. Krafthefer, L.W. Nelson, and C.A. Lane: Assessment and Control of Indoor Air Quality in a Super-insulated House. To demonstrate the effectiveness of energy retrofits, a single family residence in St. Paul, Minnesota, originally constructed in 1957, was retrofit in June, 1983. These modifications resulted in approximately 50 reduction in annual heating consumption compared to the average consumption used during the previous three years. However, complaints of poor air quality were registered by the occupants. Measurements indicated that total particulates, CO, $CO_2$, relative humidity, and temperature were at levels of some concern; $NO_2$, radon and formaldehyde concentrations were not significant. To improve the indoor air quality while maintaining energy efficiency, additional modifications to the HVAC system have now been made. Results indicate that acceptable environmental quality can be achieved with minimal impact on energy consumption.

RESUME

J.E. Woods, B.C. Krafthefer, L.W. Nelson, and C.A. Lane: Evaluation et Réglage de la Qualité d'Air à l'Interieur d'une Maison Super-Insolée. Pour démontrer l'efficacité de la rétro-adaptation d'une maison pour économiser l'énergie, une maison habitée par une famille seulement construite en 1957, a eté rétro-adaptée in juin, 1983. Ces modifications ont eu comme résultat une diminution d'environ 50% de la dépense annuelle pour chauffage en comparison de la dépense moyenne pour les trois années précédentes. Mais, les habitants se plainaient de la mauvaise qualité de l'air. Des mesures ont indiqué que la matière en particule, CO, $CO_2$, et l'humidité rélative, one été au niveau de souci; $NO_2$, radon et formaldéhyde n'étaient pas présents en concentrations importantes. Pour améliorer la qualité de l'air à l'intérieure de la maison et, en même temps maintenir l'efficacité de l'énergie, des modifications supplémentaires ont été apportées au système HVAC. Les résultats indiquent q'une qualité d'environment admissible peut être accompli avec un effet minimum sur la consommation de l'énergie.

KURZFASSUNG

J.E. Woods, B.C. Krafthefer, L.W. Nelson, and C.A. Lane: Nachweis und Regelung der Luftqualität in einem hochwärmegedämmten Haus. Zum Nachweis von effektiven Energieeinsparungsmassnahmen wurde ein Einfamilienhaus in St. Paul, Minnesota (Baujahr 1957) mit solchen Massnahmen ausgestattet. Diese Massnahmen verursachten eine ca. 50%-ige Heizenergieeinsparung, bezogen auf den Energieverbrauch in den drei Jahren davor. Jedoch beklagten sich die Einwohner über mangelhafte Luftqualitat. Gemessene Werte für Staub, CO, $CO_2$, rel. Feuchtigkeit und Temperatur bezeugten diese Unbehaglichkeit, während die Konzentrationen für $NO_2$, Formaldehyd und Radon normal ausfielen. Zur Verbesserung der Luftqualität haben wir jetzt weitere Änderungen am Heiz- und Lüftungssystem angebracht. Die Ergebnisse zeigen, dass befriedigende Luftqualität erreich wurde, mit minimalen Einfluss auf die Energiekosten.