NIST Technical Note 1673

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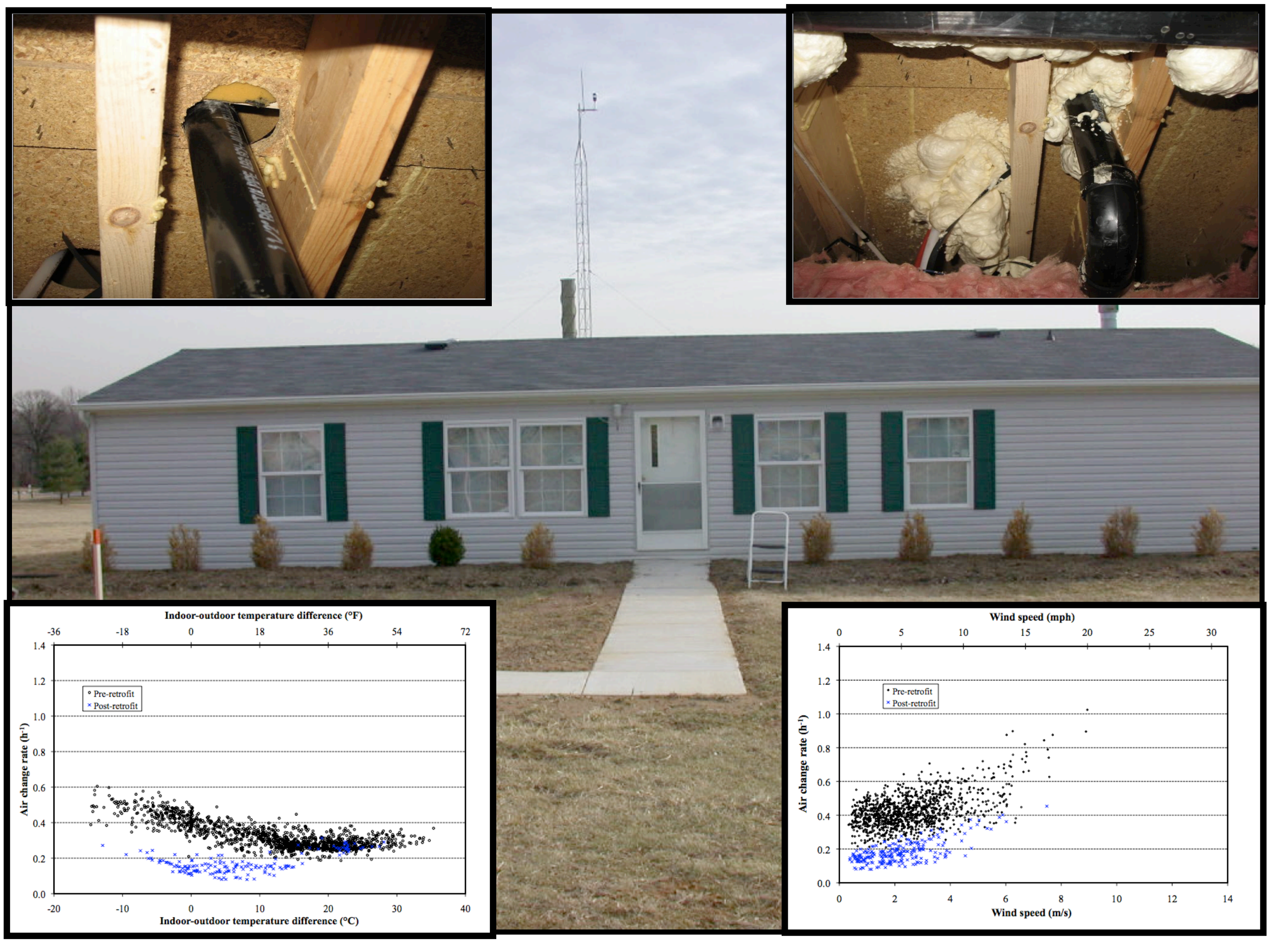

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ABSTRACT

A retrofit study was conducted in an unoccupied manufactured house to investigate the impacts of airtightening on ventilation rates and energy consumption. This report describes the retrofits and the results of the pre- and post-retrofit assessment of building airtightness, ventilation, and energy use. Building envelope and air distribution systems airtightness were measured using fan pressurization. Air change rates were measured continuously using the tracer gas decay technique. Energy consumption associated with heating and cooling was monitored through measurement of gas consumption by the forced-air furnace for heating and electricity use by the air-conditioning system for cooling. The results of the study show that the retrofits reduced building envelope leakage by about 18 % and duct leakage by about 80 %. The reduction in the house infiltration rates depended on weather conditions and the manner in which the heating and cooling system was controlled, but in general these rates were reduced by about one third. The energy consumption of the house for heating and cooling was reduced by only about 10 %, which is relatively small but not unexpected given that infiltration only accounts for a portion of the heating and cooling load. An existing multizone airflow model of the building was modified to reflect the airtightening retrofits, and the predicted infiltration rates agreed well with the measured values over a range of weather and system operation conditions.

Keywords: duct leakage, energy consumption, manufactured housing, mechanical ventilation, residential, retrofit, ventilation.

1. INTRODUCTION

Single-family residential buildings have traditionally been ventilated via weather-driven infiltration through unintentional leakage sites in the building envelope. More recently, there has been a trend towards the use of mechanical ventilation to provide more predictable ventilation rates and air distribution that are less dependent on weather conditions. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, requires mechanical ventilation in many U.S. climates (ASHRAE 2010). However, only a small fraction of site-built, low-rise residential buildings employ mechanical ventilation. The situation is different in manufactured homes, for which the U.S. Department of Housing and Urban Development Manufactured Home Construction and Safety Standards (HUD 1994) contain requirements for mechanical ventilation for these dwellings. In the implementation of the HUD standards, and for mechanical ventilation in low-rise residential buildings in general, questions exist regarding the actual ventilation rates in homes built to the HUD and other standards, the approaches being used to provide mechanical ventilation, and the energy and indoor air quality impacts of mechanical ventilation (Lubliner, Stevens et al. 1997). Specific questions also exist regarding how duct leakage, local exhaust fans and ventilation inlets affect ventilation rates, air movement patterns, and building pressures.

Based on 2005 statistics, manufactured homes constitute about 6 % of U.S. households and about 5 % of U.S. residential energy consumption (DOE 2005). These same data show that on average manufactured homes consume more energy per unit floor area on an annual basis, 850 MJ/m^2 (75000 Btu/ft^2), than detached homes, which consume 450 MJ/m^2 (39,800 Btu/ft^2). Given the smaller size of manufactured homes, the average energy consumption per household is about 74 GJ/y (70 MBtu/y) compared with 114 GJ/y (108 MBtu/y) for detached homes. Low energy manufactured homes have been constructed, with annual energy consumption as low as 52 MJ/y (49 MBtu/y) (Lubliner, Hadley et al. 2004). Therefore, while manufactured homes constitute a small fraction of the national housing stock, they also provide an opportunity for significant energy savings through improved design, construction and operation.

The manner in which residential buildings, including manufactured homes, are ventilated and the roles of weather-driven infiltration and mechanical ventilation are becoming increasingly important in the context of national efforts to reduce residential energy consumption in new and existing buildings. Working with HUD and various state energy offices, the U.S. Department of Energy is undertaking a major effort to retrofit large numbers of residences (DOE 2010). A number of other efforts are underway to increase the energy efficiency of new residential buildings. One key component of energy efficiency in both new and existing residences is the control of infiltration through tight envelope construction and the provision of adequate amounts of outdoor air to meet the health and comfort needs of the occupants. Efforts to improve building design and to implement effective retrofits are raising the same questions noted previously about how to provide ventilation in residential buildings and how ventilation and energy performance are impacted by duct leakage, fan operation and other effects.

To obtain insight into the issues of residential infiltration and ventilation, a modeling study was performed on a manufactured home to investigate different ventilation scenarios (Persily and Martin 2000). The results of that study showed that assuming a single value of 0.25 h^{-1} for the weather-driven infiltration rate, as is done in the HUD standard, is inherently problematic given the strong dependence of infiltration on weather. The simulated infiltration rates varied by as much as 5 to 1 based on variations in weather conditions alone. Including the impacts of exhaust fan and forced-air fan operation more than doubled the amount of variation in the air change rates. In addition, the predicted infiltration rates were lower than this assumed value under milder weather conditions, even in relatively leaky buildings. Therefore, assuming an infiltration rate of 0.25 h^{-1} in modern manufactured homes may be too high, but more importantly ignores variations due to weather and fan operation. The study also showed that employing an outdoor air intake duct on the forced-air return duct can be effective in raising air change rates and distributing ventilation air throughout the house. However, the overall impact on the building air change rate is a strong function of the operating schedule of the forced-air system, which in turn depends on the extent of system over-sizing and the specific strategies used to control the system operation such as manual switches and timers. While increased forced-air fan operation provides higher ventilation rates, there is an energy cost associated with the increased fan operation, particularly when the forced-air fan has a high wattage rating. Also, given the existence of significant duct leakage, this ventilation approach was associated with high air change rates (relative to requirements in standards), particularly when weather-driven infiltration was high.

In order to investigate these residential ventilation issues, as well as a range of other indoor air quality issues, a manufactured house was built on the NIST campus in 2002. The house and its airtightness, ventilation and energy performance, as installed, have been described previously (Nabinger and Persily 2008). Since that time, the building was subject to a series of retrofits to improve the airtightness of the building envelope and the air distribution system ductwork. This report summarizes the impacts of these retrofit on the building airtightness, ventilation rates and energy consumption.

2. DESCRIPTION OF HOUSE AND VENTILATION SYSTEMS

The study was performed in a double-wide manufactured home on the NIST campus, shown in Figure 1. This house was built to the HUD standard that applies nationwide to manufactured homes (HUD 1994). Additional details on the house can be found in Nabinger and Persily (2008). Figure 2 is a schematic floor plan of the test house, showing the three bedrooms, two baths, kitchen, and the family, dining and living area. The house has a floor area of 140 m^2 (1500 ft^2), a volume of 340 m^3 (12,000 ft^3) and a cathedral ceiling over its full length that is 2.7 m (9.0 ft) high at the center and slopes down to 2.1 m (7.0 ft) at the front and back walls.

The exterior construction consists of insulated wood-frame walls, with exterior vinyl siding and an interior finish of vinyl covered drywall without taped and textured joints, as well as a vapor retarder in the walls, ceiling and floor. The house sits on a cinder block foundation forming a crawl space with moisture sealed walls and a floor of polyethylene sheet over crushed stone. The crawl space has a floor area of 140 m^2 (1500 ft^2) and a volume of roughly 140 m^3 (5000 ft^3). The crawl space contains the belly of the house in two sections corresponding to the front and rear of the house, each 4.1 m deep x 17 m wide (13.5 ft x 56 ft). As seen in Figure 3, the belly contains the supply duct work within an insulated membrane (i.e., belly blanket). The house has an asphalt-shingled roof with five roof vents and eave vents spanning its perimeter.

The house's heating, ventilating and air-conditioning (HVAC) system consists of a 22 kW (77,000 Btu/h) gas furnace, a 15 kW (3 ton) air conditioner, and a forced air re-circulation fan with a design airflow rate of 470 L/s (1000 cfm). In addition there are whole house, kitchen, and two bathroom exhaust fans in the house. The whole house and bathroom ventilation fans have an airflow capacity of 24 L/s (50 cfm), while the kitchen fan capacity is 47 L/s (100 cfm). Both of these airflow capacities are per manufacturer claims.

There are several options for ventilating the house. One option is simply to rely on envelope infiltration driven by the wind and indoor-outdoor temperature differences, as is done in most single-family dwellings. Infiltration may be supplemented by periodic operation of local exhaust fans in the bathrooms and kitchen. The house can also be ventilated through an outdoor air intake duct on the return of the forced air fan, which draws in outdoor air whenever the fan is operating. This fan can operate either continuously or by thermostat control. In addition, the whole house exhaust fan can be operated with or without passive window vents open.

Figure 1: Photograph of the manufactured house

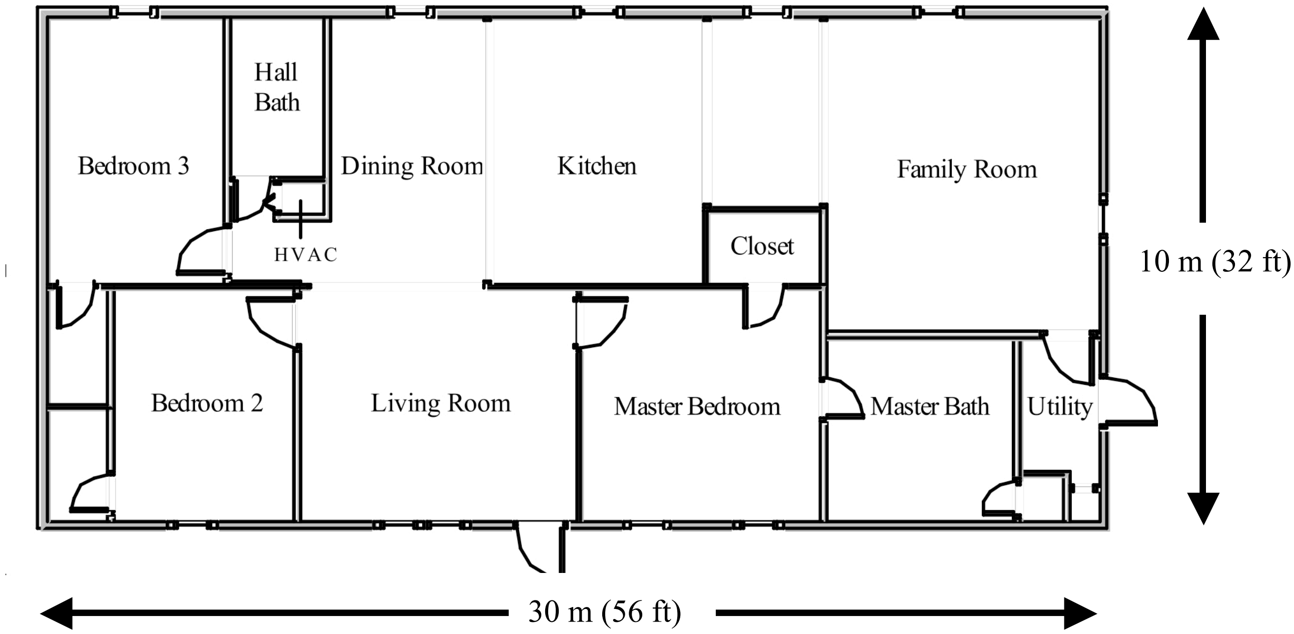


Figure 2: Schematic of floor plan of manufactured house

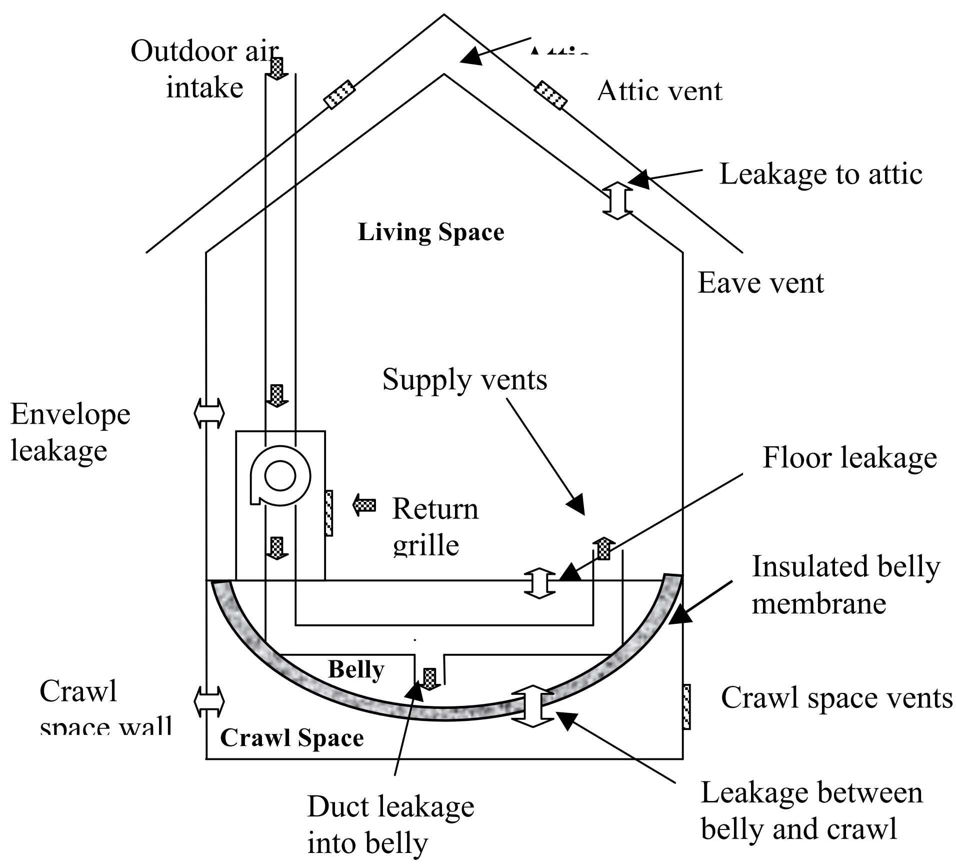


Figure 3: Schematic elevation of manufactured house

3. MEASUREMENT METHODS

This section summarizes the measurement techniques and instrumentation used in the test house, with additional details available in Nabinger and Persily (2008).

3.1 Whole house air change rates

Whole house air change rates were measured using the tracer gas decay technique as described in ASTM test method E-741 (ASTM 2006). These rates reflect the combination of the rate at which outdoor air enters the house from mechanical ventilation and outdoor air entry due to infiltration through leaks in the house's envelope. The air change rate measurements in the house were made with an automated tracer gas monitor system employing sulfur hexafluoride (SF_6) as the tracer gas that injects tracer gas into the building and monitors the concentration at multiple locations.

Tracer gas was injected every 4 h to 6 h to achieve an initial tracer gas concentration of about 0.7 mg/m^3 (120 ppb(v)) in the house. After injection, the gas was allowed to mix for about 10 min to obtain a uniform concentration throughout the house. The house's forced-air system was used to distribute and mix the tracer gas in many of the tests. In tests with the forced-air fan off or controlled by the thermostat, three mixing fans were operated. Tracer gas concentrations were monitored at seven indoor locations, one outdoor location, the crawl space and the attic, with the concentration at each location measured once every ten minutes. The tracer gas system is capable of measuring SF_6 concentrations with an uncertainty of about 5 % of the reading with an estimated uncertainty in the estimated air change rates of 10 %.

3.2 Exterior envelope and duct leakage

Exterior envelope leakage of the house was measured using whole building pressurization testing per ASTM E779 with a blower door (ASTM 2003). These whole building tests were performed with the air distribution system off but with all the vents in their normal operating positions (unsealed) and then again with all the supply and return air vents sealed with plastic (sealed). The latter test provides an indication of the envelope leakage independent of any leakage via the air distribution system, while the unsealed test provides an overall leakage for the envelope and air distribution system in combination. Additional tests using two pressurization fans were used to estimate the leakage from the living space to the belly, the belly to the crawl space, and the crawl space to outside. The blower doors were calibrated using a fan calibration chamber in accordance with ASTM E1258 (ASTM 2003). The measurements of airtightness using the blower door have an accuracy of roughly +/- 10 % of the measured value based on the calibrations performed. Pressurization tests were also used to determine the leakage from the air distribution system using ASTM E1554 (ASTM 2003), which also has a measurement uncertainty of about +/- 10%.

3.3 Airflow rates

HVAC system and local exhaust fan airflow rates were measured on several occasions. These flows included the return and supply airflow rates at each vent and the outdoor air intake rate. A differential pressure grid was used to measure the return airflow rate into the system through the return grill of the furnace. A flow hood was used to measure the airflow rate through the outdoor air intake duct as well as the individual supply vents and the kitchen and bathroom exhaust fans. The accuracy of the differential pressure grid is +/- 7 %. The accuracy of the flow hood is stated to be +/- 3 % of full scale plus 1 L/s (2 cfm) of the measured flow rate.

3.4 Energy consumption

Energy consumption for heating and cooling was monitored to determine any reductions due to the airtightness retrofits. The electrical energy consumption of the air conditioning system was measured using a 240 V power transducer, and the energy used by the forced-air fan was monitored with 120 V energy meters. The energy use by other items in the house, and therefore contributing to the interior heat gain, were monitored separately. The 240 V power transducers have an accuracy of +/- 0.5 % of full scale and a resolution of 0.1 W. The 120 V energy meters have an accuracy of +/- 0.2 % of full scale and a resolution of 3.6 W•h. The heating energy was measured using a calibrated gas flow meter that recorded the natural gas flow rate into the furnace. The gas meter has a measurement range of 0 L/s to 0.94 L/s (0 cfm to 2 cfm), an accuracy of 1 % of full scale and a resolution of 0.0002 L/s (0.0004 cfm).

3.4 Environmental and System Parameters

Additional sensors were used to monitor air temperature, relative humidity, wind conditions and operating status of the forced-air system fan.

Temperatures of the indoor and outdoor air were measured using epoxy coated polymer thermistors with a maximum error no greater than 0.5 ºC (0.9 ºF). Relative humidity was monitored with capacitive thin film polymer sensors that are accurate within 2 % RH of the measured value over the range of 0 % RH to 90 % RH and within 3 % RH over the range of 90 % RH to 100 % RH for temperature conditions between -40 ºC and 60 ºC (-40 ºF and 140 ºF). Differential pressure sensors are located on each of the exterior walls of the house to measure the pressures across the building envelope. An additional sensor was used to measure the pressure difference from the house to the attic, and two more to measure across the floor to the crawl space. These transducers are capable of measuring pressure differences of +25 Pa to -25 Pa (0.1 in. wg to -0.1 in. wg) with an accuracy of 0.5 Pa (0.002 in. wg) and a resolution of 0.1 Pa (0.0004 in. wg).

Wind speed and direction are measured at the top of a 10 m (33 ft) tower located approximately 5 m (16 ft) south of the southernmost wall of the house. The anemometer is capable of measuring wind speeds between 0 m/s to 50 m/s (0 mph to 110 mph) with an accuracy of 0.5 m/s or 5 % and a resolution of 0.1 m/s (0.2 mph). Wind direction is measured within 5 % accuracy at wind speeds greater than 4.5 m/s (10 mph). Fan status switches are wired into the electrical circuits of the forced air fan and the four exhaust fans to detect and record whether each fan is on or off.

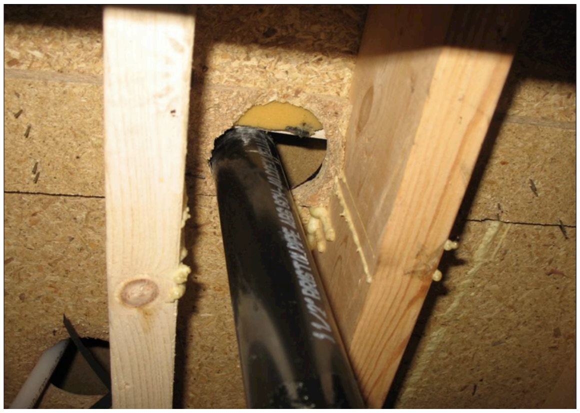
4. RETROFITS

The retrofits focused on increasing the airtightness of the building envelope and the air distribution system supply ductwork. The envelope retrofits included installation of a house wrap over the exterior walls and sealing of leaks in the belly and living space floor. The house wrap installation involved removing the siding from the house and installing the wrap from the top of the crawl space to the top of the walls, and then replacing the vinyl siding. The wrap was a flash spunbonded olefin, non-woven sheet material and was installed per the manufacturer’s instructions. The second portion of the envelope airtightening effort involved sealing the leakage sites in the flooring of the house and in the insulated belly that encloses the ductwork. Sealing the flooring involved spraying a two-part foam, which expanded and hardened to seal the leaks. The leakage sites included the accessible portions of the marriage line between the front and back section of the house; holes in the floor made for the water drainage pipes, "P-traps" in the bathrooms; and gas and other utility lines.

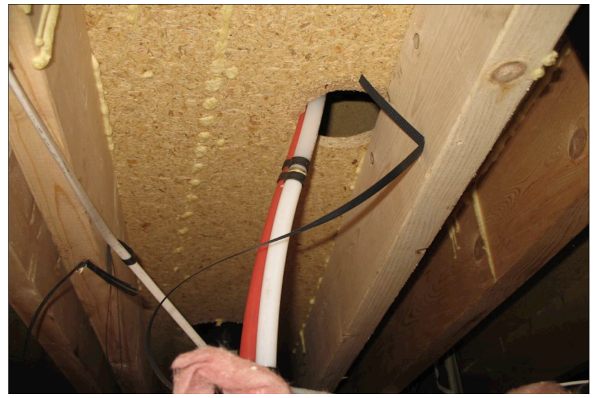
Figure 4 shows several of these leakage sites, before and after sealing. The top two photographs show drain and water lines in the floor of the living area, viewed from below, showing these lines passing through large holes that constitute significant leakage sites. The existence of such leakage sites is not unusual in residential construction, though recent efforts to build tighter homes result in such airflow paths being sealed during construction. The photograph on the lower right shows both of these leakage sites sealed with spray foam. The photograph on the lower left shows a supply air register in the floor, viewed from above, after it was sealed with mastic. In this house, and many others with supply ductwork under the floor, significant leakage occurs where the vertical supply duct connects with the floor register.

Additional air sealing was performed in the air distribution system in the belly space, including large leaks in the four ends of the two main supply ducts in the front and rear halves of the house and the large connection to the underside of the HVAC system. Foam was also used to seal leaks at the ends of the two crossover ducts joining the two main HVAC ducts at each end of the house. Such duct leakage is not uncommon in manufactured homes and can have a major effect on the overall system efficiency and thereby the energy consumption for heating and cooling (Francisco and Palmiter 2007).

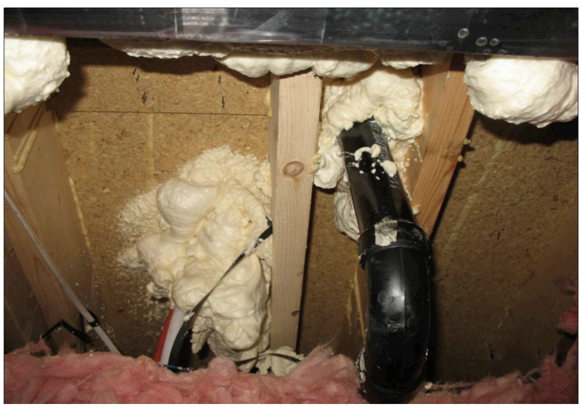
As noted elsewhere in this report, it is much easier and cost-effective to achieve a tight envelope during construction than as part of a retrofit effort. The retrofits reported on here were thorough, even to the extent of removing the siding to install a house wrap, but some leakages sites were inaccessible. No leaks in the ceiling of the house could be accessed or sealed, and there were probably additional leaks in the floor and the belly that could not be repaired.



Drain line in floor (from below), leakage associated with large hole in floor relative to pipe diameter



Water line in floor (from below)



Drain and water lines after sealing

Floor register (from above) after sealing with mastic

Figure 4 Air leakage sites in floor, before and after sealing

5. RESULTS

This section presents the results of the measurements of the impact of the retrofits on the building and air distribution system tightness, ventilation system airflow rates, whole building air change rates and energy consumption for heating and cooling.

5.1 Airtightness

As noted above, pressurization test methods were used to measure the exterior envelope leakage, the leakage between the living space and the crawl space, and the leakage of the air distribution system ductwork. The results of these measurements are shown in Table 1. In terms of the air change rate at 50 Pa (0.2 in w.g.), the whole building pressurization leakage was reduced by 24 % relative to the pre-retrofit results with the system unsealed and by about 11 % relative to pre-retrofit leakage with the system sealed. As noted before, the unsealed tests were conducted with the air distribution system off but with all vents in their normally open positions, while the sealed tests were conducted with all supply and return vents sealed. The leakage reduction in terms of the effective leakage area (ELA) at 4 Pa (0.016 in. wg) was similar on a percentage basis. Relative to the average of the unsealed and sealed pre-retrofit values, the house leakage was reduced by 18 % by the airtightening retrofits. Table 1 also shows the impact of the retrofits on the air leakage from the living space to the belly and from the belly to the crawl space. The post-retrofit measurements did not allow a reliable determination of these values separately, only of their combined leakage. If these two leakage paths are assumed to be equal, the living space to belly leakage is reduced by about 65 % and the belly to crawl space leakage by about 30 %. The duct leakage reduction is quite significant, about 82 % relative to the pre-retrofit value.

Table 1 Pre- and Post-Retrofit Airtightness Test Results

	Pre-retrofit		Post-retrofit	
Whole building pressurization	Airflow at 50 Pa, h^{-1}	ELA at 4 Pa, cm^2 (in^2)	Airflow at 50 Pa, h^{-1}	ELA at 4 Pa, cm^2 (in^2)
Forced-air system unsealed	11.8	728 (113)	9.0*	555 (86)*
Forced-air system sealed	10.1	636 (99)		
Air leakage, living space to belly		510 (80)		181 (28)**
Air leakage, belly to crawl space		258 (40)		181 (28)**
Air leakage, crawl space to outside		787 (122)		Unchanged
	Pre-retrofit		**Post-retrofit**	
	ELA at 25 Pa, cm^2 (in^2)			
Duct leakage		320 (50)		58 (9)

* Post-retrofit values with the system sealed and unsealed are not significantly different relative to measurement uncertainty.

** Combined leakage from living space to crawl space measured directly and assumed to be equally distributed between these two leaks.

5.2 System airflow rates

Airflow rates through the forced air distribution system were measured before and after the duct sealing efforts. Note that these airflow rates are the flows when the system is operating, which are distinct from the duct leakage values discussed above. The latter values are measured under an imposed pressure difference using an external fan system installed temporarily for the purpose of the leakage test. Table 2 shows the results of the airflow measurements, first for the supply airflows. Figure 5 is the floor plan of the house showing the numbered supply vents referred to in Table 2. Before the retrofit the supply airflow rates range from about 15 L/s to 30 L/s (40 cfm to 60 cfm) for the individual vents, with the exception of vent #6 in bedroom #3, which has a much higher airflow rate. This vent was upstream of a crushed, and therefore restricted, crossover duct, which may explain the high value. The table also shows a significant difference in the supply airflow between the front and rear sections of the house before the retrofit. The airflow rate to the front of the house was about half of that to the back, which was likely due to the partially crushed crossover duct. The post-retrofit supply airflow rates were all higher than the pre-retrofit values, presumably due to a combination of the tightened ductwork and the sealing performed at the vents themselves.

Table 2: Supply airflow rate measurements

		Airflow rate L/s (cfm)	
Supply airflows			
Room	**Vent No.**	**Pre-retrofit**	**Post-retrofit**
Family	1	39 (83)	54 (114)
Family	2	32 (67	44 (94)
Kitchen	3	33 (69)	39 (82)
Dining	4	32 (67)	41 (87)
Bath2	5	22 (47)	40 (85)
Bed3	6	67 (142)	62 (132)
Bed2	7	15 (32)	21 (44)
Living	8	18 (39)	27 (57)
Living	9	21 (44)	28 (59)
Bed1	10	22 (47)	29 (62)
Bed1	11	16 (34)	25 (53)
Bath1	12	12 (25)	17 (37)
Utility	13	15 (32)	24 (50)
Subtotal-rear	1 to 6	224 (475)	280 (593)
Subtotal-front	7 to 13	120 (255)	170 (360)
Total	**1 to 13**	**344 (729)**	**450 (953)**
Outdoor air intake		8 (16)	13 (28)

Table 2 also shows the airflow measured at the outdoor air intake, with the post-retrofit value about 60 % higher than the pre-retrofit value. The increase is presumably due to the reduced duct leakage, which increases the airflow rates through the desired paths. However, the outdoor air intake rate is still only about half of the mechanical ventilation requirement based on the HUD MHCSS, which is 25 L/s (53 cfm) for this house.

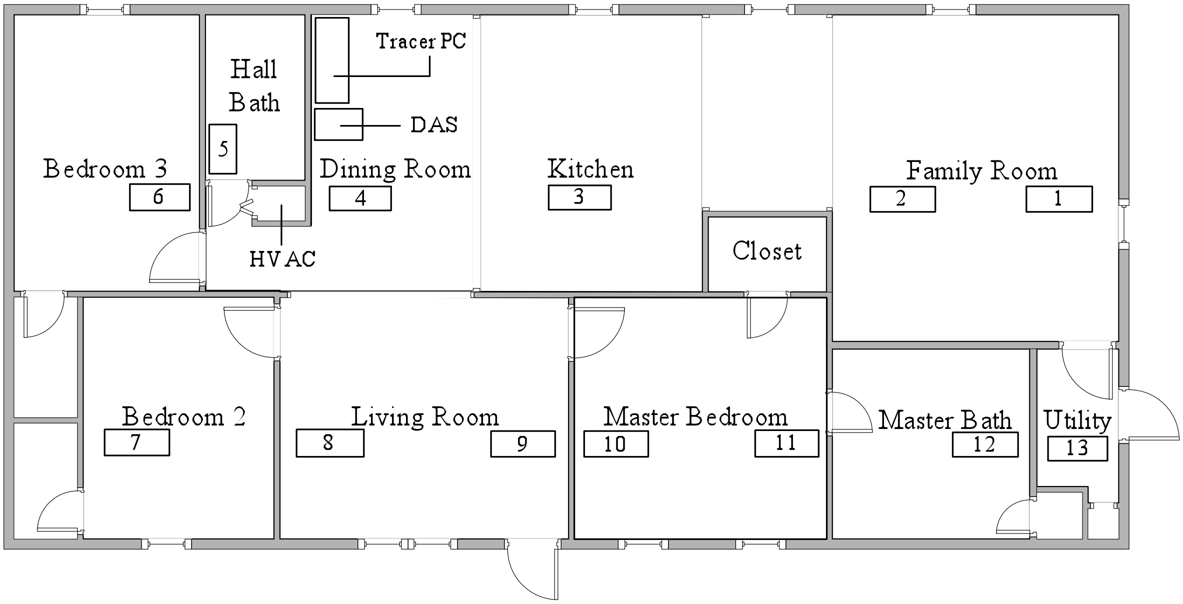


Figure 5 Floor plan with supply vent locations

5.3 Air change rates

The air change rates in the house decreased after the airtightening retrofits as expected. Figure 6 shows the pre- and post-retrofit air change rates measured with the forced-air system off (Condition 0) as a function of the indoor-outdoor temperature difference under low wind speed conditions (less than 2 m/s). While the data exhibit a fair bit of scatter, the post-retrofit rates are roughly 20 % lower than the pre-retrofit values, which is close to the reduction in the whole building leakage measured by pressurization testing seen in Table 1. Figure 7 shows the pre- and post-retrofit air change rates with the forced-air system off as a function of wind speed (u) under low indoor-outdoor temperature differences (ΔT), i.e., absolute values less than 10 °C (18 °F). There are only a relatively small number of post-retrofit points, but the reduction in air change rates is again roughly 20 % relative to the pre-retrofit values.

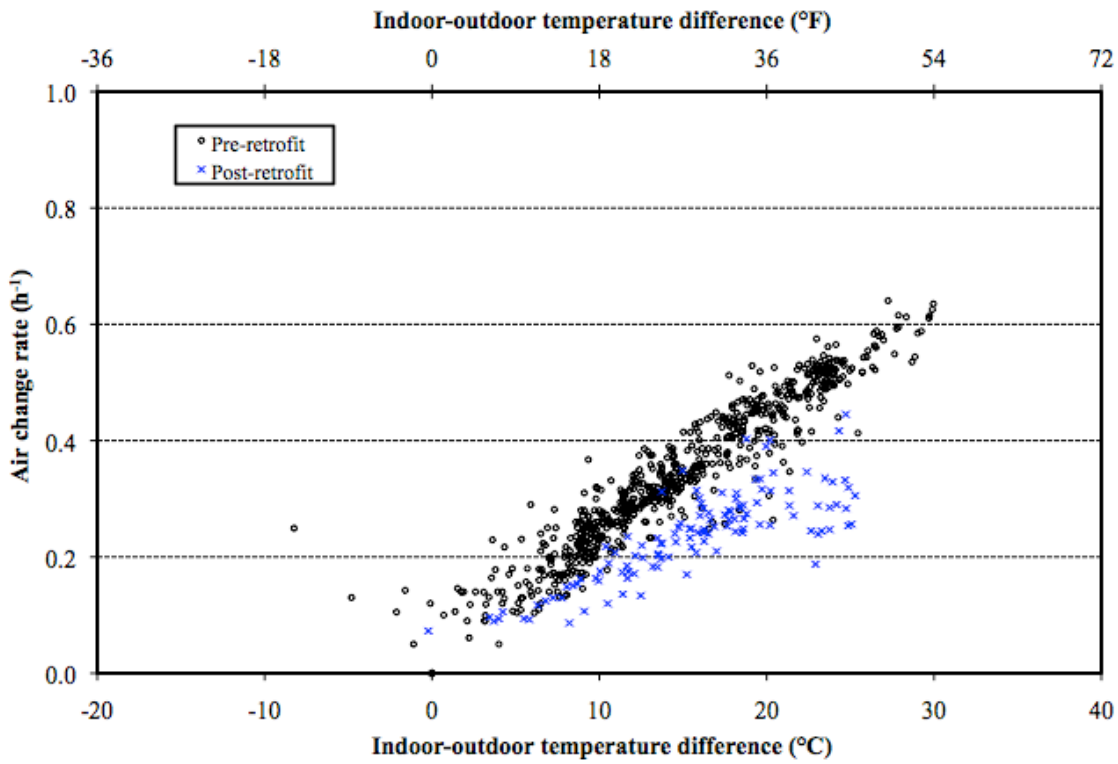


Figure 6 Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): Forced-air fan off (Condition 0)

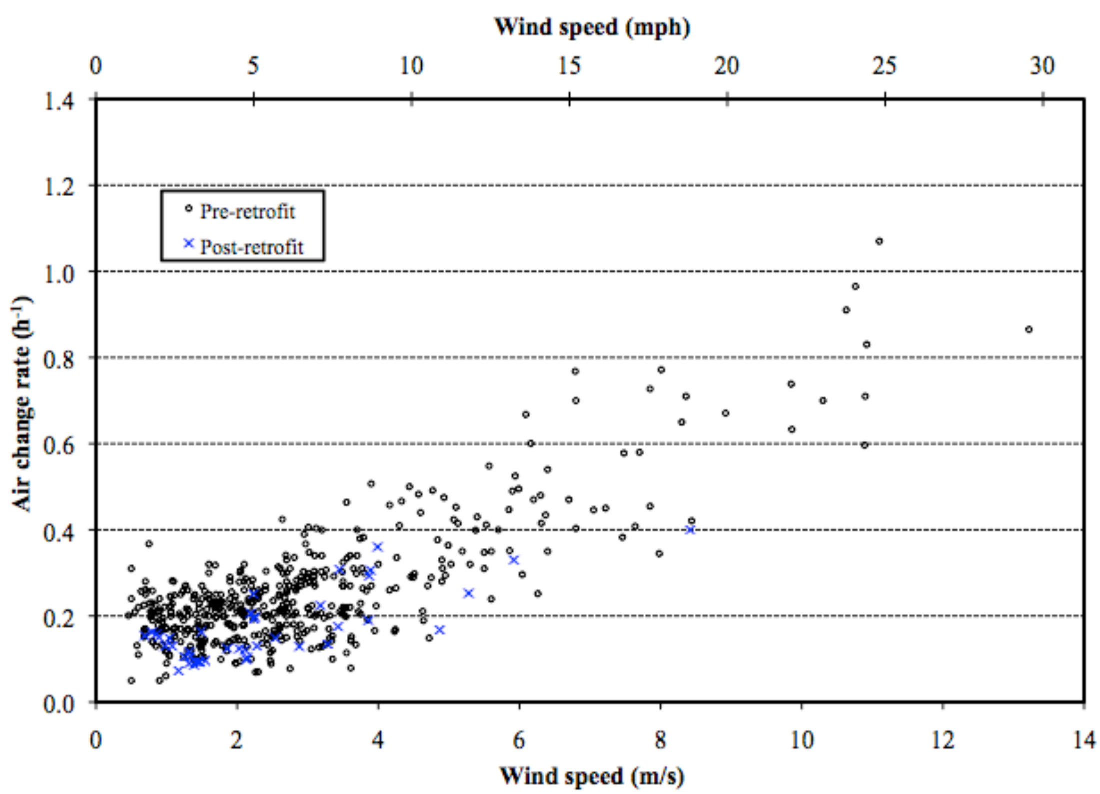


Figure 7 Pre- and post-retrofit measured air change rates as a function of wind speed (low ΔT): Forced-air fan off (Condition 0)

Figures 8 and 9 show the pre- and post-retrofit air change rates with the forced-air fan on and the outdoor air intake closed (Condition 1a), plotted against temperature difference and wind speed respectively. As seen in Figure 8, the air change rate reduction with the system on is much larger than the reduction with the system off due to the impacts of the reduced duct leakage, particularly at low temperature differences. The pre-retrofit data exhibit an unusual dependence on temperature difference as discussed previously (Nabinger and Persily 2008) because of the duct leakage pressurizing the volume under the living space. With the improved airtightness of the ductwork and the belly volume, the dependence of air change rate on temperature difference is more consistent with the pattern seen in other buildings. Figure 9 shows a significant reduction in the post-retrofit air change rates as a function of wind speed, larger than that seen for the fan-off data in Figure 7. The reduction is more pronounced with the fan on because these data correspond to low temperature-differences, where the reduced duct leakage has a large impact on the post-retrofit rates.

The pre- and post-retrofit air change rates for Condition 1b (forced-air fan on and outdoor air intake open) are similar to the results seen for Condition 1a and plots of those data are not presented in this report.

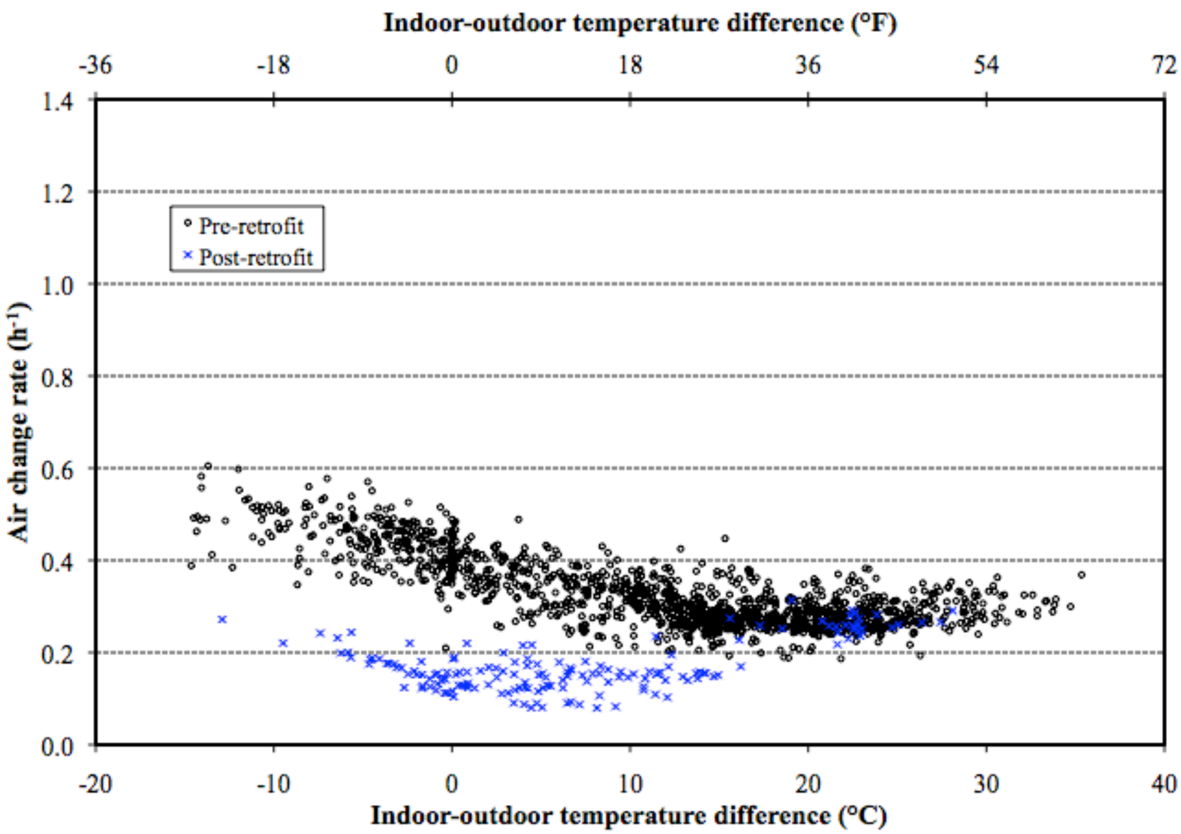


Figure 8 Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): Forced-air fan on, outdoor air intake sealed (Condition 1a)

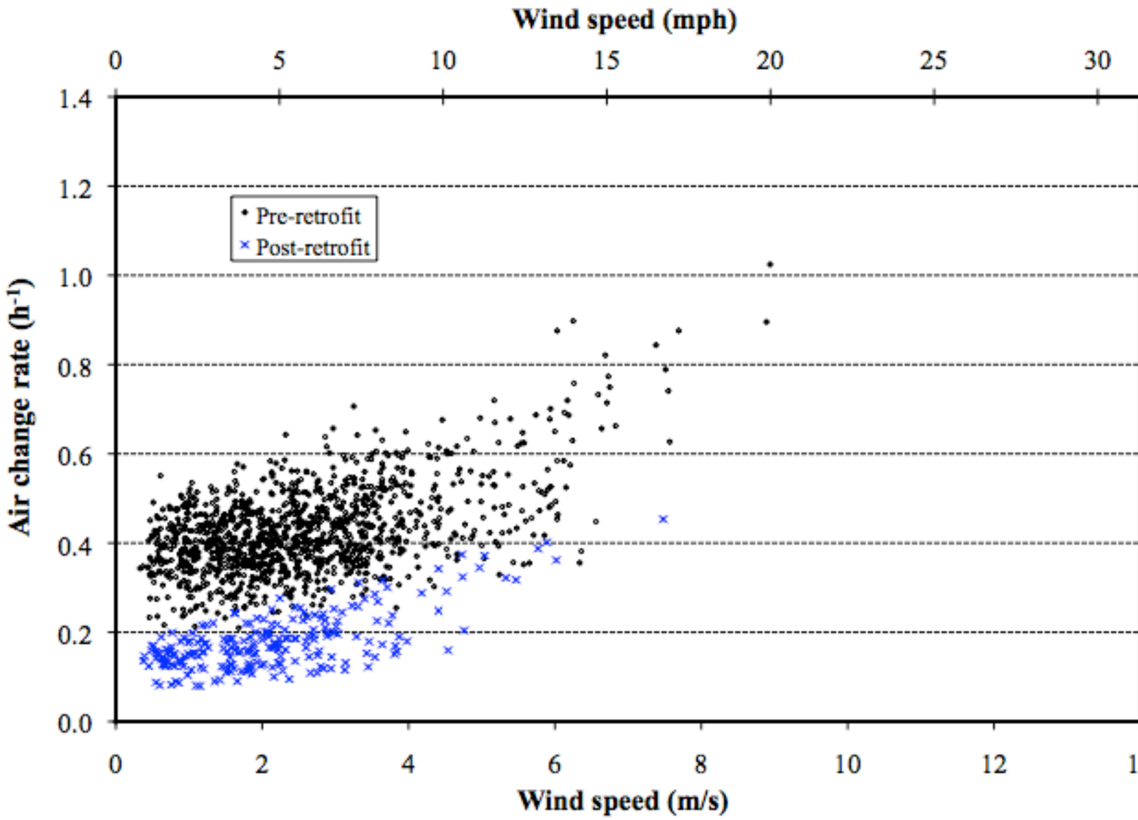


Figure 9 Pre- and post-retrofit measured air change rates as a function of wind speed (low ΔT): Forced-air fan on, outdoor air intake sealed (Condition 1a)

Figures 10 and 11 show the pre- and post-retrofit air changes rates with the forced-air fan controlled by the thermostat and the outdoor air (OA) intake closed (Condition 2a), plotted against temperature difference and wind speed respectively. As seen in Figure 10, the air change rates reductions are less pronounced at the larger, positive temperature differences, as those conditions are associated with longer fan operation and therefore correspond more closely to Condition 1a, where the reductions are lower than when the fan is off (Condition 0). The reductions seen in Figure 11 are similar to those seen in Condition 1a, which would be expected given that the fan run-times at these lower temperature differences are relatively short. As a result, Condition 1a and 2a air change rates are not very different for these small values of ΔT. The pre- and post-retrofit air change rates for Condition 2b (forced-air fan controlled by the thermostat and outdoor air intake open) are similar to the results seen for Condition 2a and plots of those data are not presented in this report.

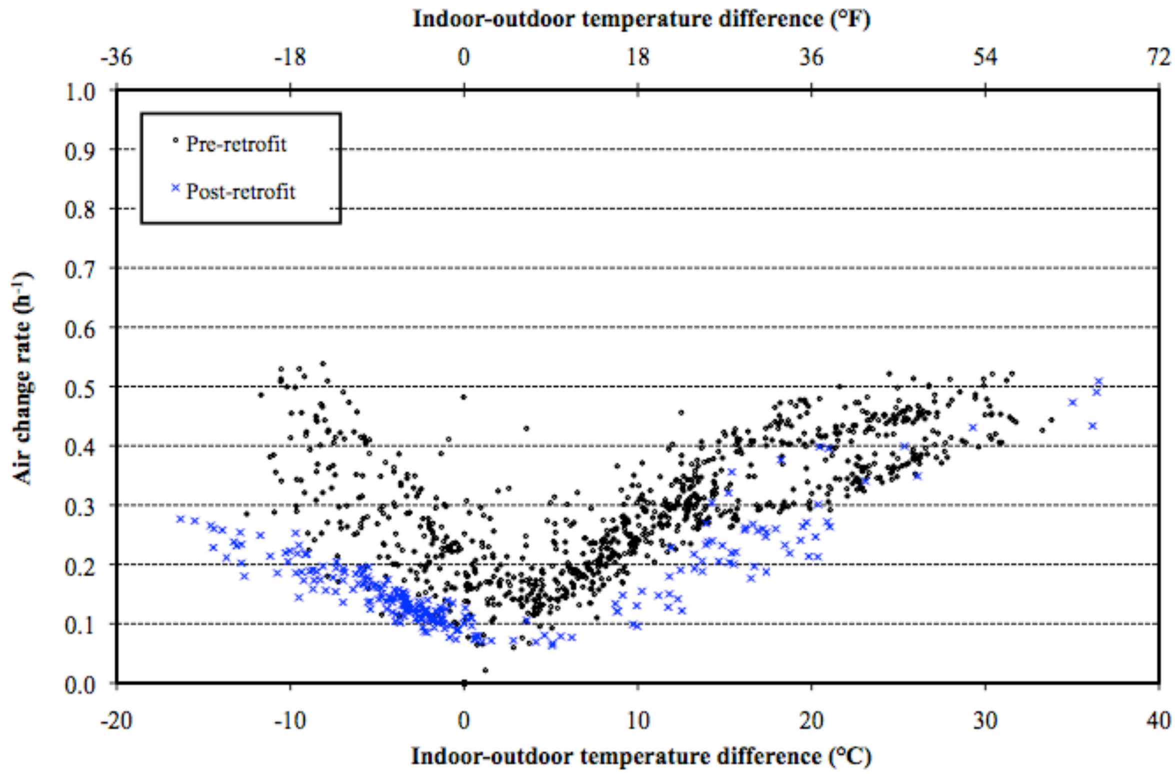


Figure 10 Pre- and post-retrofit measured air change rates as a function of temperature difference (low wind speed): Forced-air fan controlled by thermostat, OA intake sealed (Condition 2a)

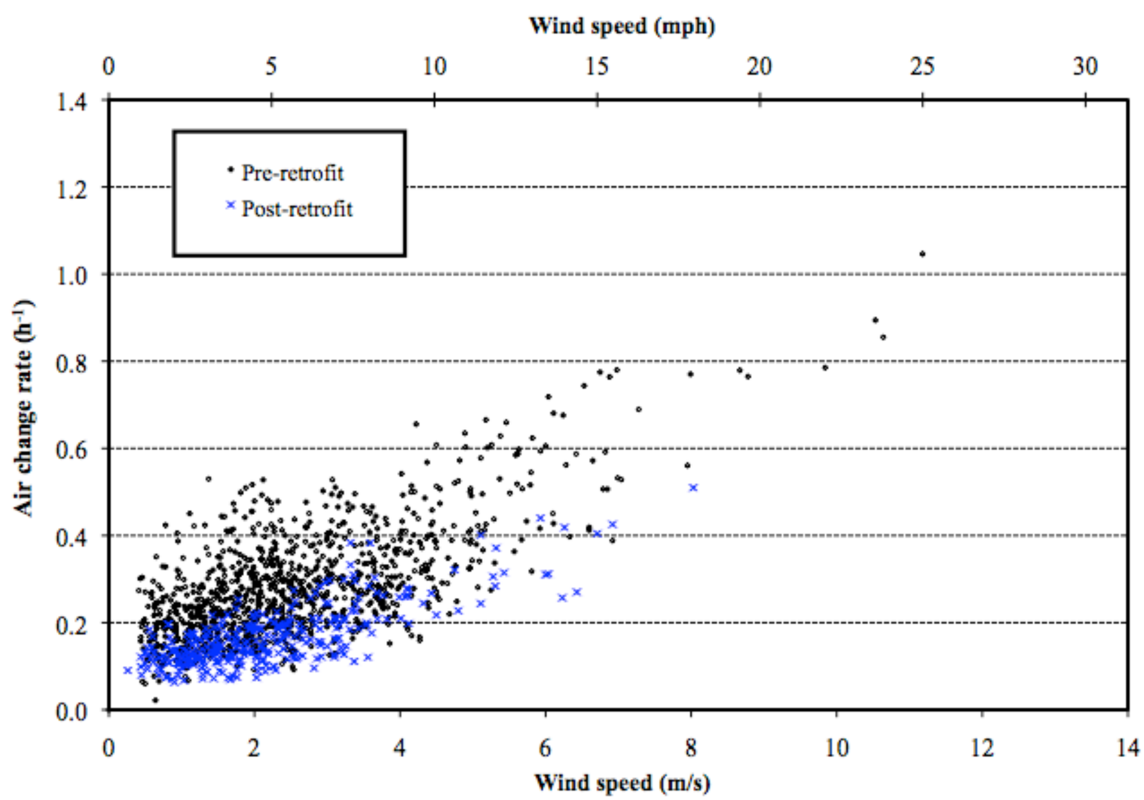


Figure 11 Pre- and post-retrofit measured air change rates as a function of wind speed (low ΔT): Forced-air fan controlled by thermostat, OA intake sealed (Condition 2a)

Table 3 summarizes the air change rate reductions for the various conditions of fan operation and for specific ranges of outdoor weather. Each mean air change rate in the table is calculated for the test condition and noted weather. The last column shows the percentage reduction in the post-retrofit air change rate relative to pre-retrofit value. Most of the mean air change rates decrease by about 25 % to 35 %, with some exceptions. There is very little reduction for high ΔT and low wind speed for conditions 1a and 1b as discussed earlier. The reductions for low ΔT with the fan on tend to be larger than 30 %, as large as 50 % in one case. As noted earlier, these reductions are impacted by the decrease in duct leakage more than the other cases.

Table 3 Summary of Pre- and Post-retrofit air change rates

	Mean air change rate (h^{-1})		
	Pre-retrofit	**Post-retrofit**	**% reduction**
Condition 0 (fan off)			
ΔT = 10 °C to 20 °C, u < 2 m/s	0.34	0.24	29
u = 4 m/s to 6 m/s, |ΔT| < 10 °C	0.36	0.25*	31
Condition 1a (fan on, intake sealed)			
ΔT = 0 °C to 10 °C, u < 2 m/s	0.35	0.24	31
ΔT = 20 °C to 30 °C, u < 2 m/s	0.27	0.26	4
u = 4 m/s to 6 m/s, |ΔT| < 10 °C	0.50	0.31	38
Condition 1b (fan on, intake open)			
ΔT = 0 °C to 10 °C, u < 2 m/s	0.39	0.19	51
ΔT = 20 °C to 30 °C, u < 2 m/s	0.34	0.34	0
u = 4 m/s to 6 m/s, |ΔT| < 10 °C	0.52	0.31	41
Condition 2a (fan controlled by thermostat, intake sealed)			
ΔT = 10 °C to 20 °C, u < 2 m/s	0.30	0.23	23
u = 4 m/s to 6 m/s, |ΔT| < 10 °C	0.39	0.29	26
Condition 2b (fan controlled by thermostat, intake open)			
ΔT = 10 °C to 20 °C, u < 2 m/s	0.34	0.28	18
u = 4 m/s to 6 m/s, |ΔT| < 10 °C	0.39	0.33	15

* Only 3 post-retrofit air changes rates in this range of weather conditions.

5.4 Energy Consumption

After the retrofits were completed, the energy used to heat and cool the building was measured for several months in order to compare it with the energy use before the retrofits. Figures 12 and 13 show the pre and post gas (heating) and electrical (cooling) energy use respectively. Each point in these plots corresponds to 24 h of heating or cooling energy consumption, versus the average indoor-outdoor temperature difference during that same 24-h period. The gas energy consumption values are based on the rate of gas consumption times the heating system's claimed of efficiency value of 85 % and therefore correspond to the energy to heat the house. The electrical energy consumption values are based on the system's rated COP of 2.93 to yield the cooling energy required. The plots show, but do not distinguish between, data collected when the forced air fan is always on (condition 1), and when the fan operation is controlled by the thermostat (condition 2).

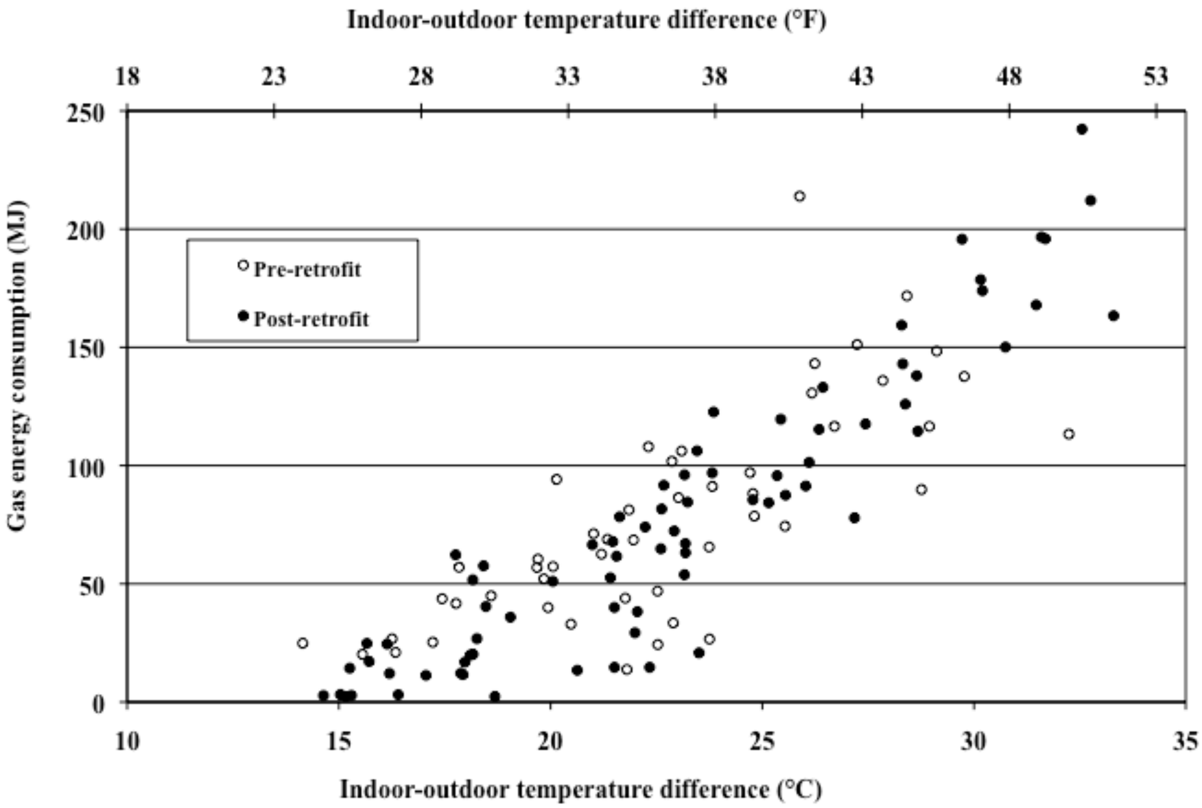


Figure 12 Pre-post gas heating energy versus indoor-outdoor temperature difference

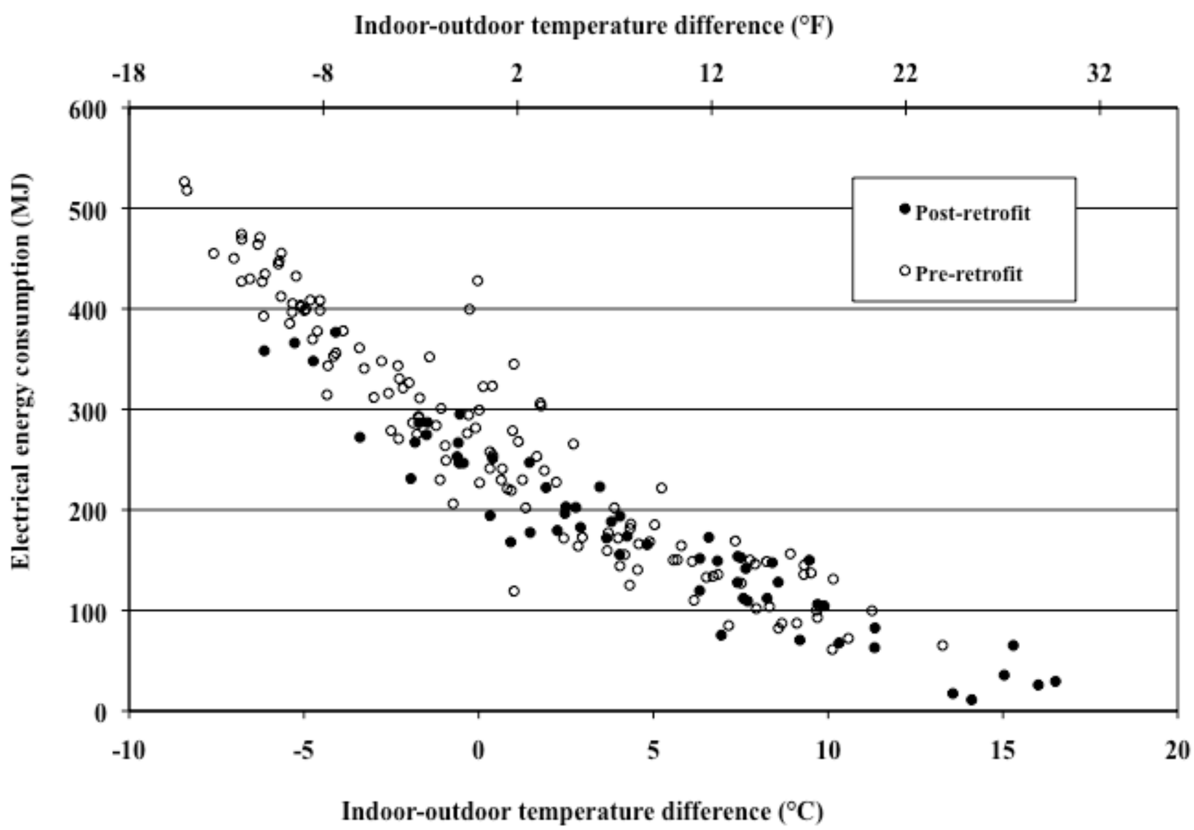


Figure 13 Pre-post electric cooling energy versus indoor-outdoor temperature difference

The data in both Figures 12 and 13 exhibit a lot of scatter, making it difficult to see the difference in the pre and post energy consumption. In order to estimate the difference, the average heating energy use before and after the retrofit was determined for a temperature difference range of 25 °C to 30 °C (45 °F to 54 °F). As seen in Figure 12, this temperature range appears to be better behaved than other ranges and has sufficient points to determine reliable averages. In this temperature range, the pre-retrofit daily average heating energy consumption is 137.5 MJ and the post-retrofit average is 125.6 MJ, corresponding to a reduction of 8.6 %. In the case of cooling, Figure 13, the average energy use was calculated for temperature differences between -6 °C and -1 °C (-10.8 °F and -1.8 °F). Again, the data in this range exhibit less scatter than at the higher temperature differences. In this temperature range, the pre-retrofit daily average cooling energy consumption is 371.9 MJ and the post-retrofit average is 328.7 MJ, corresponding to a reduction of 11.6 %. Based on the standard deviations of the mean energy consumption values for heating and cooling, the uncertainty in the energy reduction for heating and cooling are quite large because of the large uncertainty in the difference between the pre- and post-retrofit energy consumption. In both cases the uncertainties are estimated to be larger than the reductions themselves.

Analysis of the pre-retrofit heating and cooling yielded slopes of about 22 MJ/°C and 10 MJ/°C respectively (Nabinger and Persily 2008). These two values should have been the same based on conduction heat losses (gains) alone, but the factor of two difference is not unreasonable given the use of assumed values for the system efficiencies, the impact of solar and other internal gains, the lack of consideration of latent loads, and the variation of infiltration with weather. A simple heat loss calculation for the building, assuming an air change rate of 0.5 h^{-1}, yields a heat loss rate through the envelope of 15 MJ/°C, which is roughly halfway between the two measured, pre-retrofit values. The same heat loss calculation was used to examine the energy impacts of the infiltration rate reductions. Considering the air change rates plotted in Figures 8 through 11, the heat loss was calculated for a pre-retrofit air change rate of 0.4 h^{-1} and a post-retrofit rate of 0.2 h^{-1}. The corresponding reduction in heat loss for the building is 13.5 %, which is reasonably close to the estimated energy reductions above of 8.6 % and 11.6 %.

6. AIR CHANGE RATE PREDICTIONS

In the previous report on the pre-retrofit assessment of the house (Nabinger and Persily 2008), the multizone airflow model CONTAM (Walton and Dols 2005) was used to predict the air change rates under various conditions of fan operation and weather. Those predictions were in fairly good agreement with the air change rates measured with the tracer gas system in the house. The model was used again after the retrofits to predict the air change rates.

Table 4 shows the input values used in the CONTAM model of the house for both pre- and post-retrofit conditions. Only those airflow paths that were impacted by the retrofit efforts are seen to be different post-retrofit. The leakage values for the exterior envelope of the living space that are above floor level only decrease by about 10 %, but the leakage to the belly, the belly to the crawl space, and the duct leakage decrease by a much larger fraction.

Table 4 Model Inputs for Pre- and Post-Retrofit Conditions

		ELA at 4 Pa	
	Airflow path	**Pre-retrofit**	**Post-retrofit**
Living space envelope	Exterior wall	0.14 cm^2/m^2	0.13 cm^2/m^2
	Ceiling wall interface	0.81 cm^2/m	0.73 cm^2/m
	Floor wall interface	1.24cm^2/m	1.12 cm^2/m
	Window #1	5.00 cm^2	*
	Window #2	1.94 cm^2	*
	Corner interface	0.81 cm^2/m	0.73 cm^2/m
	Exterior doors	18.7 cm^2	*
	Living space to belly	3.65 cm^2/m^2	1.43 cm^2/m^2
Interior airflow paths	Interior walls	2 cm^2/m^2	*
	Bedroom doorframe	410 cm^2	*
	Open interior doors	2 m x 0.9 m	*
	Bathroom doorframe	330 cm^2	*
	Interior doorframe	250 cm^2	*
	Closet doorframe	4.6 cm^2	*
Attic	Attic floor	2 cm^2/m^2	*
	Roof vents	0.135 m^2/each	*
	Eave vents	106 cm^2/m	296 cm^2/m **
Crawl space and belly	Exterior walls of crawl space	25 cm^2/m^2	*
	Rear crawl space vents	323 cm^2	*
	Front crawl space vents	465 cm^2	*
	Crawl space access door	206 cm^2	*
	Crawl space to “belly”	258 cm^2	181 cm^2
	Duct leak into belly	320 cm^2	58 cm^2

* Same as pre-retrofit

** The eave vent values were remeasured and the values were corrected in the post-retrofit model.

Figure 14 shows the measured and predicted post-retrofit air change rates under condition 0 (forced-air fan off) plotted against indoor-outdoor temperature difference. The values in this plot correspond to wind speeds less than 2 m/s. The predictions match the measurements very well, though the measured values exhibit some scatter due in part to variations in wind speed and direction. Figure 15 shows the measured and predicted rates plotted against wind speed, again for condition 0, corresponding to indoor-outdoor temperature differences between -10 °C and +10 °C. Again, the predictions match the measurements fairly well.

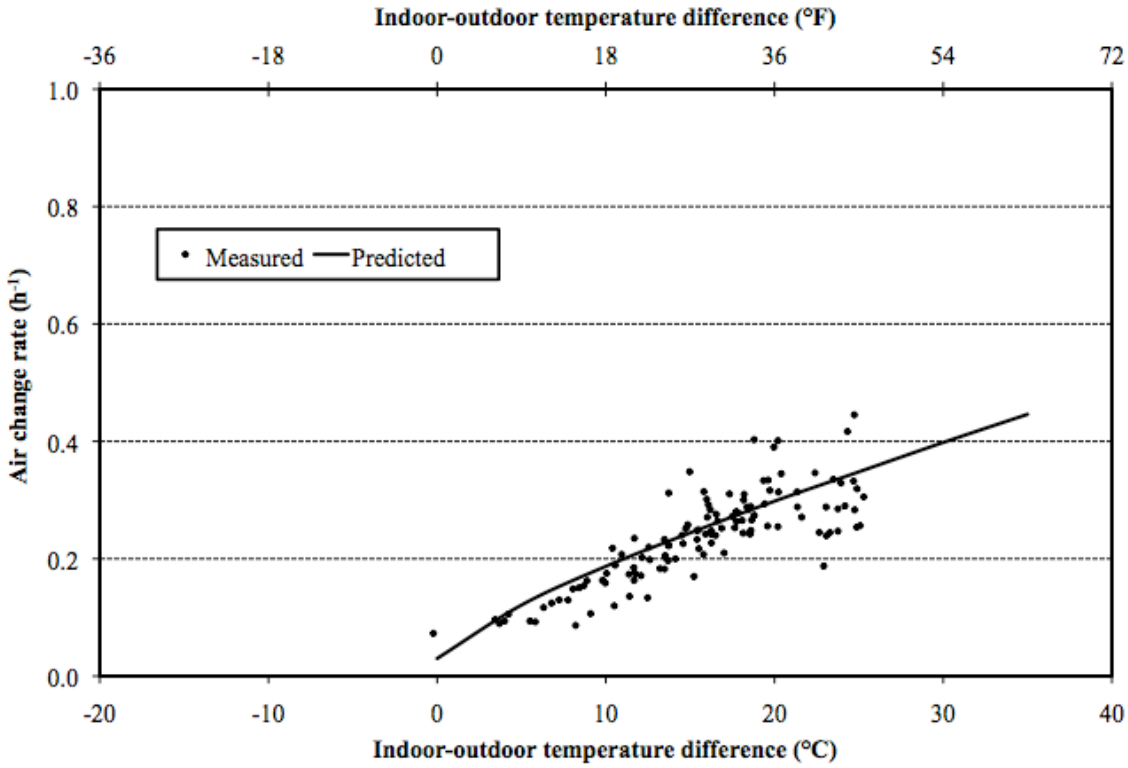


Figure 14 Measured and predicted post-retrofit air change rates as a function of temperature difference (low wind speed): Forced-air fan off (Condition 0)

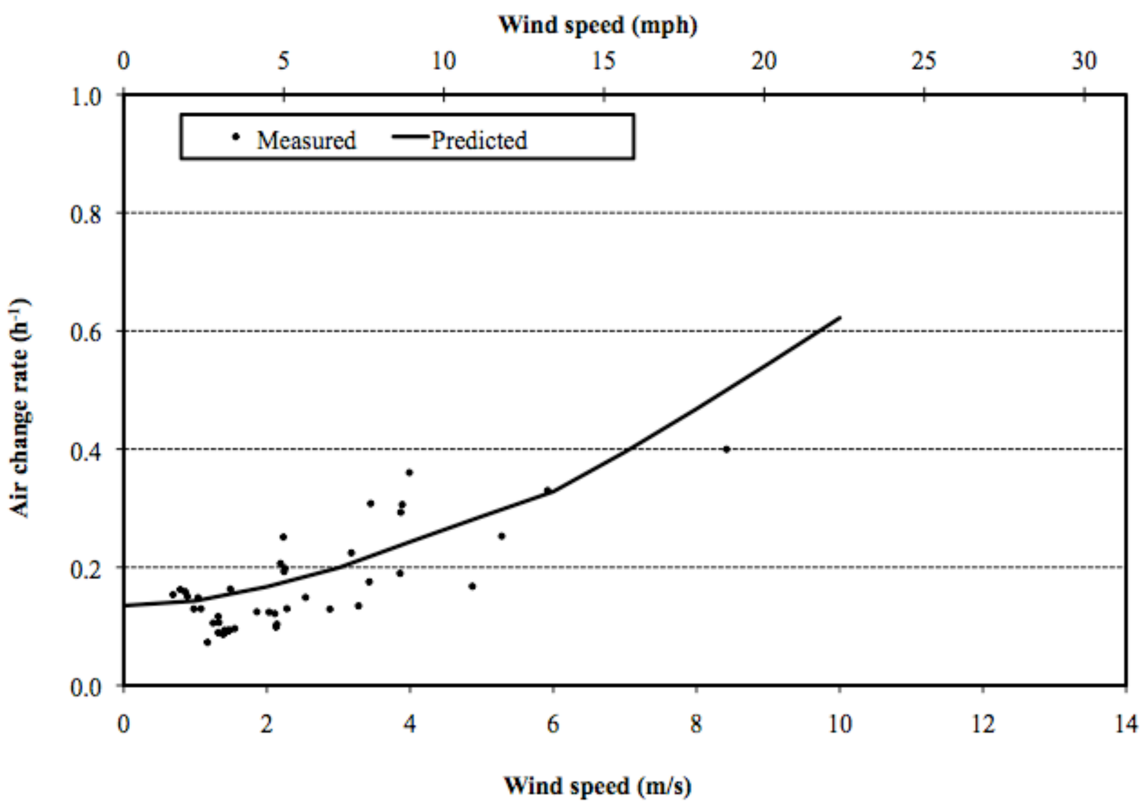


Figure 15 Measured and predicted post-retrofit air change rates as a function of wind speed (low temperature difference): Forced-air fan off (Condition 0)

Figures 16 and 17 show the measured and predicted air change rates as a function of temperature difference and wind speed respectively for condition 1a (forced-air fan on, outdoor air intake closed). The predictions match the general trend seen in the measurements but tend to under predict, particularly for near-zero and negative temperature differences. The predicted air change rates in Figure 17 are somewhat higher than the measured values at low wind speeds. The plots of measured and predicted air change rates for condition 1b (the same as 1a except the outdoor air intake is open) show very similar trends to those seen in Figures 16 and 17 and are not shown in this report.

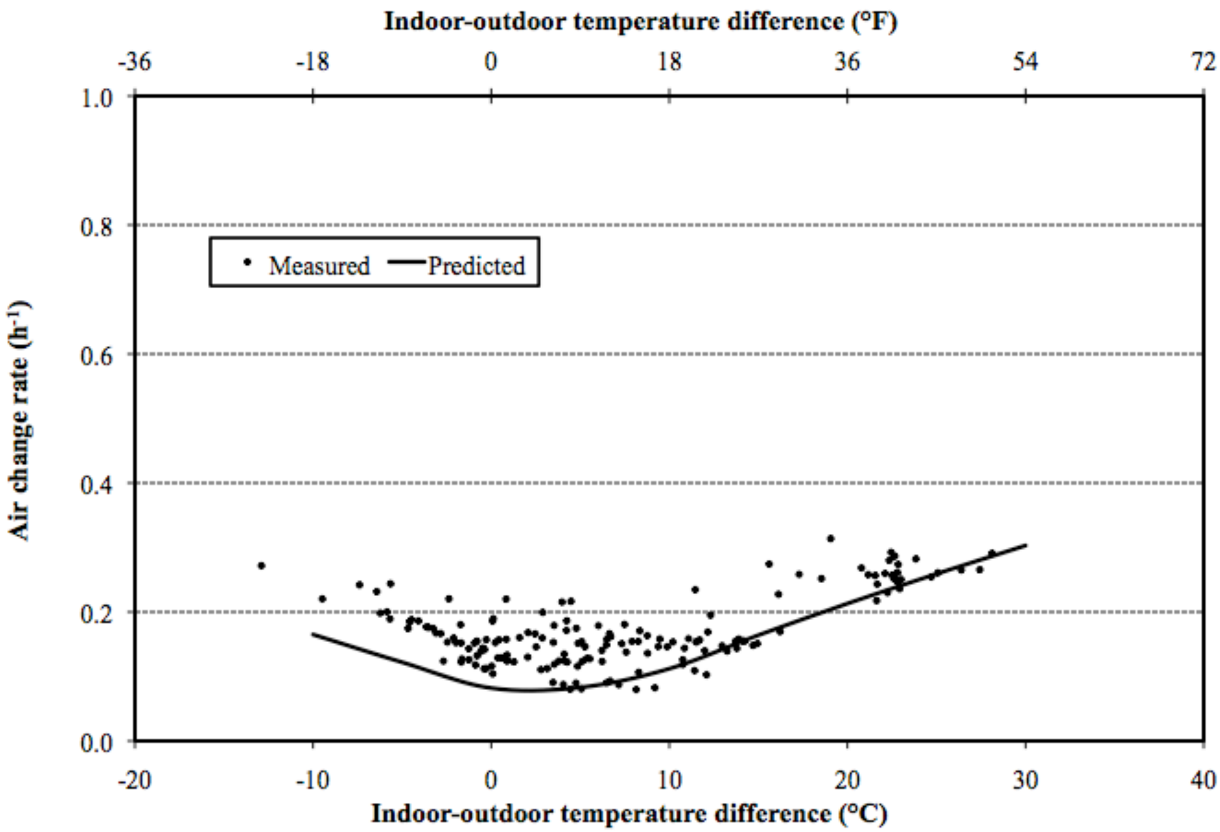


Figure 16 Measured and predicted post-retrofit air change rates as a function of temperature difference (low wind speed): Forced-air fan on, outdoor air intake sealed (Condition 1a)

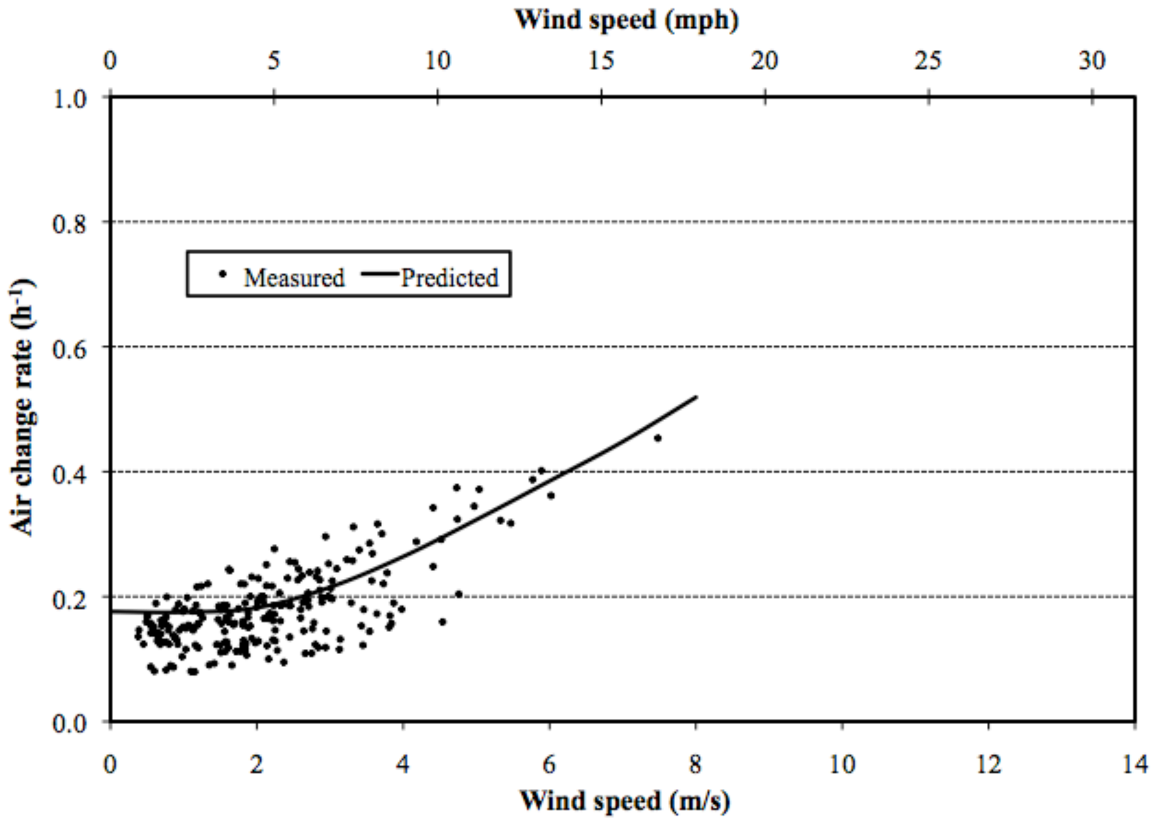


Figure 17 Measured and predicted post-retrofit air change rates as a function of wind speed (low temperature difference): Forced-air fan on, outdoor air intake sealed (Condition 1a)

Figures 18 and 19 are plots of the measured and predicted air change rates as a function of temperature difference and wind speed for condition 2a (forced-air fan controlled by the thermostat, outdoor air intake closed). The predicted air change rates for these cases are based on the rates predicted for the fan-off (condition 0) and fan-on (condition 1a) cases, combined using the fan run-time fraction for the temperature difference corresponding to the prediction. The fan run-time was measured, and a correlation of fractional run-time per hour with indoor-outdoor temperature difference was developed. This correlation was used to combine the condition 0 and 1a air change rate predictions to determine the predicted rate with the system controlled by the thermostat. The predictions in both plots match the measured values fairly well. Due to the relative oversizing of the heating and cooing systems, the run-time fractions are generally fairly low, typically on the order of 25 % except under extremely warm conditions. Therefore, the air change rates under condition 2a more closely match those with the system off. The plots of measured and predicted air change rates for condition 2b (the same as 2a except the outdoor air intake is open) show very similar trends to Figures 18 and 19 and are not shown in this report.

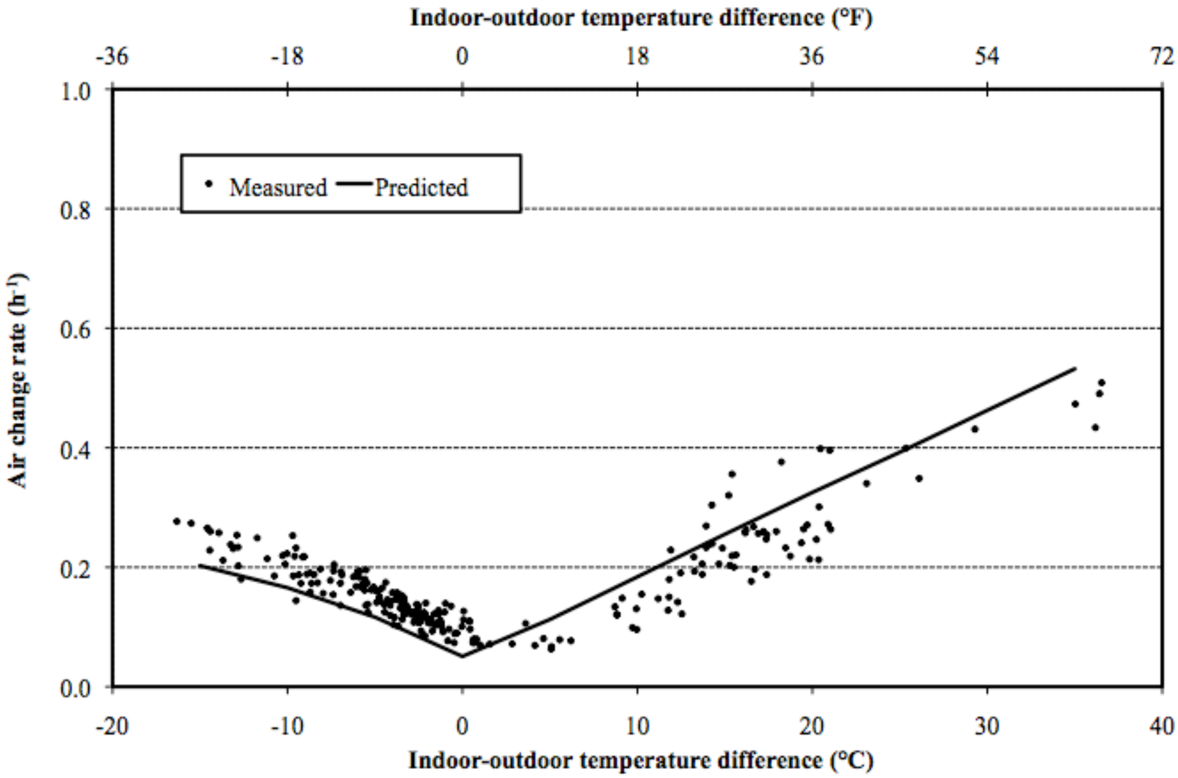


Figure 18 Measured and predicted post-retrofit air change rates as a function of ΔT (low wind speed): Forced-air fan controlled by thermostat, outdoor air intake sealed (Condition 2a)

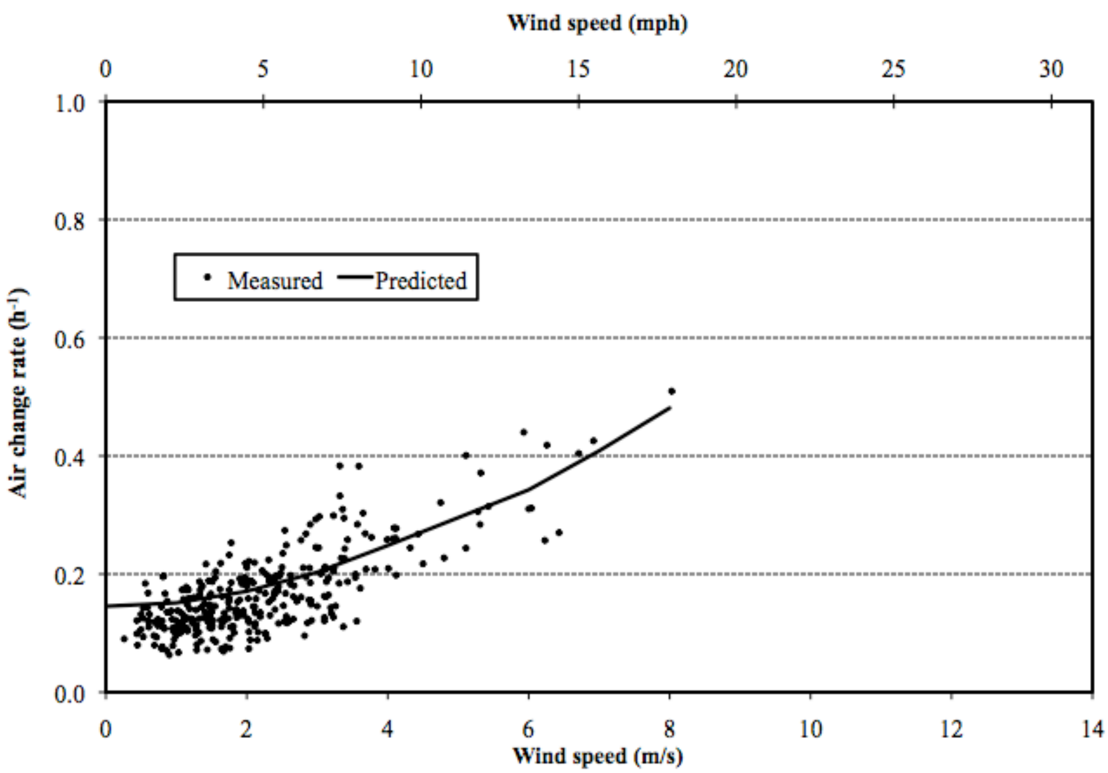


Figure 19 Measured and predicted post-retrofit air change rates as a function of wind speed (low ΔT): Forced-air fan controlled by thermostat, outdoor air intake sealed (Condition 2a)

Overall, as was the case with the pre-retrofit data, the air change rates predicted with CONTAM are in fairly good agreement with the measurements. Even with different conditions of fan operation and weather, the good agreement is sustained. Table 5 summaries the agreement of the predicted and measured air change rates for the different cases of system operation. For each case, a linear regression of the predicted air change rate against the measured rate was performed for temperature and wind dominated conditions. The values of R-squared and the standard error of the regression are presented for each of the five cases. The values of R-squared range from 0.54 to 0.78 with one exception and the standard error of regression values are all about 0.04. The agreement tends to be better for the temperature dominated conditions, which is not surprising given that it is generally more challenging to predict wind-driven air change rates.

Table 5 Summary Statistics of Predicted versus Measured Air Change Rates

	Temperature difference		**Wind speed**	
Case	**R-squared**	**Std error of regression**	**R-squared**	**Std error of regression**
0 – Fan off	0.685	0.04	0.572	0.05
1a – Fan on, intake sealed	0.615	0.03	0.542	0.04
1b - Fan on, intake open	0.696	0.03	0.308	0.05
2a – T-stat control, intake sealed	0.784	0.04	0.597	0.05
2b - T-stat control, intake open	0.755	0.05	0.752	0.04

7. DISCUSSION

This study was conducted to evaluate the impacts of airtightening retrofits on building airtightness, ventilation rates and energy consumption in an existing, unoccupied manufactured home. In this study, a manufactured home constructed in 2002 was subjected to a series of airtightening retrofits including installing house wrap over the exterior walls, sealing a number of leakage sites in the living space floor, tightening the insulated belly layer, and sealing leaks in the air distribution system. These retrofits reduced the whole house leakage, as determined by a fan pressurization test, by about 18 % and the duct leakage by about 80 %. Whole house infiltration rates were reduced by about one-third, with the specific reduction dependent on weather conditions and how the forced-air system was operating. The energy consumption rate for heating and cooling was reduced by about 10 %.

While the retrofits did improve the airtightness of the house and reduce the energy consumption, the effectiveness of the effort was limited by the challenges of airtightening an existing building. In general, it is easier to construct a tight building envelope than to achieve one through retrofits (Hale, Davis et al. 2007). Manufactured homes in particular have the potential for high levels of airtightness performance given the quality control that can be achieved in the factory. Similarly, quality design and construction of these homes has been shown to yield high levels of energy performance (Lucas, Fairey et al. 2007).

It is important to note that the post-retrofit infiltration rates were often below the target ventilation rate of 0.35 h^{-1} in the HUD manufactured housing standard (HUD 1994). As seen in Table 3 under conditions 1b and 2b, the mean air change rates are all below 0.35 h^{-1} with the outdoor air intake open. Theses conditions of under-ventilation occur in part because the airflow through the intake is less than half of the HUD requirement. Also, in the case of condition 2b when the forced-air fan is controlled by the thermostat, the intake only operates when there is a demand for heating or cooling and is otherwise not bringing any outdoor air into the building.

While the mechanical ventilation system is not providing the rates required by the HUD standard, the reduced duct leakage combined with the tighter envelope does provide much better control of envelope infiltration rates. Figures 8 through 11 show the reduced infiltration rates with the intake sealed, which highlights the potential to provide better ventilation control through a mechanical approach than was possible before the retrofits. However, a mechanical ventilation system must still be provided to meet the overall ventilation requirements of house, either using an adequately sized intake, a whole house exhaust fan or some other approach. Ideally, the mechanical ventilation will be controlled independent of the demand for heating or cooling.

This study also demonstrated the ability of multizone airflow modeling, in this case using the CONTAM model, to predict whole building air change rates with good accuracy. Before the retrofits, the air change rate exhibited an unusual dependence on temperature due to the duct leakage pressurizing the belly space, but this behavior was predicted by the model. After the retrofits, the new leakage values were entered into the model and the predicted air change rates matched the measurements quite well. These results show the potential value of building airflow modeling for analyzing the ventilation and infiltration performance of residences, which can be extended to simulating indoor contaminant levels as a means of understanding the impacts of building design, construction, and operation on indoor air quality.

8. ACKNOWLEGEMENTS

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