Stock Characterization and Energy Savings Potential in Forced Air Systems in Frostbelt Homes

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The importance of air sealing and insulating forced air distribution systems in unconditioned spaces such as attics or crawlspaces is well known, and the energy savings which accrue from such treatments are fairly predictable. However, many homes in the northern part of the United States (the ''Frostbelt'') have forced air heating distribution systems that are located in basements that are isolated from the outside to some extent and are unintentionally heated by thermal contact with conditioned spaces as well as duct and equipment losses. Basement temperatures are often only 5° to 15° F cooler than living space temperaturs in such homes, and it is not clear that energy savings resulting from improvement of a distribution system in this situation would be significant. Additionally, system improvements may allow the basement temperature to drop to the point where occasional usage is not comfortable, living space floors become colder, or plumbing is threatened during very cold weather.

This investigation measured envelope leakage, duct leakage, energy consumption, and basement temperatures both before and after basement distribution system retrofits in 19 houses in New York and Wisconsin. The retrofits included air sealing and insulation, at an average cost of $650. Basement supply and return duct leakage both decreased by an average of 55 percent, estimated annual heating energy consumption decreased by an average of 9 percent, and basement temperatures decreased by an average of 5° F following retrofit.

INTRODUCTION

Forced air distribution systems have gained recognition as important players in overall energy usage in the buildings that include them. In particular, forced air distribution components which pass through spaces controlled by outdoor conditions have been shown to lose a significant portion of the energy they are designed to deliver because they are not air sealed or insulated (Cummings 1990, Davis & Roberson 1993, Modera & Jansky 1992, Modera 1993, Palmiter 1993, Parker et al. 1993, Proctor 1991). Studies show that the costs of such treatments may often be reclaimed quickly by the energy savings that result (Jacobson, Proctor & Polak 1992, Jump & Modera 1994). Diagnostic techniques for identifying areas of potential treatment, as well as deciding how far to go in treatment while remaining cost-effective, have been developed for ducts in unconditioned spaces and are now in use (Davis & Roberson 1993).

However, there has been less energy conservation research connected with forced air distribution systems installed in unconditioned basements (GEOMET 1992, Nelson et al. 1993, Treidler & Modera 1994). When these systems have leaks or are uninsulated, energy is lost to the basement, not directly to the outside or to an unconditioned space that is well connected to the outside. Part of this ''lost'' basement energy may reduce the heating load of the conditioned space above. Therefore, it is not as apparent that sealing leaks or insulating the ducts will result in significant energy savings. Further, duct losses may be needed to keep the basement above a certain minimum temperature. This minimum temperature may be necessary for comfort during occasional usage, to prevent very cold floors above, or even to prevent plumbing freeze-ups during extreme winter weather.

This paper presents some results from an instrumented field study that included 19 homes with such systems located in their basements. The field study examined 11 single-family homes in New York state and eight single-family homes in Wisconsin. The field work at each house included: (1) recording the physical characteristics of the home and its duct system, (2) monitoring long-term temperatures and energy consumption, (3) diagnostic protocols on the house and duct system, (4) retrofit of the duct system, and (5) repeating the diagnostic protocols after the duct system improvements. Measurements from the diagnostic protocols that are compared in this paper include zone depressurization, envelope leakage, and duct leakage. In addition, changes in energy consumption and basement temperature are discussed.

METHODOLOGY

Field Study Participant Selection

The 19 field study participants were selected from a telephone survey of house and duct system characteristics in

412 Frostbelt homes. This list of homes was compiled from several previous utility survey respondent lists furnished by the project's sponsors. In order to qualify as a potential participant, a house had to: (1) have an unconditioned basement that included most of a forced air heating system, and (2) have insulation on no more than 50 percent of the ductwork. Most eventual participants had no duct insulation at all.

Qualified and interested potential participants were mailed a project information packet. If their interest continued, an introductory visit was scheduled. The inspector ''passed'' a house if: (1) it truly met the criteria of items 1 and 2 above, (2) the homeowner said that the basement door was kept closed all of the time, (3) there were no safety problems with the house or systems, (4) secondary heating was minimal or monitorable, (5) occupancy level was reasonably steady, and (6) no alterations to the house that would affect thermal performance were planned during the 1 1/2 year term of the project.

Diagnostic Protocols

The diagnostic protocols used in the field study typically required one full day to accomplish at each house, both before and after retrofit of the duct systems. Some of the protocol results are affected by weather and operating conditions during testing, and pre-retrofit and post-retrofit tests were conducted under similar such circumstances whenever possible.

Zone Depressurization. The zone depressurization protocol measured the air handler's contribution to worst case depressurization of the living space zone with respect to the outside, as well as worst case depressurization of the basement zone with respect to the outside. To find the worst case for each of these two zones, depressurization was measured during three scenarios of equipment operation that could potentially be implemented by the homeowner: (1) running all of the exhaust fans, including the clothes dryer, (2) running all of the exhaust fans, including the clothes dryer, and running the air handler, and (3) running only the air handler. Within each of these three scenarios, interior doors were positioned to result in the highest level of depressurization possible.

Building Leakage. Four different building leakage tests were conducted, all using pressurization by a blower door to determine four different equivalent leakage areas (ELA):

(1) The basement was pressurized to 50 Pa with the living space open to the outside;

(2) The living space was pressurized to 50 Pa with the basement open to the outside;

(3) The living space and the basement were pressurized together to 50 Pa with the basement open to the living space; and

(4) The living space was pressurized to several different pressures with the basement closed to both the living space and the outside, according to ASTM Standard 779 (1991), to supply the exponent for all four calculations of ELA. These calculations use:

$$ELA(cm^2 \ @4Pa) = \frac{Q_{test\#j}}{50^n}\left[4^{n-1/2}(\rho/2)^{1/2}\right] \times 10{,}000 \qquad (1)$$

where $Q_{test\#j}$ = blower door fan flow in m^3/sec at an induced pressure difference of 50 Pa
n = the exponent determined from building leakage test #4 (usually 0.5–0.8)
ρ = density of air in kg/m^3

In addition, ELA between the living space and the basement was calculated by solving the following three simultaneous equations to determine K_{bi}:

$$K_{bi}50^n + K_{be}50^n = Q_{test\#1} \qquad (2)$$

$$K_{bi}50^n + K_{ie}50^n = Q_{test\#2} \qquad (3)$$

$$K_{ie}50^n + K_{be}50^n = Q_{test\#3} \qquad (4)$$

where n = the exponent from building leakage test #4
K_{bi} = the flow coefficient between the basement and the living space
K_{ei} = the flow coefficient between the exterior and the living space
K_{be} = the flow coefficient between the basement and the exterior

K_{bi} was then substituted for the $Q_{test\#j}/50^n$ term in Eq. 1. Specific leakage area (SLA) is calculated by dividing ELA by the floor area of the house in m^2 (A_{floor}):

$$SLA(cm^2/m^2) = \frac{ELA}{A_{floor}} \qquad (5)$$

Duct Leakage. Duct leakage was measured by pressurizing ductwork to 25 or 50 Pa using a calibrated fan connected at the air handler cabinet with all registers temporarily sealed. Supply and return duct pressure measurements used a single point 3′–6′ from the plenum, or two-point averages if there were no trunks, two trunks, or a very long trunk. Duct pressure measurement points were the same for post-retrofit protocols as for pre-retrofit.

Direct pressurization was used to estimate total duct leakage flow for the whole duct system, the return ducts only, and the supply ducts only. Further, duct pressurization was combined with blower door pressurization to estimate basement and outside duct leakage together, as well as outside duct leakage only. This allowed an estimate of basement-only duct leakage by subtraction. Flow through the fan during all pressurization tests was converted to duct ELA using the same form as Eq. 1, but assuming a value of 0.6 for n:

$$ELA(cm^2\ @4Pa) = \frac{Q_{fan}}{P_{test}^{0.6}} [4^{0.6-1/2}(\rho/2)^{1/2}] \times 10{,}000 \quad (6)$$

where Q_{fan} = measured fan flow in m^3/sec at an induced pressure difference of P

P_{test} = the induced pressure difference in Pa

ρ = density of air in kg/m^3

Duct SLA, like building SLA, was calculated using Eq. 5.

Estimation of Normalized Annual Energy Consumption

Long-term monitored data was collected from each house both pre-retrofit and post-retrofit in order to estimate normalized annual consumption (NAC) for both periods. The two data sets from each house generally represented approximately equal-length periods from 5 to 10 weeks long during the same time span within the months of January, February, March, and April of 1995 (pre-retrofit period) and 1996 (post-retrofit). Three temperatures were monitored as hourly averages: (1) outside temperature in the shade, (2) inside temperature near the thermostat, and (3) basement temperature 6″ to 12″ below the ceiling joists and away from appliances, supply ducts, and outside walls. Although lower temperatures might be expected nearer the floor, this ceiling basement temperature indicated the heat transfer rate between the basement and the living space most accurately, and was presumably more sensitive to duct retrofit than temperatures further away from the ceiling. Run-time in seconds for gas or fuel oil burners was totaled each hour. In the case of heat pumps, total hourly compressor kWh was recorded in addition to run-time.

Daily energy consumption was estimated by combining daily run-time, measured gas flow or oil burner nozzle size, and standard fuel energy content. Steady state equipment efficiency was measured for each period to reveal any changes coinciding with the duct retrofit. Monitored daily heat pump kWh was converted to Btus directly. Air handler power was not included in energy consumption monitoring except in house #1321.

For each monitored day, 24 hourly $T_{in} - T_{out}$ (dT) averages were averaged to give a daily average dT. Linear regression analysis was performed on Btu consumption as a function of dT. Outlier data values were discarded to give a final group of days representing the period, a final regression with $r^2 > 0.9$, and a final Btus/dT/Day figure for each period. This Btus/dT/Day figure allowed comparison of daily energy consumption from two different periods based on any given daily average dT. In addition, the final regression revealed as its x-intercept the dT at which the heating system first calls for heat. This dT was subtracted from the average inside temperature for the period to give T_{bal}, the outside balance temperature at which the heating system first calls for heat. This value of T_{bal}, which was routinely different after retrofit, was used to normalize the final Btus/dT/Day figure to annual consumption for each period.

The expression for NAC used here is from Holt (1985), and is given by a function N, such that:

$$N = \frac{(m\ H)\ Btu}{10^6\ Btu/MMBtu} \quad (7)$$

where H = the number of heating degree days in the heating season

M = the value for Btus/dT/Day returned by the regression

The quantity N thus has units of millions of Btu, or, MMBtu. The quantity H is given as a function of the balance temperature, T_{bal}. The formula for H is:

$$H = Y\frac{T_a - T_m}{\pi}\left[\sqrt{1 - X^2} - XCos^{-1}X\right] \quad (8)$$

where Y = 365.25 (days per sidereal year)

T_a = annual average temperature

T_m = annual monthly minimum temperature = $1.036\ T_j - 0.036\ T_a$

T_j = average January temperature

$X = (T_a - T_{bal})/(T_a - T_m)$

Temperatures used in Eq. 8 for the New York homes were 50° F and 24° F, for annual and January averages, respectively, and 45.5° F and 18.5° F for the Wisconsin homes.

Since all other components of Eq. 3 are historical constants, the primary source of variance in this function is T_{bal}. This value represents the consumption regression line's termination in a low-dT region of house operation, as would be found on warm winter days. In this low-dT region, actual energy consumption may be somewhat below the regression line due to the homeowners' tolerance of low indoor air temperatures. This may cause the NAC to be slightly overestimated. For the work presented here, a move in T_{bal} and NAC following retrofit should be considered a trend rather than an amount. Analysis of the amount of potential bias regarding this issue has yet to be completed for this project.

Retrofits

Following pre-retrofit diagnostic protocols, all supply ducts and return ducts received air sealing treatment using duct mastic, mesh tape and foil tape. Air sealing was conducted without concurrent diagnostics to assess progress or locate leaks. The technicians simply used lights, inspection mirrors, and a systematic approach. Disconnects or major holes were repaired before sealing, and filter slot covers were fabricated where necessary. All circumferential and longitudinal seams were sealed. Holes between panned-in return ducts (return ducts created by closing in a joist space on one side with sheet metal or other type of sheet stock) and other building cavities were sealed if possible. Any holes in return pan joists, as well as the joist-subfloor joints, were sealed. Register grills were removed and the ducts behind were sealed where possible. Ducts enclosed within walls and floors were not treated, except in house #1421, where a second floor return duct was blocked off from open floor cavities.

Following air sealing, ducts were insulated with foil-faced fiberglass designed for installation on ducts. It is available in 4′ × 30″ diameter rolls, in various thicknesses and densities. Two thicknesses of low-density fiberglass were chosen for use: 1 1/2 inches, to give installed R-4.2, and 3 inches, to give installed R-8.3. There were differences between the insulation strategies used in New York and Wisconsin. In the 11 New York homes, located in the central Hudson Valley, supply ducts were insulated with 3-inch insulation, but returns were not insulated. In the eight Wisconsin homes, returns were insulated with 1 1/2-inch insulation in addition to the 3-inch insulation used on supplies. The thinner stock was sometimes used on supplies in very tight spots.

Retrofit costs were computed using wholesale material prices and labor at $15 per man-hour. Retrofit man-hours were provided entirely by the research team rather than outside contractors, and included set-up, dust protection when necessary, moving stored basement items when necessary, pack-up, and cleaning.

PRE-RETROFIT RESULTS

Initial house characteristics are presented in this section, as well as pre-retrofit envelope and duct leakage values, which are compared to those observed in other studies. Some distributions are based on measurements from less than 19 homes due to discrepancies in the data sets, and unavailable data is denoted ‘‘N/A.’’

Initial House Characteristics

Some characteristics of the 19 homes, in their original pre-retrofit conditions, are listed in Table 1. Houses having 1.5 stories were either cape cods or bungalows, where portions of the second floor walls adjoined crawlspaces rather than being true exterior walls. There were no ducts in any of these second floor crawlspaces except for an eight foot branch run in house #581, shown in the exterior cavities column in Table 1. The exterior cavity duct shown for house #627 was an extremely well-caulked return floor pan under a converted porch that did not have foundation walls.

Five of the houses had ductwork in crawlspaces that were adjacent to the basement. These crawlspaces all had sizable openings to the basement and were well-isolated from the outside. Diagnostics with the basement pressurized revealed them to be far more connected to the basement than to the outside. The crawlspace ducts in houses #206 and #627 were entirely branch ducts, while about 25 percent of the crawlspace duct surface area in houses #256 and #581 were the ends of trunks. House #628 had 90 percent of the supply branch runs and 20 percent of the supply trunk in a crawlspace.

None of the basements had wall or ceiling insulation except for #1301, which featured firred-out walls with R-11 fiberglass batts, and #256 and #628, which included R-19 fiberglass on the ceiling of crawlspaces adjacent to the basement. Supply ducts in these houses were constructed exclusively of uninsulated rectangular and round steel, with the exception of house #206, which included about 20 feet of R-4.2 plastic flex duct, house #256, which had R-11 building fiberglass installed on the crawlspace ducts, and house #628, which featured insulated ductboard trunks and R-4.2 plastic flex duct handling 90 percent of the branch runs. All return duct systems were uninsulated and combined rectangular and round steel ducts with wood framing cavities that had been panned with sheet steel, masonite, or sheetrock.

Zone Depressurization

None of the 19 houses had more than two exhaust devices installed, including the clothes dryer. The air handler's contribution to depressurization of the basement averaged 0.6 Pa across the sample. House #628, containing the second greatest amount of return ELA in the study at 658 cm^2, was the only house in which the air handler depressurized the basement by more than 2 Pa, coming in at 3.4 Pa. Much of this leakage was very inconveniently located above the furnace in a large multi-panned conglomeration that was restrained by electrical wires and plumbing. The retrofit reduced leakage by only 34 percent, and depressurization dropped by 1.0 Pa.

Building Leakage

The four different house configurations used during building leakage testing allowed estimation of four types of building

Table 1. *Pre-Retrofit Characteristics of Houses, Heating Equipment, and Duct Systems*

House ID[a]	No. of Stories	Age (yrs)	Forced Air Heating Equipment[b]	Floor Area (sq. ft.)	1st Floor Percent Over Basement/ Percent Over Crawlspace	Percent of Duct Surface Area in Crawlspace	Percent of Duct Surface Area in Interior Cavities	Percent of Duct Surface Area in Exterior Cavities
118	1.5	51	fuel oil	1,602	100% / 0%	0%	19% sup	0%
206	2	106	fuel oil	2,799	77% / 23%	5% sup	14% sup	0%
256	2	56	natural gas ND	1,456	66% / 34%	26% sup	28% sup	0%
263	2	61	natural gas ID	1,169	100% / 0%	0%	28% sup	0%
316	2	116	fuel oil	1,010	100% / 0%	0%	37% sup	0%
352	1.5	51	natural gas SC	963	100% / 0%	0%	16% sup	0%
363	2	61	natural gas ND	1,217	100% / 0%	0%	33% sup	0%
525	1	44	natural gas ND	913	100% / 0%	0%	0%	0%
581	1.5	41	fuel oil	1,152	73% / 27%	16% sup	7% sup	6% sup
627	2	54	natural gas SC	1,205	83% / 17%	9% sup	25% sup	14% ret
628	2	60	natural gas SC	1,812	68% / 32%	49% sup	13% sup	2% sup
1028	1	31	natural gas SC	1,132	100% / 0%	0%	0%	0%
1033	1	46	natural gas SC	1,232	100% / 0%	0%	0%	0%
1042	1	29	natural gas ND	1,576	100% / 0%	0%	0%	0%
1301	1	6	GW heat pump	1,356	100% / 0%	0%	0%	0%
1321	2	7	GW heat pump	1,344	100% / 0%	0%	30% sup 10% ret	0%
1416	1.5	70	natural gas ND	1,635	100% / 0%	0%	36% sup 19% ret	0%
1421	1.5	61	natural gas SC	1,098	100% / 0%	0%	28% sup	0%
1460	1	34	natural gas SC	1,924	100% / 0%	0%	0%	0%

[a]House ID numbers less than 1000 are in New York; ID numbers greater than 1000 are in Wisconsin
[b]ND = natural draft, ID = induced draft, SC = sealed combustion, GW = ground water

ELA. In addition, SLA was determined for the normal configuration of the house and for the living space envelope alone. The pre-retrofit building leakage results are shown in Table 2.

The average normal ELA for all 19 houses is 968 cm^2, and the average normal SLA is 7.3 cm^2/m^2. Most of these houses were built between 1935 and 1965, and the sample on average is leakier than some newer homes covered in other studies. Providing context to the current results are a study of 277 houses in the United States built between 1961 and 1983 (Sherman et al. 1984) which found an average SLA of 5.4 cm^2/m^2, and a study that found an average ELA of 542 cm^2 and an average SLA of 2.6 in 60 houses in New York State, 85 percent of which were built between 1973 and 1983. Approximately two-thirds of these homes had basements (Nitschke et al. 1985).

Another study of 31 slab-on-grade and crawlspace homes in California (Modera et al. 1991) found average SLA of 6.0

Table 2. Pre-Retrofit Equivalent Building Leakage Area and Specific Building Leakage Area

	NORMAL ENVELOPE[a]		LIVING SPACE ENVELOPE		BASEMENT ENVELOPE	BASEMENT TO LIVING SPACE	
House ID	ELA (cm^2@4Pa)	SLA (cm^2/m^2)	ELA (cm^2@4Pa)	SLA (cm^2/m^2)	ELA (cm^2@4Pa)	ELA (cm^2@4Pa)	Percentage of Basement Env. ELA
118	1,484	10.0	2,977	20.0	2,695	2,140	79%
206	2,356	9.1	3,384	13.0	3,209	2,017	63%
256	772	5.7	1,379	10.2	1,499	1,057	71%
263	824	7.6	1,428	13.2	1,290	950	74%
316	1,001	10.7	1,183	12.6	1,321	608	46%
352	539	6.0	672	7.5	819	456	56%
363	901	8.0	1,479	13.1	1,109	811	73%
525	945	11.1	1,253	14.8	1,446	809	56%
581	897	8.4	1,229	11.5	1,492	824	55%
627	1,466	13.1	1,939	17.3	1,190	783	66%
628	1,758	10.4	2,281	13.6	1,687	1,041	62%
1028	368	3.5	565	5.4	518	351	68%
1033[b]	503	4.4	791	6.9	814	520	64%
1042	454	3.1	678	4.6	429	303	71%
1301[b]	435	3.5	639	5.1	514	355	69%
1321[b]	498	4.0	936	7.5	735	552	75%
1416	1,560	10.3	2,072	13.6	1,764	1,098	62%
1421[b]	662	6.5	676	6.6	1,043	210	20%
1460[b]	N/A	N/A	N/A	N/A	1,148	N/A	N/A
Avg.	968	7.3	1,420	10.6	1,301	827	63%
S.D.	548	3.1	822	4.6	706	531	14%

[a]Refers to pressurization of the living space using the normal day-to-day configuration of the house, with the doors between the living space and the basement and between the basement and the outside both closed.
[b]Pre-retrofit normal leakage test was N/A or yielded $0.90 < r^2 < 0.99$. Exponent (n) used in pre-retrofit building ELA calculations for this house is 0.66.

cm^2/m^2 and 3.9 cm^2/m^2 for pre-1980 and post-1979 houses, respectively. Average ELA and SLA for eight new conditioned-basement houses in Minnesota were 620 cm^2 and 2.2 cm^2/m^2, respectively (Nelson et al. 1993). In these homes ELA was measured with the basement door open, so that measured leakage is from the house and basement to the attic and outside. Four basement homes in Baltimore, MD built after 1970 were tested with the basement open to the outside, giving average living space ELA of 800 cm^2 and SLA of 4.1 cm^2/m^2 (Treidler & Modera 1994).

In the current study, comparisons between basement ELA, living space ELA, and basement/living space interface ELA are available. In Table 2, average basement envelope leakage is 1,301 cm^2, nearly equal to average living space envelope leakage of 1,420 cm^2. In many of these houses the basement is leakier than the living space. In addition, in most of the cases the ELA between the house and the basement is 50 percent to 75 percent of the basement envelope leakage, with an average of 827 cm^2 (63 percent).

Duct Leakage

Equivalent duct leakage area was measured for both the supply and return sides of each duct system. For each side of the system, measurements were made of (1) total duct ELA, (2) basement and outside duct ELA together, and (3) outside duct ELA only. Subtracting (3) from (2) then gave an estimate of basement duct ELA only. Table 3 shows the pre-retrofit duct leakage results.

Total supply duct ELA averaged 261 cm^2, with an average SLA of 2.2 cm^2/m^2 and an average basement ELA of 180 cm^2, or 70 percent of the total. On the return side, total ELA averaged 338 cm^2, with an average SLA of 2.7 cm^2/m^2 and an average basement ELA of 242 cm^2, or 75 percent of the total. Combining supply and return leakage together gives an average total whole system ELA of 599 cm^2 and SLA of 4.9 cm^2/m^2. Outside duct ELA varied widely between 0 percent and 20 percent within these small samples. The multi-storey homes probably contained duct leakage in interior wall or floor cavities that in turn leaked to the outside through an attic or crawlspace, causing outside ELA to register despite the lack of exterior cavity ducts.

As with envelope leakage, the homes' duct systems were leakier than ductwork studied in the previously-cited research. In Nelson et al., total duct ELA and SLA, including both supply and return leakage, averaged 780 cm^2 and 2.8 cm^2/m^2 respectively. The study of four basement houses in Baltimore (Treidler & Modera 1994) revealed average supply and return ELAs of 203 cm^2 and 190 cm^2, respectively,

Table 3. *Pre-Retrofit Equivalent Duct Leakage Area, Specific Duct Leakage Area, and Normal Operating Pressures*

	SUPPLY ELA (cm^2@4Pa), SLA and OPERATING PRESSURE					RETURN ELA (cm^2@4Pa), SLA and OPERATING PRESSURE				
House ID	Total ELA	Total SLA (cm^2/m^2)	Basement ELA	Outside ELA	ΔP (Pa)	Total ELA	Total SLA (cm^2/m^2)	Basement ELA	Outside ELA	ΔP (Pa)
118	395	2.7	N/A	N/A	13	893	6.0	N/A	N/A	18
206	166	0.6	91 (55%)	32 (19%)	17	148	0.6	106 (72%)	26 (17%)	15
256	325	2.4	174 (54%)	37 (11%)	31	217	1.6	154 (71%)	18 (8%)	14
263	259	2.4	144 (56%)	17 (7%)	39	401	3.7	331 (83%)	20 (5%)	20
316	308	3.3	200 (65%)	63 (20%)	7	75	0.8	61 (81%)	8 (11%)	36
352	126	1.4	N/A	N/A	25	173	1.9	N/A	N/A	56
363	262	2.3	153 (58%)	0	7	278	2.5	193 (69%)	0	16
525	417	4.9	323 (78%)	33 (8%)	12	334	3.9	259 (78%)	38 (11%)	25
581	361	3.4	257 (71%)	46 (13%)	22	278	2.6	182 (66%)	54 (19%)	60
627	368	3.3	282 (77%)	17 (5%)	15	373	3.4	311 (83%)	6 (2%)	12
628	311	1.8	177 (57%)	51 (16%)	20	659	3.9	658 (100%)	0	59
1028	149	1.4	118 (79%)	0	47	305	2.9	233 (76%)	45 (15%)	75
1033	146	1.3	114 (78%)	0	14	442	3.9	442 (100%)	0	19
1042	207	1.4	175 (84%)	0	53	249	1.7	180 (72%)	29 (12%)	61
1301	187	1.5	171 (91%)	0	26	399	3.2	144 (36%)	0	40
1421	214	2.1	165 (77%)	11 (5%)	20	298	2.9	212 (71%)	29 (10%)	45
1460	235	1.3	162 (69%)	34 (15%)	31	223	1.2	157 (70%)	42 (19%)	46
Avg.	261	2.2	180 (70%)			338	2.7	242 (75%)		
S.D.	92	1.1	63 (12%)			195	1.4	149 (15%)		

Note: All percentages are with respect to total ELA; data for houses #1321 and #1416 not available and average supply and return SLAs of 1.0 cm^2/m^2 and 0.9 cm^2/m^2. These two groups of basement homes featured much tighter duct construction than the houses in the current study, probably primarily because they were newer buildings.

In Modera et al. (1991), supply and return total SLA averaged 0.4 cm^2/m^2 and 0.5 cm^2/m^2 in 31 California residences, which, as the authors pointed out in a later study, may be the result of both seamless flex duct between trunks and registers and less duct surface area per unit floor area than in houses more similar to those covered here.

POST-RETROFIT RESULTS

While these houses provided important as-found data on envelope leakage and duct leakage, the 19 retrofits also supplied information on what might happen when such duct systems are improved by sealing leaks and installing insulation. Specifically, post-retrofit changes in building and duct leakage, energy consumption, and basement temperatures were examined.

Building Leakage

The duct system retrofits were expected to reduce equivalent leakage area between the living space and the basement, which would also reduce basement envelope leakage, living space envelope leakage, and to a lesser extent normal envelope leakage. If duct retrofit resulted in a significant reduction in living space ELA or normal ELA, a house might be expected to use less energy even when the air handler was not running. The post-retrofit changes in building leakage area are shown in Table 4.

The sample is small and the standard deviations are large, but Table 4 suggests that ELA between the basement and the living space needed to change by 30 percent to 60 percent to have an effect on normal ELA. In addition, it appears from comparing the last column in Table 2 to the same in Table 4 that these duct retrofits did not have a large effect on the percentage of the basement envelope that is leakage to the living space.

Duct Leakage

The outside duct leakage areas in Table 3 were not found to change by a significant amount except for supply leakage in houses #316 (-19 cm^2), #363 ($+25$ cm^2), #525 (-23 cm^2), #581 (-27 cm^2), and #1460 (-23 cm^2). Post-retrofit changes in duct leakage beside outside leakage are shown in Table 5.

Whole system basement duct leakage was reduced by an average of 56 percent and whole system total duct leakage by 46 percent, with average supply and return duct leakage reductions being similar. The post-retrofit specific leakage area averaged 1.3 cm^2/m^2 and 1.4 cm^2/m^2 on the supply side and return side, respectively, with standard deviations of 0.8 and 0.7. In a comparison of two values that both estimate the change in leakage area between the basement and living space (dELA), Basement to Living Space dELA from Table 4 and Whole System Basement dELA from Table 5 show good agreement for houses #263, #316, #363, and #581, but no pattern emerges for the other eight homes with data.

Energy Consumption, Temperatures, and Retrofit Economy

The changes in energy consumption and monitored temperatures in Table 6 give a detailed look at performance differences after the duct retrofits.

The effect of a change in a house's balance temperature (T_{bal}) on NAC following retrofit is clearly illustrated in Table 6. Several houses, notably #581, #1321, and #1028, operated much differently following retrofit, with their heating system being called upon at substantially higher or lower outdoor temperatures. This reduced or increased the annual savings possible from the reduction in Btus/dT/Day, which itself was fairly significant across the sample, averaging 11 percent.

The inside temperatures were kept about the same post-retrofit as pre-retrofit for all of the homes, but average basement temperature dropped in nearly all cases by an average of 5° F, giving an average post-retrofit basement temperature of 55.9° F. The minimum average daily basement temperature decreased by an average of 5.5° F across the sample, with two houses showing a decrease of more than 10° F. In these two houses, the basement temperature at the ceiling was alternately just below and just above 40° F for 24 hours, which is probably too low for comfort. Ironically, client complaints of cold basements came from house #1460, with the highest post-retrofit average basement temperature, and from house #1028, also one of the highest post-retrofit basement temperatures, where water pipes became slushy near a 2 sq. in. crack in the foundation wall during a -30° F cold snap.

Importantly, outside temperatures decreased by an average of 4.9° F, about the same amount as the average basement temperature experienced. The three temperatures, inside, outside, and basement, must be subjected to additional analysis to determine with more confidence the basement temperature reduction's dependence on the outside temperature reduction. However, increased dependence of basement temperature on outside temperature would be a reasonable effect of duct retrofit.

Table 4. Post-Retrofit Changes in Equivalent Building Leakage Areas

House ID	POST-RETROFIT CHANGE IN ELA (dELA - cm^2 @ 4 Pa) Normal Envelope[a] dELA	Living Space Envelope dELA	Basement Envelope dELA	Basement to Living Space dELA	New Percentage of Basement Envelope
118	+175 (+12%)	−277 (−9%)	−480 (−18%)	−494 (−23%)	74%
206	−249 (−11%)	−280 (−8%)	+68 (+2%)	+90 (+4%)	64%
256	−63 (−8%)	−226 (−16%)	−563 (−38%)	−374 (−35%)	73%
263[b]	+2 (+0%)	−18 (−1%)	−339 (−26%)	−171 (−18%)	82%
316	−135 (−13%)	−189 (−16%)	−255 (−19%)	−157 (−26%)	42%
352	+59 (+11%)	+275 (+41%)	−263 (−32%)	−39 (−8%)	75%
363	−5 (−1%)	−178 (−12%)	−33 (−3%)	−103 (−13%)	66%
525	+1 (0%)	−46 (−4%)	−157 (−11%)	−151 (−19%)	51%
581	−18 (−2%)	−215 (−18%)	−105 (−7%)	−172 (−21%)	47%
627	−2 (0%)	−126 (−6%)	−160 (−13%)	−162 (−21%)	60%
628	−24 (−1%)	−143 (−6%)	−266 (−16%)	−210 (−20%)	58%
1028	−12 (−3%)	−101 (−18%)	−172 (−33%)	−150 (−43%)	58%
1033	−10 (−2%)	+54 (+7%)	−64 (−8%)	−103 (−20%)	56%
1042[b]	+163 (+36%)	+35 (+5%)	−2 (−1%)	−57 (−19%)	58%
1301	−64 (−15%)	−235 (−37%)	−237 (−46%)	−222 (−63%)	48%
1321[b]	+4 (+1%)	−265 (−28%)	−154 (−21%)	−182 (−33%)	64%
1416	−488 (−31%)	−887 (−43%)	−851 (−48%)	−644 (−59%)	50%
1421[b]	N/A	N/A	−41 (−4%)	N/A	N/A
1460[b]	N/A	N/A	−63 (−5%)	N/A	N/A
Avg.	−39 (−2%)	−166 (−10%)	−218 (−18%)	−194 (−26%)	60%
S.D.	151 (14%)	236 (19%)	221 (15%)	172 (17%)	11%

Note: All percentages are with respect to pre-retrofit values except last column.
[a] Refers to pressurization of the living space using the normal day-to-day configuration of the house, with the doors between the living space and the basement and between the basement and the outside both closed.
[b] Post-retrofit normal leakage test was N/A or yielded $0.90 < r^2 < 0.99$. Exponent (n) used in post−retrofit building ELA calculations for this house is 0.66.

A possible alternative to duct system retrofit in houses with basements has been to tighten the exterior basement envelope and leave the ducts alone. This approach presumably would cause most of the heat lost from the ducts to be retained within the basement, easing the heating load of the living space above. Using this line of reasoning, the homes with tighter basements in this study would have shown less savings from duct retrofit than other homes, since the lost heat in the pre-retrofit condition was being effectively contained within the basement anyway. In fact this effect was difficult to discern here, with three out of the five tightest homes showing above-average reductions in NAC.

Pre-retrofit annual consumption, costs of retrofit, and resultant annual savings at 16 houses with strong data are shown in Table 7. The savings are based on the post-retrofit changes

Table 5. Post-Retrofit Changes in Equivalent Duct Leakage Area

House ID	SUPPLY DUCTS dELA Total (cm^2@4Pa)	SUPPLY DUCTS dELA Basement (cm^2@4Pa)	RETURN DUCTS dELA Total (cm^2@4Pa)	RETURN DUCTS dELA Basement (cm^2@4Pa)	WHOLE SYSTEM dELA Total (cm^2@4Pa)	WHOLE SYSTEM dELA Basement (cm^2@4Pa)
118	−45 (−11%)	N/A	−602 (−67%)	N/A	−647 (−50%)	N/A
206	−32 (−19%)	−36 (−40%)	−17 (−11%)	−42 (−39%)	−49 (−16%)	−78 (−39%)
256	−34 (−10%)	−69 (−40%)	−112 (−51%)	−91 (−59%)	−146 (−27%)	−160 (−49%)
263	−63 (−24%)	−52 (−36%)	−187 (−47%)	−173 (−52%)	−250 (−38%)	−225 (−47%)
316	−115 (−37%)	−102 (−51%)	−8 (−11%)	−19 (−32%)	−123 (−32%)	−121 (−47%)
352	−22 (−18%)	N/A	−42 (−24%)	N/A	−64 (−21%)	N/A
363	−48 (−18%)	−30 (−20%)	−92 (−33%)	−70 (−36%)	−140 (−26%)	−100 (−29%)
525	−203 (−49%)	−168 (−52%)	−181 (−54%)	−171 (−66%)	−384 (−51%)	−339 (−58%)
581	−183 (−51%)	−166 (−64%)	−55 (−20%)	−52 (−28%)	−238 (−37%)	−218 (−50%)
627	−77 (−21%)	−106 (−38%)	−171 (−46%)	−167 (−54%)	−248 (−33%)	−273 (−46%)
628	−134 (−43%)	−62 (−35%)	−197 (−30%)	−224 (−34%)	−331 (−34%)	−286 (−34%)
1028	−109 (−73%)	−92 (−78%)	−216 (−71%)	−180 (−77%)	−325 (−72%)	−272 (−77%)
1033	−52 (−36%)	−55 (−49%)	−316 (−71%)	−343 (−78%)	−368 (−62%)	−398 (−72%)
1042	−145 (−70%)	−149 (−85%)	−201 (−81%)	−154 (−86%)	−346 (−76%)	−303 (−85%)
1301	−125 (−67%)	−122 (−72%)	−340 (−85%)	−106 (−74%)	−465 (−79%)	−228 (72%)
1321	N/A	N/A	N/A	N/A	−197 (−50%)	N/A
1416	N/A	N/A	N/A	N/A	−412 (−72%)	−333 (−80%)
1421	−113 (−53%)	−109 (−66%)	−76 (−25%)	−61 (−29%)	−189 (−37%)	−170 (−45%)
1460	−170 (−73%)	−125 (−77%)	−75 (−34%)	−86 (−55%)	−245 (−54%)	−211 (−66%)
Avg.	−98 (−40%)	−96 (−54%)	−170 (−45%)	−129 (−53%)	−272 (−46%)	−232 (−56%)
S.D.	57 (22%)	45 (19%)	147 (24%)	85 (20%)	148 (19%)	91 (17%)

Note: All percentages are of pre-retrofit values; all whole system values are simple sums of supply and return except houses #1321 and #1416, where whole system leakage was measured directly

in NAC from Table 6. Total consumption reduction for the group is 99.8 MMBtus, or 8 percent of the total pre-retrofit NAC. Sample energy costs of 7$/MMBtus and $13/MMBtus yield savings of $699 and $1,297, respectively.

CONCLUSIONS

This project shows that meaningful reductions in annual energy consumption are available through the retrofit of basement duct systems. Important savings were observed in high consumers and in low consumers; in leaky homes and in not-so-leaky homes.

On average the duct system retrofits resulted in a reduction in Btus/ΔT/Day consumed by the heating equipment, which implies an improvement in both delivery efficiency and distribution efficiency. Additional work remains in calculating delivery efficiency for these homes according to the design pathway set forth in ASHRAE SPC 152, and comparing those results with the monitored changes in Btus/dT/Day. In addition, the monitored basement temperature data from

Table 6. *Changes in NAC, Btus/dT/Day, and Inside, Outside, and Basement Temperatures*

	POST-RETROFIT CHANGES		PRE-RETROFIT			POST-RETROFIT CHANGES			BASEMENT PRE-RETROFIT[b]		BASEMENT POST-RETROFIT CHANGES	
House ID	NAC[a]	*Btus dT Day*	Avg. T_{in}[b] (°F)	Avg. T_{out}[b] (°F)	T_{bal} (°F)	Avg. T_{in} (°F)	Avg. T_{out} (°F)	T_{bal} (°F)	Avg. (°F)	Min. (°F)	Avg. (°F)	Min. (°F)
118	0%	− 6%	69.6°	28.1°	62.4°	− 0.4°	− 2.8°	+ 1.8°	56.0°	53.8°	− 6.7°	− 10.4
206	− 11%	− 20%	65.7°	31.7°	58.7°	+ 0.4°	− 7.7°	+ 2.8°	52.4°	51.3°	+ 0.2°	+ 0.7
256	− 9%	− 9%	67.4°	29.9°	54.7°	+ 0.4°	− 6.2°	0.0°	64.7°	61.7°	− 6.5°	− 8.5
263c	− 22%	− 32%	64.7°	32.6°	55.4°	− 1.7°	+ 16.1°	+ 3.6°	58.4°	54.3°	0.0°	+ 1.8
316d	− 12%	+ 4%	73.8°	28.1°	72.0°	− 1.2°	+ 1.4°	− 5.1°	63.7°	60.1°	− 4.8°	− 4.6
363	− 1%	− 1%	66.7°	30.5°	48.2°	+ 0.1°	− 4.9°	− 0.1°	55.2°	53.0°	− 3.4°	− 3.3
525	− 13%	− 13%	69.5°	31.1°	67.4°	− 1.9°	− 6.3°	− 0.1°	66.5°	64.4°	− 6.9°	− 8.5
581	− 2%	− 31%	63.7°	30.0°	62.7°	− 0.2°	− 6.3°	+ 10.5°	61.2°	57.8°	− 6.4°	− 6.8
627	− 7%	− 8%	64.8°	36.7°	56.5°	− 0.4°	− 9.3°	+ 0.2°	61.9°	59.2°	− 3.3°	− 3.2
628	− 3%	− 16%	66.7°	37.6°	58.5°	+ 2.2°	− 6.5°	+ 3.7°	53.9°	49.3°	− 5.0°	− 8.2
1028	− 22%	+ 1%	69.0°	42.6°	60.2°	− 1.1°	− 13.3°	− 7.2°	67.2°	63.8°	− 7.7°	− 5.9
1033	− 22%	− 12%	69.7°	31.0°	71.9°	+ 0.3°	− 5.1°	− 1.6°	60.6°	58.3°	− 7.5°	− 9.6
1042	− 14%	− 19%	64.0°	28.8°	63.0°	− 0.3°	− 5.3°	+ 4.1°	64.7°	58.6°	− 8.7°	− 3.7
1301	+ 3%	− 8%	68.8°	36.9°	66.6°	+ 0.3°	− 9.3°	+ 3.2°	62.2°	60.8°	− 3.6°	− 3.9
1321	− 27%	+ 10%	69.3°	30.3°	73.5°	0.0°	− 2.9°	− 9.6°	59.8°	55.3°	− 5.4°	− 4.4
1416	− 12%	+ 1%	66.3°	34.4°	58.9°	− 0.1°	− 4.3°	− 3.9°	59.3°	55.1°	− 8.2°	− 14.2
1421	+ 9%	− 12%	69.2°	32.2°	62.8°	+ 0.2°	− 8.4°	+ 6.4°	61.8	58.6°	− 3.2°	− 6.9
1460	− 2%	− 20%	67.0°	37.1°	59.1°	0.0°	− 7.5°	+ 6.3°	66.0°	61.4°	− 2.4°	+ 0.9
Avg.	− 9%	− 11%	67.6°	32.7°	61.8°	− 0.2°	− 4.9°	0.8°	60.9°	57.6°	− 5.0°	− 5.5°

Note: House #352 data unavailable
[a] Normalized to T_{bal} for each period
[b] 24 hour averages
[c] Due to bank foreclosure, pre-retrofit period 2/3/95–3/21/95; post − retrofit period 3/29/95–5/15/95
[d] Due to remodelling, pre-retrofit period 1/19/95–3/1/95; post-retrofit period 11/15/95–12/30/95

these houses will be compared to values predicted by SPC 152.

The telephone survey that generated the 19 actual field study participants, conducted on houses known to have some kind of duct system, revealed that 153 out of 412 respondents live in homes with forced air furnaces and distribution systems located in unheated basements. In addition, among 342 respondents who said they had ducts in either a heated or unheated basement, 152 said the ducts were not sealed and

Table 7. *Retrofit Economy*

House ID	Pre-Retrofit NAC (MMBtu)	Cost of Retrofit	Annual Heating Savings (MMBtus)
118	111.2	$711	− 0.4
206	113.7	$460	12.7
256	58.6	$466	5.2
363	45.5	$404	0.6
525	108.4	$313	14.4
581	67.1	$555	1.2
627	84.6	$760	6.0
628	120.9	$290	3.8
1028	52.0	$675	11.3
1033	76.6	$1,023	16.8
1042	85.8	$996	12.2
1301	15.5	$949	− 0.5
1321	20.9	$771	5.6
1416	129.8	$1,017	15.2
1421	67.6	$844	− 6.1
1460	84.1	$1,263	1.8
TOTAL	1,242.3	$11,497	99.8 (8%)

Note: Houses #263, 316, and 352 removed

92 said that they were not sure if the ducts were sealed. Of the same group of 342 respondents, 233 respondents said there was no duct insulation and 34 said they were not sure.

This evidence indicates that of homes with duct systems, many are located in unheated basements, and further that many basement duct systems are not sealed or insulated. Therefore, there may be a significant number of single-family homes that approximate the initial characteristics of the studied group and would demonstrate similar energy savings following retrofit.

The fact that these duct retrofits may have resulted in basement ceiling temperatures between 40° F and 45° F in some houses suggests that basement envelope sealing may be advisable in conjunction with retrofit to mitigate both comfort and pipe freezing problems. Further, in light of the apparent savings in some of the tighter basements in this study, it is possible that a two-pronged approach would work in many cases: tighten the exterior basement envelope to prevent excessive reduction in basement temperature and possible increase in balance point, and retrofit the duct system to increase delivery efficiency to the living space.

ACKNOWLEDGMENTS

This project was sponsored by the Electric Power Research Institute, the New York State Energy Research and Development Authority, the Central Hudson Gas and Electric Corporation, and the Energy Center of Wisconsin. Thank you to Joel Anderson, John Andrews, Michael Blasnik, Bob Carver, the folks at the Energy Conservatory, Richard Hackner, John Karriger, Sekhar Kondepudi, Mark Modera, Eric Neumann, John Proctor, Joe Rizzuto, and to all the homeowners who participated.

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