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ACEEE 1990 Summer Study on
Energy Efficiency in Buildings

Final Report

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ATTIC INSULATION PERFORMANCE, AIR LEAKAGE, AND VENTILATION: MEASURED RESULTS IN FLAT ROOF ROWHOUSES

Michael Blasnik
GRASP

The initial results of a detailed study of attic insulation performance in flat roof rowhouses are presented. A mathematical model of attic heat and moisture transfer which includes an air leakage model was formulated. Simple and inexpensive techniques were devised to measure ceiling and roof airtightness and short term air exchange rates for the attic spaces. In order to verify the attic model and quantify the performance of attic insulation, six occupied houses were instrumented to monitor hourly averages of temperatures, pressure differences, humidities, and heating system status for 1-2 winters each. Wood moisture content was also periodically measured.

Each of the instrumented attics was given a series of treatments consisting of a combination of bypass sealing, insulation, and venting. The performance of the treatments at three of the sites was analyzed with the attic model. The model performed well overall and provided reasonable estimates of attic performance.

The study demonstrates that the performance of common flat roof insulation methods falls short of standard predictions because of substantial air leakage from the house below. The effectiveness of, and difficulties inherent to, several approaches for sealing bypasses in limited access flat roof attics is presented. When significant bypasses are present, effective treatment can dramatically and cost-effectively improve attic retrofit performance. But the most cost-effective strategy is site specific. Evidence is also presented that standard passive roof ventilation is often ineffective, unnecessary, and counterproductive in these houses, leading to potentially significant additional heat loss. An attic airtightness test is described which can help estimate the impact of insulation, bypass sealing, and venting strategies.

INTRODUCTION

Although attic insulation is one of the most common residential energy retrofits, little work has been done to measure actual performance. The most extensive field research was conducted at Princeton University in the 1970's (Woteki and Dutt 1977). The Princeton researchers discovered that house to attic air leakage and convective loops dramatically reduced attic insulation performance. These 'thermal bypasses' created attic heat loss rates three to seven times greater than standard calculations would predict. Fortunately, simple and inexpensive methods for fixing most thermal bypasses in accessible attics are available and used by knowledgeable practitioners.

In flat roof buildings, however, bypass sealing is considered difficult and expensive and the savings are not well documented. But the effectiveness of insulating and venting without sealing bypasses is also questionable. The situation is further complicated by the potential for moisture damage caused by bypass air leakage. The lack of adequate moisture models and documented field experience has caused building engineers to question existing attic ventilation standards. Practitioners are also debating the proper approach to flat roof attics (Wilson 1989). Their questions concern finding effective treatments and determining which bypass, insulation, and ventilation methods lead to cost-effective savings while minimizing moisture damage potential.

GRASP, a Philadelphia based non-profit energy training and research organization, designed a research project to study and optimize attic retrofit performance for the more than 500,000 older flat roof rowhouses in southeastern Pennsylvania. This paper summarizes the four phases of the research: attic model development, field monitoring, treatment research, and analysis.

THE ATTIC MODEL

Because attic heat and moisture transfer rates cannot be directly measured, attic performance must be modeled mathematically in terms of measurable quantities such as temperatures. If the model describes the actual data well, transfer rates can then be calculated. A validated model can also be used to simulate performance under different building and climate conditions.

The basis of the GRASP attic model is an hourly three node thermal and one node moisture model (Burch et al 1984). Burch's model, which performed well in a controlled setting, simultaneously solves the heat balance equations for three points (nodes) in the attic: attic floor (top surface of ceiling), attic air, and underside of roof deck. Convection and radiation exchanges between the nodes are modelled explicitly and remaining paths (e.g. sidewalls) are each treated as having a single R-value encompassing all modes of heat transfer. The moisture portion of the model includes storage on wood surfaces in addition to diffusion and air transported moisture.

GRASP expanded this model by explicitly modeling air leakage, and including heat transfer across common walls between rowhouses, an estimated parallel UA value for conduction from the living space to attic through the common walls, and lumped thermal mass terms for the ceiling and roof (Ford 1982).

Modeling Attic Air Leakage Rates.

The rate of air flow through a building component, Q, is a function of the airtightness of the component and the pressure difference acting across it. This relationship is often represented as a power law:

$$Q = K \cdot P^n \tag{1}$$

where K and n (called the flow coefficient and flow exponent) characterize the leakage site, and P is the pressure difference across the leak. The values of K and n are well defined for the cases of orifice flow and fully developed turbulent and laminar flow regimes, but are generally empirically determined using a blower door for typical building leaks. The use of equation 1 to model attic air flows requires the measurement of component flow coefficients and exponents, and the modeling of natural pressure differences.

Measuring Attic Airtightness. Because existing techniques were not well suited to flat roof attic spaces, GRASP developed the Attic Airtightness Test (Blasnik 1989) for measuring the airtightness of air leakage paths from house to attic, referred to as ceiling, and attic to outside, referred to as roof. The method is based on the relationship between the pressure drops across surfaces in series and their relative airtightness. The test procedure involves measuring the pressure differences induced across the ceiling and roof when pressurizing a house. A hole is cut in the ceiling and the pressures are measured again. Assuming the added hole behaves as a sharp edged orifice and the flow exponents are equal to 0.65 (typical of whole house results), then the mass balances in the attic before and after adding the hole can be solved for the ceiling and roof flow coefficients:

$$Kc = \frac{1.06 \cdot A}{[(P_{r2} \cdot P_{c1} / P_{r1})^{.65} / P_{c2}^{.50}] - P_{c2}^{.15}} \tag{2}$$

$$Kr = Kc \cdot (P_{c1}/P_{r1})^{.65} \tag{3}$$

where:
K = flow coefficient ($CFM/Pa^{.65}$)
A = Area of added hole (sq. in.)
P = Pressure Difference (Pascal)
r,c = across roof, ceiling
1,2 = before, after hole is added

The constant 1.06 is the product of orifice flow equation constants for the hole and unit conversion factors needed to use area in square inches and produce results in the 'standard' U.S. mixed units of $CFM/Pa^{.65}$. Although this method has not been validated with a dual blower door technique, the flow coefficients have been consistent and reasonable (accounting for 10%-35% of whole house leakage) and have varied according to expectations. Good agreement has been found between measured and estimated changes in whole house air tightness after attic air sealing. Potential improvements to the method include: using an orifice plate instead of a hole, adjusting pressures to eliminate the roof pressure terms in equation 2, and testing at several pressure levels to statistically estimate flow exponents.

Modeling Attic Pressure Differences. Attic pressure differences are modeled as functions of stack and wind effects. The total stack effect, calculated from the standard expression, is divided between the ceiling and roof based upon an attic mass balance calculated from the measured values of Kc and Kr (with Kr allocated between exterior and common wall leakage). Wind pressures are modeled with standard expressions. Several alternative assumptions for conversion of wind speeds to on-site estimates and surface pressure coefficients were tried. Wind and stack pressures are added for each roof exposure. Because air leakage is modeled from house to attic (bypasses) and from outside to attic (ventilation), only pressures acting into the attic are used in calculating air flows. Pressure differences were monitored at the field sites to validate the pressure models.

Model Assumptions and Data Requirements. Some of the primary attic model assumptions include: equation 1 is valid at natural pressure differences; the attic air is one zone; and closed convective loop effects either don't exist or can be specified as a parallel UA path. The attic model requires information on house characteristics and hourly driving forces. The house characteristics include: areas and R-values of all surfaces enclosing the attic space, thermal capacitances of the attic floor and roof deck, flow coefficients (Kc and Kr by direction), area and moisture content of wood surfaces, and wind pressure coefficients of attic walls (if pressures are modeled). The hourly driving forces data required are: indoor, outdoor, sol-air, and any adjacent attic temperatures; indoor and outdoor humidity ratios; and wind speed and direction or pressure measurements across each roof exposure. Instead of modeling sol-air temperature, outside roof surface temperatures were measured.

DATA COLLECTION

An instrumentation package was developed to measure the impacts of treatments and provide the data needed for the attic model. The instrumentation plan called for measuring temperatures, relative humidities, heating system status, pressure differences, and wood moisture content at six occupied rowhouses. Planned wind measurements were not made because no representative location could be found due to the complex wind patterns typical of city blocks of rowhouses. Dataloggers scanned all sensors 54 times each hour and then stored the processed data. Site data was retrieved via modem.

A total of 15 temperature sensors were used to provide: inputs to the attic model (4-5), outputs for comparison to the model (3), alternate locations for measurements (4), and a check for unmodeled nodes (3-4). Solid state temperature sensors were calibrated to ± .5 F. Humidity transducers rated ± 5% RH were used in each house and attic. Outdoor humidity ratios were taken from local weather station data. Moisture pins were embedded in the roof deck (2), a roof rafter, and a ceiling joist at each house. Moisture content was measured biweekly initially and then less frequently. The pressure difference across the top floor ceiling and across two attic walls were monitored at each site. The multiplexed transducer (range ± 25 pascal, rated accurate ± 1% of full scale) was zeroed as part of each cycle of measurements to improve accuracy at very low pressures. Positive and negative pressure differences were recorded separately. Heater run time was also monitored.

To measure attic air change rates, GRASP developed a low cost tracer gas method. A spot light and a photovoltaic cell were positioned diagonally across from each other in the attic space (typically 15-20 feet apart). The light was turned on and the output of the PV cell was recorded. A smoke bomb was then ignited in the attic and the PV output monitored at regular intervals (typically once per minute). The net reduction in PV output at a given time was used to measure the density of the smoke in the path between the light and PV. These values were then used as standard concentration values analogous to any tracer gas decay method. After waiting for adequate mixing (3-8 minutes) excellent logarithmic decays were generally found (typical R^2>.95), yielding estimates of attic air change rates. Tests were performed at the sites under differing conditions and measured air change rates ranged from 2-18 ACH. The method has not been compared to standard techniques.

DESCRIPTION OF FIELD SITES

Three houses were instrumented in early 1989 and three more by the following winter. Nearly 1000 site-days of data were collected. The selected houses were all two or three story flat roof brick rowhouses (3 midrow and 3 endrow) built between 1885 and 1925. Five of the houses were uninsulated. The field sites were typical of Philadelphia rowhouses. Standard construction details include:

Attic Walls. Exterior walls are two courses of brick with an interior finish of plaster on wood lath on 3/4" furring strips which create cavities extending from the basement to the attic. The front exterior brick wall typically ends at attic floor level and a metal cornice is the front attic wall. Common walls between rowhouses are two courses of poorly pointed brick which extend up through the roof deck as a parapet wall. Common walls in the living space are finished with plaster applied directly to the brick.

Roofs and Ceilings. Roof decks are pine boards 1"-1.5" thick with several layers of built up roofing .75"-1.5" thick. The roof deck is supported by 3" x 8" rafters pocketed into the brick common walls. Roof areas range from 400-850 sq.ft. and slope back from front to rear at 1:25. The attic spaces are generally 20"-30" high at the front of the house and 8"-14" at the rear wall. Ceilings are plaster on wood lath hung on ceiling joists supported by stringers from the roof rafters and interior walls.

Bypasses. Common attic bypasses include the furring spaces on exterior walls; chimney and plumbing chases; interior partition walls open to the attic due to balloon framing, leaky top plates, or changes in ceiling height (always true for original closets), and large duct chases from the original gravity warm air heat system which are framed open to the attic.

ATTIC BYPASS TREATMENT OPTIONS

Treatments were sought which could cost-effectively seal attic bypasses and be done reliably by existing contractors. Treatment options were evaluated with an infra-red camera, a blower door, and the attic airtightness test. Table 1 presents attic airtightness test results for four of the instrumented houses before and after the treatments described below.

The first treatment tested was the 'seal what you can crawl to' approach. This method was found to be effective for sealing accessible bypasses at reasonable cost. However, the rear 10-20 feet were inaccessible leaving bypasses untreated. Attic airtightness tests showed 30% to 50% reductions in ceiling leakage (Kc) from this approach (e.g. site #1 and site #3).

Another early approach was to fill bypasses with blown insulation. Although not generally considered an air barrier, 50% and 90% reductions in air leakage through cracks have been measured from just 3.5" of blown fiberglass and cellulose respectively (Jacobson et al 1987). When fiberglass (which many local contractors prefer) was used at site #4, a 43% reduction in Kc was measured. Air sealing from the interior reduced Kc by an additional 10%. Standard fiberglass insulation jobs had average reductions of 35% (e.g. site #1 and site #2).

The most effective approach found is a logical extension of the insulation method. Dense packed cellulose (> 3.5 lb/ft.^{3}) has been shown to be an effective air sealing technique in sidewalls (Fitzgerald et al 1990). The same approach was adapted to treat bypasses in the inaccessible section of the attic after the insulator 'seals what you can crawl to'. If a space is too small to reach, then it's

Table 1. . Site Data: Treatments, Airtightness, Pressures, and Air Flows

Site Info			Treatments			Airtightness (CFM/Pa^.65)		Ceiling Pressures @ dT=30F (Pa.)		Natural Air Flow Smoke Bomb (CFM)	
ID#	General	Attic Area	Phase	Method	Vent	Kc	Kr	Actual	Model	Actual	Model
1	2 Story	458	Pre	--	0	94	42	0.31	0.34	38/52	44/57
	Midrow		A/S	Crawl	0	65	40	0.60	0.49	--	--
	Hydronic		I&V	Std-FG	1	45	120	1.21	1.25	113	80
			I&NV	--	0	45	14	0.44	0.22	27	15
2	2 Story	655	Pre	--	0	192	214	0.75	0.83	117	290
	Endrow		I&V	Std-FG	2	124	244	0.92	1.13	151	251
	Forced Air		I&NV	--	0	123	131	0.64	0.80	119	115
3	2 Story	847	Pre	--	0	297	276	0.67	0.72	--	--
	Endrow		A/S	Crawl	0	177	253	1.08	1.08	--	--
	Forced Air		I&V	DP-Cel	1	17	233	1.84	1.67	--	--
4	2 Story	561	Pre	--	0	192	76	0.30	0.33	99	103
	Midrow		I	Fill-FG	0	109	50	0.33	0.39	--	--
	Grav. Air		I&A/S	Int.	0	90	48	0.41	0.47	--	--

Key: A/S= Air Sealed Bypasses, I= Insulated, V= Vented, NV= Not Vented
Crawl= Seal accessible leaks from attic, Std= Standard loose fill
FG= Fiberglass, Cel= Cellulose, Fill= Fill chases w/insulation
Int= Seal Bypasses from interior, Vent= # of 16" 'mushroom' vents

small enough to dense pack. This method was found to be very effective and a 94% reduction in Kc was measured at site #3.

ATTIC MODEL RESULTS

Air leakage rates are the key factor in characterizing attic heat and moisture transfer. The air leakage model was analyzed by evaluating the pressure models and comparing predicted flows to smoke bomb tests. The thermal and moisture models were then analyzed after revising the ventilation model.

Air Leakage Model Results

Initial analysis and field observations found that the actual ceiling pressure difference (Pc) was influenced significantly by heating system operation at every site, particularly in houses with forced air heat. The sites without forced air heat had decreases in Pc ranging from 0.1 - 0.3 pascal when the heating system operated, presumable due to chimney flows. Two sites with forced air heat had Pc increase by approximately 1 pascal from furnace fan operation, while another site had a 0.5 pascal decrease. These differences, due to either inadequate or leaky return or supply ducts, may appear small but 1 pascal is greater than the typical stack induced Pc at a 30°F dT. Multiple regression analyses of Pc as a function of dT and heater run time resulted in good fits (average R^2>.80) and found both factors to be highly significant.

The Pc model was evaluated for stack effect pressures by using the regression results for each phase of each site to estimate values of Pc at a 30°F dT with the heat off. These characterizations of the measured values and the corresponding model predictions are shown in Figure 1 and listed in Table 1. The overall excellent agreement (R^2=.93) indicates that the attic airtightness test results combined with the theoretical stack effect can accurately estimate the actual stack-induced ceiling pressure differences. These results confirm the series leakage effect of the ceiling and roof and have significant implications for roof ventilation.

Comparisons of modeled and measured roof (i.e. attic wall) pressures indicated little agreement beyond the stack effect. Correlations to weather

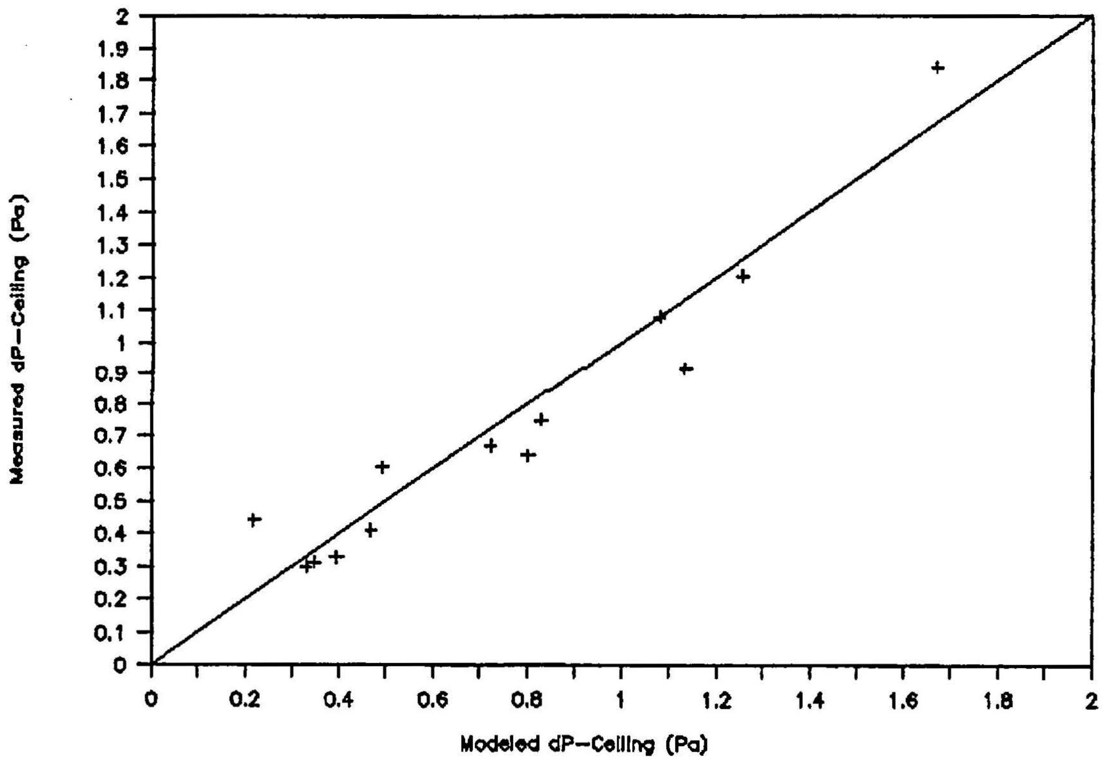

Figure 1. Modeled vs. Measured Ceiling Pressure Differences @ dT=30 F

station wind speeds were poor (R^2<.3) and wind direction data indicated that wind patterns surrounding urban rowhouses show little relation to airport data. Measured wind pressures were generally small (<0.5 Pa on average) and acted outward, adding to the stack effect. The nearly random pattern of wind pressures, particularly on windy days, indicated that two pressure measurements are inadequate for characterizing hourly wind pressures, particularly for endrow houses. The ventilation model was modified to use the greater of either measured roof pressures or the equivalent pressure from a 5 mph wind acting in opposition to the calculated stack effect over 50% of the attic wall area.

The modified attic air flow model was used to predict bypass and ventilation air flow rates from data taken during smoke bomb testing. The results of these tests are presented in Table 1 ('Natural Air Flow' column). The overall agreement is good except for site #2 during the pre and insulated & vented phases which were greatly overestimated.

Thermal Model Results

To date, field sites #1, #2, and #3 have been modeled. The required house characteristics (R-values, areas, etc) were taken from handbook values or measured as needed. Predicted and measured node temperatures were compared by inspection of time series plots, mean error, mean error between midnight and 6 AM, and the RMSE (the square Root of the Mean Squared Error). Residuals were analyzed to determine if significant correlations existed with driving forces.

Although initial models fit well for two of the three sites, air temperature errors were strongly correlated with ventilation air flow predictions. The ventilation model was modified to analyze the entire data set for each phase, predicting average ventilation rates. The hourly air flow was then modeled as half of the projected and half of the period average, resulting in better fits for all sites. Table 2 presents a summary of results for the air node, and average predicted bypass and ventilation air flows. The model performed well overall. Figure 2 presents

Table 2. Attic Model Performance and Projected Heat Loss Rates

ID#	Phase	Attic Air °F Mean Actual	Attic Air °F Mean Model	RMSE	Mean Tout	Air Flow Model Est. Ave. CFM Bypass	Air Flow Model Est. Ave. CFM Vent	Effective R-Value @dT=35°F	Annual Fuel Savings (MMBtu/yr) Predict	Annual Fuel Savings (MMBtu/yr) Measured
1	Pre	58.8	59.0	0.9	36.0	51	3	3.0	--	--
	I&V	50.9	50.9	1.4	34.6	44	8	6.2	7.1	--
	NV	49.2	48.4	2.4	34.2	25	1	11.3	10.1	--
2	Pre	54.8	54.5	0.9	38.8	102	44	2.6	--	--
	I&V	43.4	44.0	1.8	34.8	71	75	5.8	12.5	6.4 ±9.0
3	Pre	70.7	67.5	3.8	48.0	170	95	<2.0	--	--
	A/S	63.1	62.5	1.7	45.3	205	105	2.1	--	--
	I&V	51.4	50.4	3.4	37.0	28	53	18.0	45.2	53.4 ±19.0

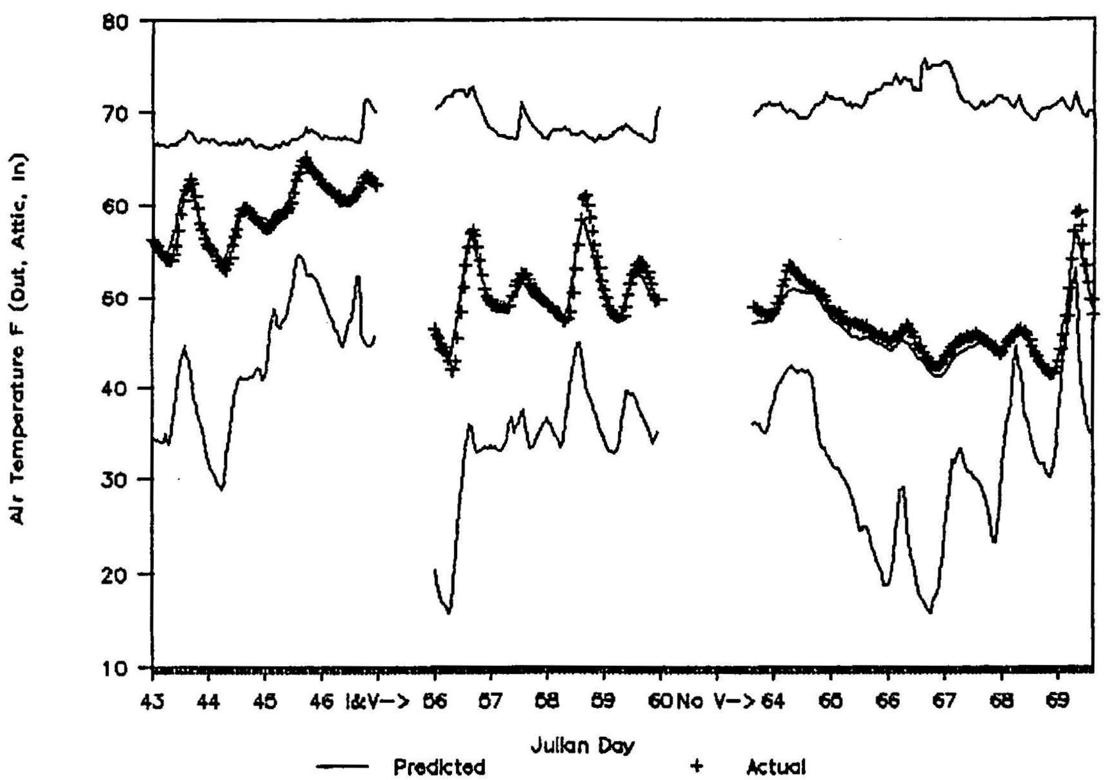

Figure 2. Predicted and Actual Attic Air Temperatures for Site #1. Pre = JD 43-46, Ins. & Vented = JD 56-60, Vent Sealed=JD 64-69 (Top Line = T-in, Bottom Line = T-out)

predicted and actual attic air temperatures (with inside and outside temperatures) for several days of each phase at site #1.

The model of Site #1 performed very well for all nodes and phases with the exception of a 3.8°F underprediction of roof deck temperatures when vented. The predicted and actual air temperatures are almost indistinguishable. The roof node error appeared at varying levels for all sites particularly when vented. The error is partially related to the inadequacy of the thermal mass terms and may also be due to temperature stratification or the definition of the attic floor surface when insulated. The model of site #1 was resistant to alternative assumptions. When conduction paths were substituted for air flow, the model performed worse.

Site #2 initially modeled poorly in both phases. Very high predicted air flow rates led to air node overpredictions of 3-5°F. The error was assumed to be the result of inaccurate values from the attic airtightness test due to either measurement error or the added hole not behaving as expected. Kc and Kr were reduced proportionally to match the smoke bomb test results. The model then performed well, as shown in Table 2. When measured Pc values (which reflect added pressure from furnace fan operation) were used instead of modeled pressures, the model performed much worse and the errors were highly correlated with the additional air flow. This surprising result may be explained by the duct chases which extend from attic to basement. Although Pc may increase from furnace fan operation, the pressure difference acting across the bypasses may experience negligible or opposite effects.

Site #3 could not be well modeled in the pre treatment period. The attic was so warm that no reasonable set of assumptions provided a good fit. The high temperatures were produced by duct leakage from a chase. This effect was not modeled and air temperature underpredictions of 3.2°F were accepted as the best model. After bypasses were sealed, the model performed well, but RMSEs were relatively high primarily due to poor modeling of roof deck mass effects.

In order to compare heat loss rates of different attics, an 'effective' attic R-value is defined as the attic area divided by its total heat loss per degree temperature difference. Because the air leakage rate is a function of temperature difference, the effective R-Value varies. Table 2 presents the effective R-Values of the attics at a 35°F temperature difference and the corresponding prediction of annual fuel savings from the retrofits. For two cases with sufficient heater run time data, the fuel savings 'measured' from regression analysis and 95% confidence intervals are given.

The attic retrofit is estimated to save 3-4 times as much energy at site #3, which received effective bypass sealing, than at site #2, a similar house treated in the standard manner. This difference is primarily attributable to the dramatic difference in ceiling air tightness (site #3 also maintained much higher indoor temperatures). The high savings for site #3 (predicted payback = 2 years) show that the overall savings potential from attic retrofits is significantly greater than expected from conduction models alone. For typical Philadelphia rowhouses, a simple payback of less than 2 years is projected for the $0.20 per square foot incremental cost of the optimal treatment. Site #2 still had a significant improvement in thermal performance and a predicted payback of 4 years even though bypasses were not sealed and roof vents were added. The air sealing ability of standard blown fiberglass and the already loose roof combined to reduce the potentially negative impact of the added vents. Site #1 illustrates the increased heat loss which can result from adding a roof vent to a relatively tight roof. Thermal performance improved significantly when the vent was sealed.

Moisture Model Results

The moisture model gave accurate predictions (within 7%) of average humidity ratios for all sites and tracked well at site #2, but performed worse at predicting diurnal cycles at site #1 and #3 (RMSEs=10% of actual). The errors were correlated with the calculated wood surface humidity ratio, indicating a misestimation of the surface transfer rate. No adjustments were tried.

The most notable moisture finding was that when roof vents were sealed, attic moisture levels were relatively unaffected. Wood moisture content levels were found to be low (6%-13%) across all phases at all houses and remained in equilibrium with average attic RH which ranged from 35%-60%. Moisture levels were low because of a combination of low indoor RHs (typically 25%-40%), a moderate climate (4500 DD65F), and relatively warm attics. Moisture damage is even less likely in these houses because of high solar gain on flat roofs, the ability of the roof deck to store substantial amounts of moisture (Burch 1984), and the dehumidifying effect of the metal cornice during adverse conditions. Different construction practices and a greater vapor drive (higher indoor RH or colder climate) may make attic ventilation necessary. But the ability of standard passive roof venting to provide this ventilation is questionable.

Roof Venting

In a tight flat roof, passive rooftop vents bring little outdoor air into the attic. This was demonstrated at site #1 which had a slightly warmer attic when vented (see Table 2). The addition of a vent shifts the stack effect pressure from the roof to the ceiling (see Table 1). The resulting additional air leakage increases heat loss and can either increase or decrease the likelihood of moisture damage depending upon the relative amounts of heat and moisture transferred. The reduced stack pressure across the roof presumably increases the likelihood that wind pressures will lead to greater ventilation. But ventilation will only increase if these pressures are present at leakage paths. The vents are unlikely to experience much wind pressure driving air into the attic and therefore a great enough combination of leakage paths and wind pressures on attic walls are needed. For tight or shielded roofs this leakage will be minimal and the vents are more likely to ventilate the house than the attic. Of course, if a roof is already loose and the ceiling is relatively tight, then passive vents have little effect on ceiling pressures. But the attic may already have sufficient ventilation. It appears that passive flat roof vents may only provide ventilation air that is both needed and significant when the vapor drive is high, the roof is moderately loose and the ceiling is relatively tight. These conditions may be more common in colder climates or other housing types. Attic airtightness testing may be a useful diagnostic tool. If conditions indicate that vents are unnecessary, then significant energy savings may result by omitting vents. If ventilation is needed and conditions aren't conducive to effective passive rooftop vents, then insulating the roof may not be worthwhile. The common alternative of wind assisted turbine vents combined with passive vents may increase bypass air leakage enough to negate any benefits of insulation.

The ceiling pressure difference model and equation 1 were used to estimate the incremental annual heat loss from the addition of passive vents to an attic in Philadelphia for tight (Kr=50), medium (Kr=100), and loose (Kr=200) roofs as a function of ceiling tightness. The results, shown in Figure 3, illustrate that venting can create large energy penalties, but the increased heat loss from air leakage will only negate the energy savings from insulation in buildings with extreme bypass problems and tight roofs.

CONCLUSIONS

Flat roof attics with significant bypasses pose difficult retrofit problems for energy conservation practitioners. Effective bypass sealing can often dramatically and cost-effectively increase energy savings and decrease the potentially adverse impacts of venting. If bypass sealing is infeasible then energy savings will be reduced, but still cost-effective in many cases due to the air sealing ability of standard insulation. An analysis of climate and site conditions may show venting to be unnecessary, further improving performance. If ventilation is needed, then insulating may not be worthwhile if site conditions conducive to effective ventilation are not present. Practitioners need to use a diagnostic approach which considers climate and site conditions for determining the best attic treatment and venting strategy.

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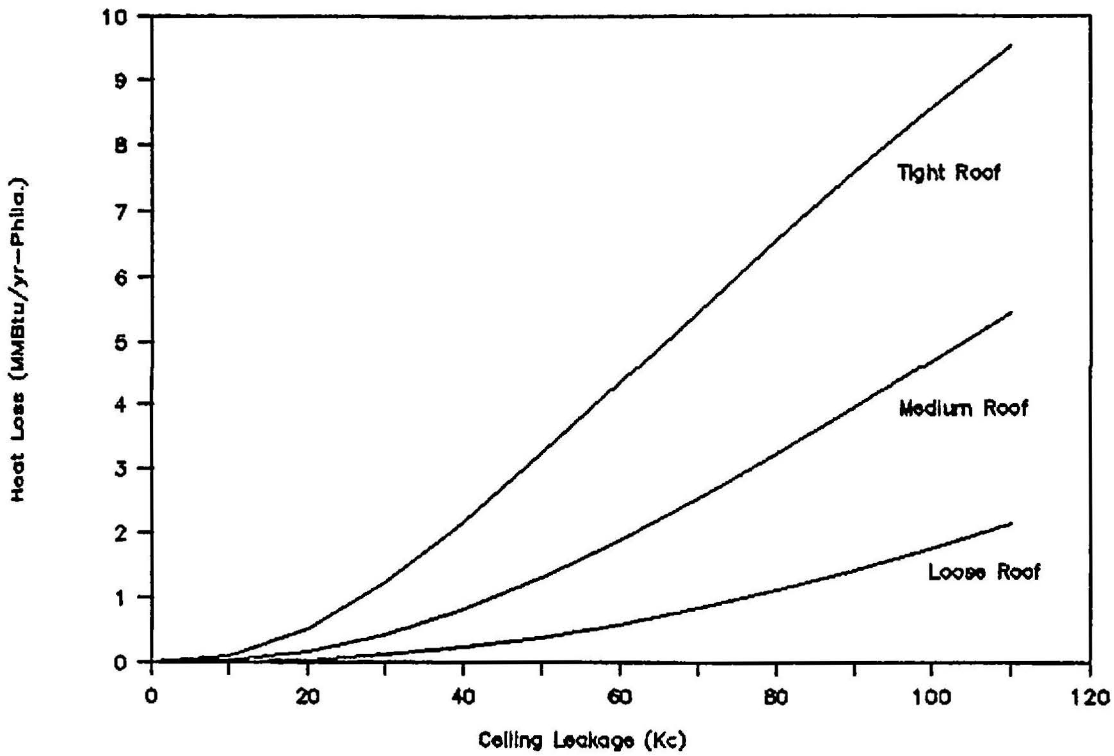

Figure 3. Projected Incremental Annual Heat Loss from Adding Roof Vents

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