Case Study of Infiltration and Ventilation Improvements in a Multi-Family Building

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The Massachusetts Electric Multi-Family Conservation program invested in the analysis and implementation of energy use reduction improvements at an eleven story building in Revere, MA. Theoretical and empirical data were developed and analyzed by Conservation Services Group, Inc, Building Science Engineering and New England Electric Services Company, to assess the effectiveness of energy improvements individually and collectively. A significant reduction in infiltration and ventilation heat loss was achieved through blower door-assisted building envelope air sealing and changes to the building ventilation systems. Flow hood measurements of ventilation stacks before and after modifications revealed greater energy savings than theoretical analysis initially indicated. This project demonstrates certain economies of scale that enhance investment incentives to building owners and utilities for infiltration and ventilation reduction projects may exist in many elevator buildings.

Introduction

The Revere Massachusetts Housing Authority owns, operates and manages the 7500 square foot per floor, eleven-story, one hundred six (106) unit apartment building with a common areas annex, that is the subject of this study. A parking garage, cafeteria, recreation and activities center and laundry facility on the ground- and first floor levels provide all the domestic and common area facilities necessary for the elderly tenants living on the upper ten floors. Steel columns support the structural concrete floor slabs and roof deck. Exterior walls are insulated with three and one-half inches of fiberglass batts finished with a split ribbed brick exterior and foil-backed gypsum wall board interior. Roof insulation consists of one and one-half inches of rigid foam under the tar and gravel roof along with the same thickness of acoustical batt insulation in the ceiling plenum. Windows are fixed tempered glass on the first floor with sliding insulated glass, nonthermal break windows in the elevator lobbies and apartments.

This building is an 11 story apartment building with small two room apartments. There is a central elevator lobby/shaft and two stair wells on opposite ends of the building. Ceiling height is 8 feet, with a 1-1/2 foot plenum above the ceiling and a concrete floor slab above for a total floor to floor height of 9'4". The building has a parking garage under the first floor. The total height from the roof of the garage to the roof of the building is 103 feet and the height above grade is roughly 110 feet. The first floor has kitchens, common and administrative offices, but no living units.

Existing central ventilation systems for the main building with exhaust fans on the main roof consisted of: one cafeteria kitchen hood belt-driven centrifugal upblast discharge exhaust blower (1200 cfm), one belt-driven centrifugal horizontal discharge exhaust blower (1080 cfm) for trash rooms, the mail room and janitor's closet, one belt-driven centrifugal horizontal discharge smoke exhaust blower (2250 cfm), and eight kitchen (1237 cfm) and six toilet (1273 cfm) belt-driven centrifugal horizontal discharge exhaust blowers to service the 106 apartments.

Another eleven (7-4000 cfm, 4-3600 cfm) dome type belt-driven centrifugal exhaust fans on the main roof were installed as part of the make-up air system. Every apartment has a motorized damper operated by a light switch in the living/bed room. The exhaust duct is connected to common duct risers, so that each occupant could control air exhausted through these dome fans from their apartments. None of the occupants nor the maintenance personnel were aware of the purpose of the switch.

Though this building is in an urban setting, the surrounding buildings are all two or three stories in height. It is only a few blocks from the shore, and completely exposed to winds from all directions. The control tower at Logan

Airport is visible from the top of the building - only about 1 mile away. This makes the use of Logan weather data very appropriate. The average wind speed at Logan is 18.5 MPH.

Multi-blade gravity operated backdraft dampers on several of the fans were still operating. The dampers were the simple gravity backdraft multi blade type, and as gusts of wind occurred, the dampers would open to their limit, and slowly close after the gust died down. Flow hood tests showed that the air flow continued in the absence of wind, but more than doubled as the gusts occurred.

Methodology

Field Conditions

The only operable roof mounted ventilation fan during the initial site visit was the cafeteria kitchen hood exhaust. All but five of the gravity backdraft dampers installed on all centrifugal vent sets were inoperable or "frozen" in a partially open position. Four of the dampers were taped closed by maintenance personnel due to excessive "banging" during the relatively high (18.5 mph) and steady coastal winds at the site.

Infiltration Control Measures

Blower door tests were performed on several of the apartments to characterize typical leakage sites, and to demonstrate savings after weatherization. All exhaust air inlets were temporarily sealed by air sealing crews during blower door tests, but post air sealing tests were performed before the ventilation system changes were made, so there was some information to help with modelling ventilation system air leakage. An infrared scan was also performed which helped to identify air leakage sites and opportunities for insulation. As shown in Table 1, the average pre-sealing leakage rate at 50 Pa was 532 CFM. After weathersealing, the average rate was 449 CFM - a reduction of 15 %. The average discharge coefficient for the blower door tests was 38 after air sealing with an exponent, n, of .633. These values were used with the Alberta Infiltration Model (AIM) infiltration model (reference 3) to estimate stack losses through the ventilation system, and to estimate annual energy savings due to weatherization.

Indoor air quality tests: After all ventilation system changes were in place and with fans operating at low speed, a CO2 test was performed to ascertain the establishment of good ventilation. The CO2 levels were all below 550 PPM or about half the ASHRAE Standard 62 maximum level of .1% or 1000 PPM.

Table 1. 50 Walnut Avenue Blower Test Reading

Apt #	Pre Air Sealing	Post Air Sealing	% Reduction
204	861	655	23.9
408	477	382	19.9
703	447	372	16.8
704	537	479	10.8
604	483	430	11.0
603	566	468	17.3
613	556	467	16.0
614	460	381	17.2
803	495	412	16.8
810	548	467	14.8
811	365	455	-24.7
901	399	316	20.8
902	431	306	29.0
1003	425	411	3.3
1002	591	497	15.9
1010	400	312	22.0
1111	1005	816	18.8
Average	532.12	448.59	14.68

Multifamily Ventilation Discussion

General

Infiltration studies in multifamily buildings are typically characterized as row houses, shaft-type, or story-type construction. The difference between shaft and story-type buildings relates to the relative transmigration of air between the building components with infinite leakage between floors for the idealized shaft-type, and zero for the idealized story type. Although there is no doubt that this building is more aptly described in the story-type category, the large number and variety of shafts (elevators, stairs, chutes, and ventilation) brings the relative permeability between floors to a high value. The shaft-type building would have no resistance to stack driven air flow and the neutral pressure zone would be at mid-level. The story-type would have a neutral pressure zone on each floor independent of the other floors but driven, in absolute terms, by the height above grade. This building is in between, and before air sealing would have been more permeable, thus more shaft-like. As the building was tightened, the apartments became less permeable to both inside corridors (hence stair and elevator shafts) and to the outdoors. Stairwells, leakage at the garage ceiling level, and elevator shafts were sealed. The remaining strong shaft connection is through the ventilation shafts. In analysis and modelling, it is desirable to treat these ventilation shafts independently in order to estimate their effects and the value of closing off some of the shafts.

Each unit had three separate ventilation systems and four exhaust grilles (two were connected to a common mechanical damper operated by a manual switch), an attempt was made to estimate the approximate ventilation rate in the initial condition. At that time nearly all of the fans were inoperable, and all were turned off, so any ventilation was driven by natural convection. The number of shafts, including ventilation, elevators, trash chutes, and stairs makes precise knowledge of pressure difference and air flow impossible, but some generalizations are possible.

Modelling

We initially attempted to estimate the volume of air escaping by natural convection through the ventilation ducts. None of the available methods was found to be reasonably accurate because of the need to estimate factors without real knowledge of the physical situation. For example, the ASHRAE flue calculation methods (reference 2) are based on sound physical principles, but require precise estimation of the resistance of the duct to air flow. As built drawings gave little information about the routing of the ventilation ducts, and it was difficult to guess even the number of elbows, much less the resistance of the broken dampers.

Equations based on physical principles were helpful in establishing working estimates of key parameters. The Bernoulli equation was used to estimate the average velocity for a frictionless duct operating at the average height of the building:

$$P2/W + V2^2 g + Z2 = P1/W + V1^2 g + Z1$$

where

P1 = atmospheric pressure at datum level (14.7 PSI)
P2 = atmospheric pressure at roof (14.65 PSI)
W = specific weight of air (2.54 lb/ft^3)
Z1 = height at datum (55 ft half the total height)
Z2 = height at roof (110 ft)
g = gravitational constant
V1 = initial velocity of air (0 ft/min in apt)
V2 = final velocity of air (at roof)

This gives a frictionless flow of 478 ft/min in an idealized duct. If such a duct were 2 ft square, the flow would be 956 CFM. Though this estimate for stack effect ventilation is based on boundary conditions that are idealized, it gives us a maximum for comparison with our measurements and other estimates.

The AIM model appeared to offer useful information for understanding some of the parameters surrounding the natural ventilation, because it considers the flue as a discrete component of exfiltration. This model treats the flue as a separate leakage site with the outlet above the roof and a shelter coefficient that may be different from that of the building. In most important respects, the flue in the AIM model is identical in characterization to the ventilation ducts in the Walnut Avenue building. The flue is assumed to add to the air exfiltration when the furnace is off and to do so at normal house temperature. Although the model is designed for single family use, it is based on first principles and, with the modifications used here, should give a reasonable prediction of natural flow volumes for taller buildings. Primary differences are the presence of fans and dampers which add resistance to the flow (although this was negligible in the dome fans), and the height of the building which was accounted for by independently treating the infiltration at each level.

In order to model the vent stack losses relative to the height of the building, the stack reference pressure was calculated for the mid-height of each floor independently as well as for the average height and mid-height of the sixth floor. The equation for the stack reference pressure is:

$$Ps = R_o\, g\, H\, (T_i - T_o)/T_i$$

where

Ps = Stack reference pressure
R = air density
H = reference height
g = gravitational constant
T = temperature

and the subscripts i and o are for indoor and outdoor conditions.

While the AIM model is similar in many respects to the Sherman Grimsrud (reference 4) model, the basic difference being that AIM uses an additive flue factor F, a power law to estimate wind induced infiltration. The F factor is added to the general stack effect leakage which is combined with the wind effect leakage to produce the overall air leakage. The equation for F is:

$$F = nY(Bf-1)((3n-1)/3))(1-(3(Xc - X)^2 R1-n)/2Bf+1))$$

where

n = flow exponent (.66 typical)
Y = flue fraction relative to total leakage
Bf = ratio of flue height to ceiling height
R = "ceiling-floor sum"
X = "ceiling-floor difference"

and Xc is the critical value of the ceiling-floor difference at which the neutral plane is at ceiling level.

R is calculated from the sum of the ceiling and floor leakage coefficients divided by the total leakage coefficient. X is similar but calculated from the difference rather than the sum. Y is the ratio of the flue leakage coefficient to the total leakage coefficient.

The range of predicted air flows is fairly narrow in the range of interest, namely for flue fractions from .1 to .4. It seems likely that the leakage due to the flue would be less than half but more than 10% of the overall leakage for the building. As shown in Table 2, the air flow calculated for this range is between 1 and 8 CFM per apartment.

Another flue related parameter, Bf, the ratio of flue height to room height, produced a similar range of values as it was varied from 1.5 (top floor) to 10.5 (second floor). In Table 1 the calculated air flows for each apartment are shown, as well as the average. Given the lack of variability, the sixth floor was taken as the measure for comparison, and the infiltration was calculated for that level with no ventilation duct assumed. The result, 3.2 CFM, is lower than the 20% flue fraction case by 4.3 CFM, or about half. Extrapolating to all ten occupied stories, this would predict 43 CFM for the exhaust vent system.

Table 2. Qs for Different Flue Fractions

Bf=6	Cf=.3	Cw=.15
Y		Qs
0		3.1
0.1		5.52
0.2		7.5
0.3		8.2
0.35		7.8
0.4		7
0.5		4.2
0.6		1.1
0.7		1.4

Table 3. *Air Flow for Different Stack Heights (each floor is 9' 4" high)*

Y=.2	Bf	Qs (cfm)
top floor	1.5	4.5
10th	2.5	5.8
9th	3.5	6.5
8th	4.5	7.0
7th	5.5	7.3
6th	6.5	7.5
5th	7.5	7.7
4th	8.5	7.8
3rd	9.5	7.9
2nd	10.5	8.0
1st	NA	NA
	Average	7 cfm
	6th Floor	7.5 cfm
	Y=0, Bf-6.5 (no duct)	3.2 cfm
	difference	4.3 cfm

AIM Results for Multifamily Buildings

Although the AIM model was instructive in focusing on the duct losses from the apartments, in this case, the model suffers from the problems of complexity in estimating the effects of many often unmeasurable parameters. The model does not seem to be sensitive to some of the assumptions about the flue or duct itself, such as its relative height or percentage of leakage relative to total leakage, but other parameters are critical. One such variable is the discharge coefficient, usually in the range of 125 in residential buildings (though it varies greatly). In this building it averaged 38, which had a large effect on the total estimated ventilation system leakage. With the originally assumed 125, the ventilation leakage was estimated at 14 CFM, while at C = 38, the ventilation leakage was estimated at 4.3 CFM per apartment. Since the measured ventilation per apartment was 726 CFM, the data used don't reflect the ventilation or the model is inadequate for high rise multizone buildings. It is likely that both are true, since we don't have measurements of the flow coefficient or exponent for the apartments with the ventilation systems open.

Although Y, the ratio of vent leakage to total leakage, enters into the wind coefficient, Bf is not used in the single family calculation model because its effect is considered negligible. This may not be true for this high rise building where Bf may be as high as 10.5 while typical values of Bf are around 1.5. Nevertheless the AIM model shows a stronger wind dependence than the LBL model and appears to more accurately model the wind dependence in residences with flues.

It was clear, from observations of gravity damper openings and from measurements of air flow at the roof exit of the fans, that wind pressure had a great deal to do with the flow rate. Flow rates increased by roughly 30% during wind gusts during the first test period. The estimated average wind speed was 12 MPH, but the velocity ranged from nearly zero to over 15 MPH. Nevertheless, stack effect is the dominant driving force, with the calibrated lowest reading (under no wind), for ventilation volume from one stack at 0 CFM, and the average calibrated lowest reading for seven fans at 40 CFM.

Results

Electric Energy Savings Analysis

The ventilation fans were not operating in the initial condition - most were broken or noisy, but because of the relative "leakiness" of the apartments, there was no perceived need for the ventilation system, though some of the apartments were "stuffy" and cooking and toilet odors were both detectable and lingering. Apartment occupants had no knowledge of the operation of the mechanical dampers that closed off the living room and bedroom vents. Questions about the usual switch position (i.e. open or closed) usually led to "I didn't know what that switch did!". Indeed, the switch did nothing in most cases, since the damper often didn't work, the fans were off, and natural ventilation was weak at the apartment in all the measured cases.

The significant modifications proposed-, and made-, to the replacement ventilation systems were: adding workable two speed fans with vibration isolation connected to the kitchen and bath vents, positive closure motorized dampers which are both interlocked with the respective fan operation and with a manually operated override switch, and removal of the ineffective living-/bedroom dome fans with weatherproof enclosures installed on the roof openings. These changes produced a much more reliable and effective ventilation system with noticeably lower noise levels (at both high and low speeds) on the top floor, and reduced overall heat loss from the building due to air infiltration and "stack" effect. The fans are now being run at low speed only, which produces air flow rates of from 30 to 50 CFM in both the kitchens and baths.

The final installed cost of this project was $43,500.00 and electric energy use for the new fans is estimated at 5655 kwh per year running at low speed (8760 hours operation). The electric use for the original fans would have been 40843 kWh if all fans had been running as designed. The original fans had power factors around .59, while the new fans had power factors of .65 and were run at low speed.

Like many conservation retrofits, the real payoff here is in non-quantifiable terms: in this case the comfort of better indoor air quality and lower sound levels at the upper floors. However, it is likely that in the long run the fans would have been replaced and it is valuable to consider the savings in electric operating costs from the originally specifications to the final actual operating conditions with all of the dome fans removed and all of the squirrel cage fans operating at low speed.

Infiltration Results

Although the building is too large to get an accurate quantitative infiltration reading with a blower door, tenants and experienced air sealing crews often commented on the excessive drafts in the building. The relatively high air leakage data collected on site also demonstrated that a comprehensive air sealing program, utilizing blower door induced air leaks as indicators should be implemented.

Table 1 shows the pre- and post- air sealing program data measured with the ventilation systems sealed off. It was difficult to achieve adequate pressure for accurate blower door tests with the vents open. Also, the measured flow coefficient, C, averaged 38 with an average flow exponent, n, of .633 weatherization.

The average savings of 83 CFM_{50} will result in an annual savings of approximately 9.6 CFM per apartment. For the total building this will result in a savings of 1035 CFM resulting in a calculated savings of 26506 kWh per year.

Ventilation Results

Measurement of exhaust air flow at the roof and in the apartments that made up the stacks leading to each of the fans showed a great discrepancy between the sum of the apartment exhausts and the amount of air exiting the roof. Duct leakage is assumed to make up the difference, and most of this leakage occurs in the ceiling plenums above the apartments. Figure 1 shows the roof measured average natural (fan off) air flow through the centrifugal fans serving the baths and kitchens, and through the dome fans serving the bedrooms and livingrooms. For domes 18 and 20, the air flow averaged 680 CFM. In contrast, the apartments connected to these fans ranged from 0 to 57 CFM with an average of 13 CFM. In this case, the great majority of the substantial leakage was coming from locations outside the intended apartments.

The initial measurement of the exhaust fans showed an average natural convection loss of 97 CFM for the rectangular fans with gravity dampers as found. The domes, which were connected to the Bedroom-Livingroom with the mechanical damper averaged 729 CFM. After sealing the domes off completely with insulated metal caps, there remained some air flow through the ventilation openings in the living rooms and bedrooms of the apartments. This attests to the conclusion that there is large scale duct leakage between floors.

Measurements of the centrifugal fans after retrofit with new, two speed fans and mechanical dampers showed that the average fan-off leakage was reduced from 97 to 43 CFM. On low speed the average CFM was 496 CFM, and at high speed, 1150 CFM. It is instructive to note that the average CFM with the new fans on low speed is less than the pre-weatherization air flow of 729 + 97 for the two fans per apartment, with the previous fans switched off.

The heat loss through the 11 dome fans averaging 729 CFM would total 190144 kWh per year. All of this is presumed saved, since they were completely closed off at the roof. For the 15 rectangular fans, the air volume increased from an average of 97 CFM to 496 CFM, this resulted in a net increase for these fans of 5985 CFM. The net added heat load would be 141914 for the rectangular fans. The overall savings would be 48230 kWh per year in electric heat, even with the new fans running all the time.

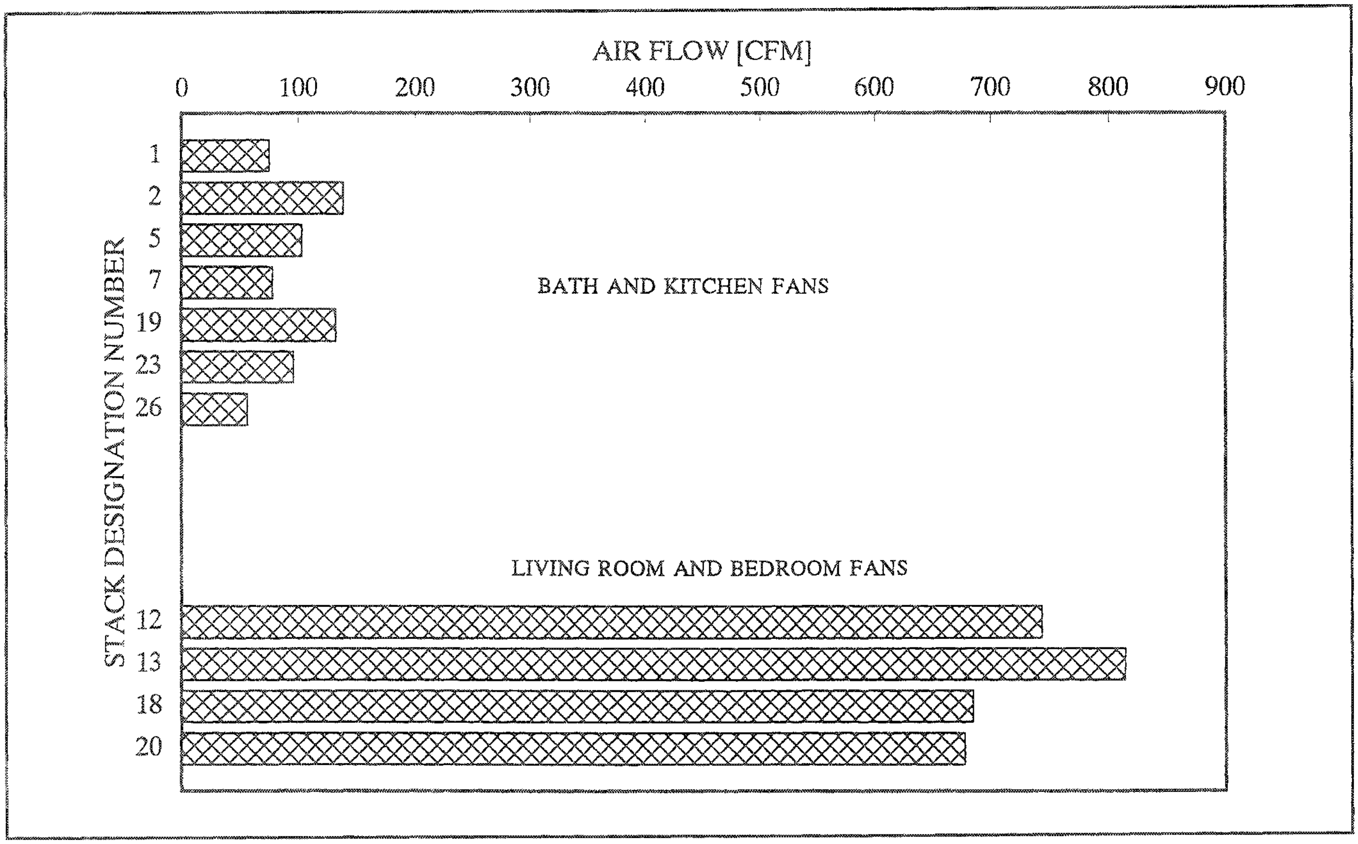

Figure 1. Measured Flows at Roof

Total Savings. Finally, if the electricity needed to run the new fans is subtracted from the heating energy savings, the net savings is 42575 kWh/year. Adding in the savings from the infiltration reduction in each apartment of 26506 kWh, gives us a total savings of 69081 kWh per year.

Conclusions

Experience with this ventilation system redesign and retrofit suggests strategies for future work to improve ventilation system in existing and new buildings.

1. Many multifamily buildings have excess ventilation built in due to oversizing. It may be possible to reduce the infiltration losses by selectively reducing over ventilation.

2. Savings can be achieved in both fan electric consumption and in heating and cooling energy, while improving air quality.

3. It would be useful to have blower door tests done without sealing ventilation grilles in order to establish a baseline for reduction of ventilation. The initial assumption that the ventilation system would remain unchanged turned out to be wrong in this case. In addition, the savings calculated as a percentage will be smaller, since both the baseline and the post-weatherization leakage will be larger. Savings in CFM should be approximately the same.

4. Selection of fans must pay strict attention to noise levels, and mounting should be carefully buffered to reduce vibration and duct-borne sound.

5. Although advanced control strategies may be useful in more precisely controlling ventilation, a simpler approach is to use variable speed or two speed fans and adjust the ventilation rate for each apartment.

6. Sealing of ducts against infiltration is important, The current trend toward smaller PVC pipe and flexible duct for ventilation duct appears to be promising. In this building, more air was vented from between floors than from the apartments.

7. The use of mechanical dampers in multifamily ventilation systems is a complete waste of money. Provision of adjustable outlets, particularly those with sound attenuating capabilities, is far more useful.

8. The sensitivity of the AIM model to the choice of variables suggests that considerable work needs to be done to characterize multifamily buildings in terms of key parameters, and that the model itself may need to be modified for multifamily purposes.

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