STATE OF FLORIDA
BUILDING COMMISSION

IN RE:

FLORIDA HOMEBUILDERS ASSOCIATION, BUILDERS ASSOCIATION OF SOUTH FLORIDA, THE RELATED GROUP OF FLORIDA, ZOM FLORIDA, INC., FLORIDA EAST COAST REALTY, RUDG, LLC, NEWGARD DEVELOPMENT GROUP, FLORIDA EAST COAST INDUSTRIES, VERZASCA GROUP, LLC, and ALLEN MORRIS COMPANY.

CASE NO. ___________

PETITIONERS NOTICE OF FILING MATERIALS IN SUPPORT OF THE PETTIION FOR EMERGENCY RULEMAKING AND PETITION FOR RULEMAKING BY THE FLORIDA BUILDING COMMISSION

The Petitioners, Florida Homebuilders Association, et al. respectfully submit to the Florida Building Commission materials in support of the relief set forth in the Petition for Emergency Rulemaking and the Petition for Rulemaking by the Florida Building Commission. The attached materials are:

Exhibit A – *Economic Impact of Pending Changes to Florida Building Code Section 403.6 Requiring Two Fire Service Elevators Instead of One Fire Service Elevator*, Hank Fishkind (June 5, 2015) (full report to supplement the executive summary attached to Petition for Emergency Rulemaking and Petition for Rulemaking).

Exhibit B – *A Review of Home Airtightness and Ventilation Approaches for Florida Building Commission Research*, Florida Solar Energy Center (June 15, 2014).

Exhibit C – *The History of Ventilation and Temperature Control*, ASHRAE Journal, John Janssen (September 1999).

Exhibit D – *Review of Residential Ventilation Technologies*, Ernest Orlando Lawrence Berkeley National Laboratory, Marion Russel et al. (August 2005).

Exhibit E – RM 24-15, Proposed Change to 2015 International Residential Code (April 2015).

Respectfully submitted,

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Attorneys for Petitioners, Florida Homebuilders Association, Builders Association of South Florida, The Related Group of Florida, ZOM Florida, Inc., Florida East Coast Realty, RUDG, LLC, Newgard Development Group, Florida East Coast Industries, Verzasca Group, LLC, and Allen Morris Company

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CERTIFICATE OF SERVICE

I hereby certify that I have this day served a copy of the foregoing by

REGISTERED EMAIL upon:

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This 9th day of June, 2015,

By: ________________
Robert S. Fine

EXHIBIT A

ECONOMIC IMPACT OF PENDING CHANGES TO FLORIDA BUILDING CODE SECTION 403.6 REQUIRING TWO FIRE SERVICE ELEVATORS INSTEAD OF ONE FIRE SERVICE ELEVATOR

June 5, 2015

Prepared for
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Prepared by
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Executive Summary

- There are 122 high rise condominium and residential rental towers in planning/design stages today throughout the State of Florida
- These buildings represent 41,631 residential units
- Addition of a second fire service elevator requires building redesign
- Redesign shrinks residential unit sizes, reduces parking, adds time and cost
- Only premier sites and buildings on the Beach can absorb these effects
- Of the 122 buildings, 44 buildings will be cancelled due to the second elevator requirements
- Of the 41,631 residential units affected 18,311 residential units will be lost
- Net construction loss to the State of Florida is $8.4 billion over three years
- This reflects spending leakage out of state and adds redesign costs
- It is assumed half of all buyers will be accommodated elsewhere in Florida
- Household spending will be lost among 9,156 households lost to Florida
- The net loss in household spending in Florida is $2.4 billion over three years
- Direct economic impact is a loss of $10.8 billion to the Florida economy
- Total economic impact is a loss of $21.1 billion to the Florida economy
- Total job loss is 58,700 jobs over the three year building code update cycle

Economic Impact of Additional Fire Service Elevator

CONSTRUCTION Impact Summary

ImpactType	Annual Employment	3-Year Wages	3-Year Output Total
Direct Effect	16,225	$2,380,827,341	$8,462,479,691
Indirect Effect	10,991	$1,668,457,825	$4,552,119,553
Induced Effect	9,153	$1,264,257,494	$3,621,377,394
Total Effect	36,369	$5,313,542,659	$16,635,976,638

HH SPENDING Impact Summary

ImpactType	Annual Employment	3-Year Wages	3-Year Output Total
Direct Effect	17,252	$1,609,080,712	$2,373,349,629
Indirect Effect	1,048	$165,096,608	$450,956,214
Induced Effect	4,033	$557,330,939	$1,597,025,046
Total Effect	22,333	$2,331,508,259	$4,421,330,888

SUMMARY of LOSS

ImpactType	Annual Employment	3-Year Wages	3-Year Output Total
Direct Effect	33,477	$3,989,908,053	$10,835,829,320
Indirect Effect	12,039	$1,833,554,432	$5,003,075,767
Induced Effect	13,186	$1,821,588,433	$5,218,402,440
Total Effect	58,702	$7,645,050,918	$21,057,307,527

Source: Fishkind & Associates, Inc. and Minnesota IMPLAN Group, Inc., 2015

Fiscal Impact of Lost Units

	Total Taxable Value*	City Ad Valorem	County Ad Valorem	School Ad Valorem	Total Ad Valorem	Documentary Stamps
Broward County	$2,348,853,947	$13,445,384	$13,442,491	$17,470,776	$58,844,801	$16,441,978
Miami-Dade County	$7,202,517,440	$58,123,873	$38,900,076	$57,432,874	$161,716,640	$75,626,433
Palm Beach County	$61,869,211	$159,375	$558,889	$469,835	$1,330,504	$433,084
Hillsborough County	$589,860,000	$3,381,431	$5,328,441	$3,747,145	$12,344,531	$4,129,020
Sarasota County	$27,690,000	$98,590	$135,202	$215,345	$449,137	$193,830
Statewide Total	**$10,230,790,598**	**$75,208,654**	**$58,365,100**	**$79,335,974**	**$234,685,613**	**$96,824,345**

- At least 5 counties will be negatively impacted by the decrease in construction of high-rise towers.
- Taxable value of over $10.2 Billion will be lost.
- Cities will lose $75.2 million in ad valorem revenue each year.
- Counties will lose $58.3 million in ad valorem revenue each year.
- Schools will lose $79.3 million in ad valorem revenue each year.
- The total loss of ad valorem will reach $234.6 million each year.
- Documentary Stamp revenue of $96.8 million will be lost.

1.0 Introduction

1.1 Assignment

Greenberg Traurig, PA ("Client"), on behalf of its clients who are involved in the development of high-rise residential towers in Florida, retained Fishkind & Associates, Inc. ("FA") to quantify the economic impacts of pending changes to the Florida Building Code ("FBC") requiring two fire service elevators instead of just one under the current FBC. FA's impact analysis will be used by the Client as part of an emergency petition to the Florida Building Commission ("Commission") requesting a one year extension of the existing FBC thereby postponing the two-elevator requirement.

1.2 Emergency Petition and Time Limitation

The need for an emergency petition to the Commission arose, because the Florida Legislature failed to enact pending bills that would have postponed the two-elevator requirement for one year allowing time for proper study and corrective action. The corrective legislation had been approved by both Chambers of the Legislature. It was awaiting final approvals when the House of Representatives abruptly and illegally adjourned failing to act on the correcting bills among much other unfinished business including the State's budget.

As a result, a number of tower projects may be cancelled or postponed at great cost to their owners and to Florida's economy giving rise to this emergency. Given this unexpected turn of events, the time available to conduct FA's study was curtailed. Nevertheless, in the time available FA has provided data and analysis reliably showing that implementation of the two-elevator rule poses an immediate threat to the economic welfare of the State of Florida.

2.0 Methodology to Quantify the Economic Impacts of the Two-Elevator Requirement

2.1 Methodology

FA designed a five step methodology to quantify the economic impact of the two-elevator rule.

1. Identify potentially affected tower projects and create an inventory and summary data for each project.

2. Select a sample set of affected tower projects and analyze the physical impacts of the two-elevator rule on each project.

3. Given the physical impacts of the two-elevator rule, quantify the direct economic impacts on the projects in terms of delay, loss of salable/rentable square feet of space, and additional cost. Determine if the project remains economically viable if the two-elevator rule goes into effect.

4. With knowledge of the direct economic impacts quantify the indirect and induced effects that would likely result.

5. Combine the direct and indirect economic impacts resulting in a measure of the total economic impact of the two-elevator rule.

2.2 Overview of How the Two-Elevator Rule Affects Tower Projects in Florida

The FBC is updated on a regular basis every three to four years. In Section 403.6 governing elevators, the current code, FBC2010, provides for one fire service elevator for towers of 120 feet or more. The incoming code, FBC2014 would require two fire service elevators along with additional corridor access changes. FBC2014 is scheduled to go into effect on June 30, 2015.

The planning and permitting process for a high rise tower of 120 feet or taller is lengthy and expensive. Most of the high rise towers in the planning and permitting stages will not be permitted on or before June 30, 2015. As a result, those high rises not permitted by June 30, 2015 will have to be redesigned to accommodate FBC2014. The addition of the second elevator and the changes to the access corridor under FBC2014 will cause the substantial loss of sellable and rentable square footage in all high rises. As a result, there will be many projects not permitted by June 30, 2015 which will be rendered financially unfeasible and cancelled. Others will be reduced in size and have their construction delayed.

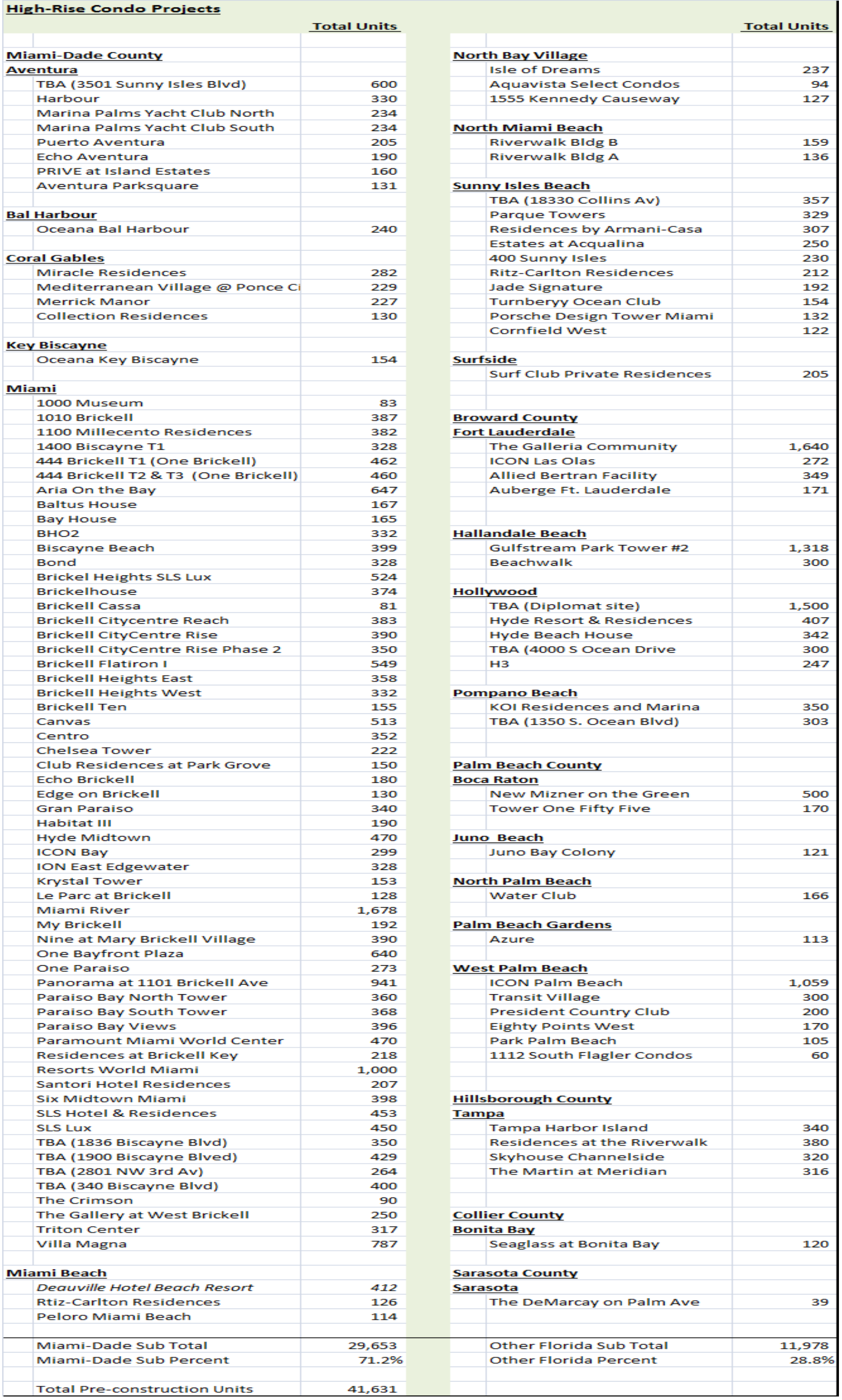
3.0 Inventory of Potentially Affected Tower Projects

3.1 Methodology for Identifying Potentially Affected Tower Projects

An internet search for pre-construction, condominium and residential rental high-rise towers was conducted. Data was gathered from business journal articles, the Miami Herald, and various Realtors specializing in high-rise units. After, the initial list was compiled, each property was researched on the internet to acquire the number of units, pricing, floor plans and number of stories. Most projects under 100 units were eliminated when tower height data was not available. Projects with complete floor plans and pricing information were assumed to be in the permitting process. Projects without this data were assumed to be in the design phase.

3.2 Inventory of Potentially Affected Tower Projects

Table 1 – Inventory of Planned Florida Hi-Rise Buildings



High-Rise Condo Projects

	Total Units		Total Units
Miami-Dade County		**North Bay Village**	
Aventura		Isle of Dreams	237
TBA (3501 Sunny Isles Blvd)	600	Aquavista Select Condos	94
Harbour	330	1555 Kennedy Causeway	127
Marina Palms Yacht Club North	234		
Marina Palms Yacht Club South	234	**North Miami Beach**	
Puerto Aventura	205	Riverwalk Bldg B	159
Echo Aventura	190	Riverwalk Bldg A	136
PRIVE at Island Estates	160		
Aventura Parksquare	131	**Sunny Isles Beach**	
		TBA (18330 Collins Av)	357
Bal Harbour		Parque Towers	329
Oceana Bal Harbour	240	Residences by Armani-Casa	307
		Estates at Acqualina	250
Coral Gables		400 Sunny Isles	230
Miracle Residences	282	Ritz-Carlton Residences	212
Mediterranean Village @ Ponce Ci	229	Jade Signature	192
Merrick Manor	227	Turnberyy Ocean Club	154
Collection Residences	130	Porsche Design Tower Miami	132
		Cornfield West	122
Key Biscayne			
Oceana Key Biscayne	154	**Surfside**	
		Surf Club Private Residences	205
Miami			
1000 Museum	83		
1010 Brickell	387	**Broward County**	
1100 Millecento Residences	382	**Fort Lauderdale**	
1400 Biscayne T1	328	The Galleria Community	1,640
444 Brickell T1 (One Brickell)	462	ICON Las Olas	272
444 Brickell T2 & T3 (One Brickell)	460	Allied Bertran Facility	349
Aria On the Bay	647	Auberge Ft. Lauderdale	171
Baltus House	167		
Bay House	165		
BHO2	332	**Hallandale Beach**	
Biscayne Beach	399	Gulfstream Park Tower #2	1,318
Bond	328	Beachwalk	300
Brickel Heights SLS Lux	524		
Brickelhouse	374	**Hollywood**	
Brickell Cassa	81	TBA (Diplomat site)	1,500
Brickell Citycentre Reach	383	Hyde Resort & Residences	407
Brickell CityCentre Rise	390	Hyde Beach House	342
Brickell CityCentre Rise Phase 2	350	TBA (4000 S Ocean Drive	300
Brickell Flatiron I	549	H3	247
Brickell Heights East	358		
Brickell Heights West	332	**Pompano Beach**	
Brickell Ten	155	KOI Residences and Marina	350
Canvas	513	TBA (1350 S. Ocean Blvd)	303
Centro	352		
Chelsea Tower	222		
Club Residences at Park Grove	150	**Palm Beach County**	
Echo Brickell	180	**Boca Raton**	
Edge on Brickell	130	New Mizner on the Green	500
Gran Paraiso	340	Tower One Fifty Five	170
Habitat III	190		
Hyde Midtown	470	**Juno Beach**	
ICON Bay	299	Juno Bay Colony	121
ION East Edgewater	328		
Krystal Tower	153	**North Palm Beach**	
Le Parc at Brickell	128	Water Club	166
Miami River	1,678		
My Brickell	192	**Palm Beach Gardens**	
Nine at Mary Brickell Village	390	Azure	113
One Bayfront Plaza	640		
One Paraiso	273	**West Palm Beach**	
Panorama at 1101 Brickell Ave	941	ICON Palm Beach	1,059
Paraiso Bay North Tower	360	Transit Village	300
Paraiso Bay South Tower	368	President Country Club	200
Paraiso Bay Views	396	Eighty Points West	170
Paramount Miami World Center	470	Park Palm Beach	105
Residences at Brickell Key	218	1112 South Flagler Condos	60
Resorts World Miami	1,000		
Santori Hotel Residences	207		
Six Midtown Miami	398	**Hillsborough County**	
SLS Hotel & Residences	453	**Tampa**	
SLS Lux	450	Tampa Harbor Island	340
TBA (1836 Biscayne Blvd)	350	Residences at the Riverwalk	380
TBA (1900 Biscayne Blved)	429	Skyhouse Channelside	320
TBA (2801 NW 3rd Av)	264	The Martin at Meridian	316
TBA (340 Biscayne Blvd)	400		
The Crimson	90		
The Gallery at West Brickell	250	**Collier County**	
Triton Center	317	**Bonita Bay**	
Villa Magna	787	Seaglass at Bonita Bay	120
Miami Beach		**Sarasota County**	
Deauville Hotel Beach Resort	*412*	**Sarasota**	
Rtiz-Carlton Residences	126	The DeMarcay on Palm Ave	39
Peloro Miami Beach	114		
Miami-Dade Sub Total	29,653	Other Florida Sub Total	11,978
Miami-Dade Sub Percent	71.2%	Other Florida Percent	28.8%
Total Pre-construction Units	41,631		

The table above contains our inventory of high-rise units in Florida that have the potential to be affected by the pending changes to the Florida Building Code requiring two fire service elevators instead of just one under the current FBC. Since most projects under 100 units were not included, there are potentially thousands of additional units that could be affected.

3.3 Conclusions

There are many high-rise building projects in permitting and on the drawing board that will be affected by the FBC change. Our initial inventory includes 122 Projects with 41,631 units. South Florida is the location for the vast majority of these projects. Over 71 percent of these units are to be located in Miami-Dade County. These projects include residential condominium as well as rental apartment units.

4.0 Direct Impacts on Representative Tower Projects

4.1 Methodology for Quantifying Physical Impacts

FA worked with the Client and team members who provided case studies of select projects impacted by the impending two-elevator FBC rule change. The case study data analysis indicated that the additional elevator would require an estimated 250 square feet per floor and would cost from $770,000 to $1.3 million for structures 12 to 16 stories tall. This results in the obvious additional construction cost and well as resulting in smaller units for-sale or for-rent. The case study findings indicate that structures with retail sales value of less than $850 per square foot would not be viable based on the new rule.

FA believes that with so many projects being made non-viable from the rule, that some projects that currently have projected sales of $750 per square foot will be able to increase the project price point due to the market effect which occurs when limiting supply. As a result, using the inventory of buildings in Section 3.3.2, FA estimated the number of buildings and respective number of units that would be lost due to the rule change. FA estimates that 44 buildings, which represent a total of 18,311 units will be lost as a result of the new building code condition. This represents over 44 percent of the unit count supply analyzed.

Table 2. – Summary of Hi-Rise Inventory
Made Non-Viable Due To New Elevator Requirement

	No. of Buildings	Total Units
Total Bldgs/Units	122	41,631
High Rise Residential Lost	44	18,311
High Rise Residential Remaining	78	23,320
	No. of Buildings	% of Bldgs
Total Bldgs/Project	122	
High Rise Bldgs Lost	44	36%
High Rise Bldgs Remaining	78	64%
	Total Units	% of Units
Total Residential Units	41,631	
High Rise Residential Lost	18,311	44%
High Rise Residential Remaining	23,320	56%

4.2 Quantifying the Economic Impacts on the Sample Projects

FA estimated the additional costs associated with the construction of the second elevator in the 78 buildings which are forecasted to remain viable. Based on the estimated construction costs per elevator, FA estimates that the rule will result in an estimated $235.8 million in additional construction costs. This additional construction cost is added to the estimated construction value lost associated with the 44 buildings which are no longer viable. FA estimates that these 44 buildings (18,311 units) represent $10.8 billion in loss of construction spending. The net impact to the State of Florida is a loss of $8.5 billion in construction spending since some of this spending would have taken place outside of Florida and therefore is not a loss due to these economic leakages.

Table 3. Net Construction Loss, Unit Loss and Household Loss

New Spending			
No. of Buildings Viable	78		
Cost of Elevator Per Remaining Building	$3,022,727		
Add'l Cost of Buildings (with new elevator)	$235,772,727		
Construction Spending Loss			
No. of Building Not Viable	44	No. of Units Lost)	18,311
Avg. Construction Cost Per Unit	$590,567		
Construction Value of Buildings Lost	$10,813,872,337		
Net Construction Spending Change	($10,578,099,610)	Total Units Lost	18,311
Local Direct Loss @80% due to leakage	($8,462,479,688)	Permanent HH Loss (50%)	9,156

FA estimates that of the 18,311 units lost, 50 percent of households, some 9,156 households and the associated household spending is permanently lost to Florida. The other 50 percent are expected to be accommodated elsewhere within Florida.

The permanent household spending loss is estimated according to the consumer expenditure spending profile of high income households, adjusted to reflect estimated household incomes of householders in the hi-rise condominium and apartments lost. These include household expenditures for retail goods, healthcare, transportation, household operations and local ad valorem taxes based on estimated household incomes of $268,500. Spending losses over three years for the 9,156 households is $2.8 billion.

5.0 Measuring the Economic Impacts of the Two-Elevator Rule on the Inventory of Potentially Affected Tower Projects in Florida

5.1 Methodology to Apply the Sample Impacts to the Inventory of Potentially Affected Towers

Having identified the net construction loss to Florida and the household spending losses, the economic impacts are calculated.

The economic impact methodology utilized to determine the multiplier effects is IMPLAN (IMpact Analysis for PLANning).

> *IMPLAN's Social Accounting Matrices (SAMs) capture the actual dollar amounts of all business transactions taking place in a regional economy as reported each year by businesses and governmental agencies. SAM accounts are a better measure of economic flow than traditional input-output accounts because they include "non-market" transactions. Examples of these transactions would be taxes and unemployment benefits.*
>
> *Multipliers*
> *Social Accounting Matrices can be constructed to show the effects of a given change on the economy of interest. These are called Multiplier Models. Multiplier Models study the impacts of a user-specified change in the chosen economy for 440 different industries. Because the Multiplier Models are built directly from the region specific Social Accounting Matrices, they will reflect the region's unique structure and trade situation.*
>
> *Multiplier Models are the framework for building impact analysis questions. Derived mathematically, these models estimate the magnitude and distribution of economic impacts, and measure three types of effects which are displayed in the final report. These are the direct, indirect, and induced changes within the economy. Direct effects are determined by the Event as defined by the user (i.e. a $10 million dollar order is a $10 million dollar direct effect). The indirect effects are determined by the amount of the direct effect spent within the study region on supplies, services, labor and taxes. Finally the induced effect measures the money that is re-spent in the study area as a result of spending from the indirect effect. Each of these steps recognizes an important leakage from the economic study region spent on purchases outside of the defined area. Eventually these leakages will stop the cycle.*

5.2 Quantifying the Economic Impacts of the Two-Elevator Rule on the Inventory of Potentially Affected Tower Projects

Economic impacts are quantified for construction losses and permanent losses. Each of these losses has a direct component and a ripple effect characterized by the indirect and induced impacts. These impacts are cumulative over a three year period reflecting the three year building code update cycle. Additional and ongoing impacts may occur beyond this three year period depending on whether and when the building code elevator requirement is changed. As these buildings would be constructed over a three year horizon the employment estimates reflect the number of workers in jobs supported continually over this three year period. Thus, while there is only one job, the wages reflect three years of wage earnings to illustrate the cumulative three year effect of the losses.

Table 4 illustrates the range of impacts resulting from construction and household spending losses to the State of Florida, as a result of the second fire elevator requirement.

Table 4. Economic Losses Due To Additional Fire Service Elevator

CONSTRUCTION Impact Summary

ImpactType	Annual Employment	3-Year Wages	3-Year Output Total
Direct Effect	16,225	$2,380,827,341	$8,462,479,691
Indirect Effect	10,991	$1,668,457,825	$4,552,119,553
Induced Effect	9,153	$1,264,257,494	$3,621,377,394
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SUMMARY of LOSS

ImpactType	Annual Employment	3-Year Wages	3-Year Output Total
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Total Effect	58,702	$7,645,050,918	$21,057,307,527

Source: Fishkind & Associates, Inc. and Minnesota IMPLAN Group, Inc., 2015

6.0 Fiscal Impacts

As Indicated in Table 3, Forty-four high-rise towers with over 18,311 units will become financially unviable. Table 5 provides a summary of the value of the lost units and their impact on individual city and county government budgets.

Table 5: Revenue Lost from Decrease in Construction

	Total Taxable Value*	City Ad Valorem	County Ad Valorem	School Ad Valorem	Total Ad Valorem	Documentary Stamps
Broward County						
Fort Lauderdale	$691,821,053	$2,985,277	$3,959,292	$5,145,765	$16,901,257	$4,842,747
Hallandale Beach	$694,724,737	$2,912,147	$3,975,910	$5,167,363	$17,517,276	$4,863,073
Hollywood	$962,308,158	$7,547,960	$5,507,290	$7,157,648	$24,426,268	$6,736,157
Broward Total	$2,348,853,947	$13,445,384	$13,442,491	$17,470,776	$58,844,801	$16,441,978
Miami-Dade County						
Aventura	$340,782,368	$588,224	$1,840,531	$2,717,399	$6,288,048	$3,578,215
Miami	$6,861,735,072	$57,535,649	$37,059,545	$54,715,475	$155,428,592	$72,048,218
Maimi Total	$7,202,517,440	$58,123,873	$38,900,076	$57,432,874	$161,716,640	$75,626,433
Palm Beach County						
Juno Beach	$61,869,211	$159,375	$558,889	$469,835	$1,330,504	$433,084
Hillsborough County						
Tampa	$589,860,000	$3,381,431	$5,328,441	$3,747,145	$12,344,531	$4,129,020
Sarasota County						
Sarasota	$27,690,000	$98,590	$135,202	$215,345	$449,137	$193,830
Statewide Total	**$10,230,790,598**	**$75,208,654**	**$58,365,100**	**$79,335,974**	**$234,685,613**	**$96,824,345**
Millage Rates						
Broward County		**City**	**County**	**School**	**Total**	
Fort Lauderdale		4.3151	5.7230	7.4380	24.4301	
Hallandale Beach		4.1918	5.7230	7.4380	25.2147	
Hollywood		7.8436	5.7230	7.4380	25.3830	
Miami-Dade County						
Aventura		1.7261	5.4009	7.9740	18.4518	
Miami		8.3850	5.4009	7.9740	22.6515	
Palm Beach County						
Juno Beach		2.5760	9.0334	7.5940	21.5051	
Hillsborough County						
Tampa		5.7326	9.0334	6.3526	20.9279	
Sarasota County						
Sarasota		3.5605	4.8827	7.7770	16.2202	
Documentary Stamps						
Statewide	$0.7/$100		* Taxable Value = Sales Price - Homestead Exemption			
Miami-Dade	$1.05/$100					

The table shows that 8 cities in 5 counties will be negatively impacted by the decreased construction. Miami-Dade County will lose over $7.2 Billion in taxable value. Broward County will lose $2.3 Billion in tax value.

Overall, the five counties will lose $234.6 million in total ad valorem revenue each year. Of this total, the cities will lose $75.2 million; the counties will lose $$58.3 million and the schools will lose $79.3 million in ad valorem revenue each year. Miami-Dade County will suffer the most fiscal damage with total annual ad valorem losses of $161.7 million, of which $155.4 million is in the City of Miami. Broward County will lose over $58.8 million in ad valorem each year.

In addition to ad valorem revenue losses, the State will lose the value of the Documentary Stamps tax that would be paid upon the sale of each property. The total Documentary Stamp tax that would be lost from the initial sales is estimated to reach $96.8 million.

7.0 Conclusions

As indicated in Table 4, total economic losses to the State of Florida reach $21 billion, representing the loss of 58,700 jobs. This includes $8.4 billion in Direct construction loss, and $2.4 billion in household spending loss. There is an additional loss of $10.2 billion in indirect and induced economic activity.

Among the jobs and wages, construction and related job loss is 36,400, equivalent to all of the construction job gains in the State of Florida in year 2014. Household spending losses will cause an additional loss of 22,300 permanent jobs. Permanent household spending losses will continue on past the three year update cycle and generate direct spending losses of nearly $800 million annually over the long term.

Five counties will lose $234.6 million in total ad valorem revenue each year. The State will lose the value of the Documentary Stamps tax that would be collected from the initial sales of residential units. This would equate to an additional $96.8 million in lost State revenues.

The emergency 90 day rule being requested is needed to make a permanent building code change which eliminates the second elevator requirement. Should the emergency rule expire without a permanent code modification, it is likely all of the losses described will come to pass.

EXHIBIT B

FLORIDA SOLAR ENERGY CENTER®
Creating Energy Independence

A Review of Home Airtightness and Ventilation Approaches for Florida Building Commission Research

FSEC-CR-1977-14

Final Report
June 15, 2014
[Revised June 30, 2014]

Submitted to

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A Review of Home Airtightness and Ventilation Approaches for Florida Building Commission Research

FSEC-CR-1977-14

1. EXECUTIVE SUMMARY

This report presents a literature review, examination of experimental data, and calculations of energy impacts of using or not using various types of ventilation systems and presents alternative approaches to achieving acceptable levels of ventilation while avoiding the risks associated with tight home enclosures and potential mechanical system failures.

This work is a follow-up to a 1995 FSEC report to the Florida Department of Community Affairs that assessed the then-current infiltration practices of the Florida Energy Code (Cummings and Moyer 1995). Finding that Florida homes had become progressively more airtight, the report concluded:

> *…we can say with confidence that nearly all new Florida homes receive less ventilation air by means of natural infiltration than is called for by the ASHRAE 62-1989 ventilation standard (it calls for 0.35 ach or more).* ***Therefore, this report concludes that Florida houses should not be made tighter.*** *Blower door test data shows that Florida houses have become three times more airtight over the past 40 years, and that the majority of this airtightening occurred before the current infiltration practices came into effect in 1986.*

The 1995 report also stated that further tightening might necessitate mechanical ventilation systems to achieve acceptable indoor air quality and contained recommendations that the Florida Building Code should be modified to make homes more airtight between indoors and the attic, garage, and crawlspace, but less airtight at locations in the house envelope where the entering air would be of higher quality.

As the Florida Building Code adopts new airtightness and mechanical ventilation requirements, new equipment and control technologies become available and the future likely holds homes continuing to become more efficient, it is important to revisit these topics.

Research performed for this project found there is wide consensus that both controlling infiltration and providing mechanical ventilation is necessary for homes, but determining appropriate levels for each is much more involved. Considerations must include energy use, indoor humidity impacts and combustion safety.

Based on the totality of the research done for this project, the authors' position is to encourage "reasonably tight" Florida homes with neutral or slightly positive pressure mechanical ventilation. Specific recommendations include:

- Do not require further airtightening beyond the 2012 IECC requirement for homes to have an air leakage rate not exceeding 5 ACH50 in Florida.

- Consistent with the 1995 recommendations, focus on airtightness between indoors and the attic, garage, and crawlspace instead of locations in the house envelope where the entering air would be of higher quality.

- The amount of airflow required in ventilation standards has limited health-related validation. A health metric needs to be incorporated into ventilation standards and to do that, building scientists and medical researchers will need to collaborate. Although such research will take a long time, it should be conducted as there are health consequences in the balance.

- To minimize risk of health consequences source control should be advised more regularly than present. The means of doing so is beyond the scope of this study, but the public needs better education of the risk of pollutant sources in homes. Furthermore, residents need education on storing certain materials and chemicals outside the home.

- Ventilation systems should be designed to have the following features:
    - Flexible airflow rate. As standards change and more health-related research is conducted, the recommended flow rates may change. Furthermore, a system with adjustable rates will allow for field or seasonal adjustments.
    - Highly efficient fans. The ventilation system will use power and there is a fair amount of variation in energy use of fans. Oversized fans that run on slow speed may meet the needs for flexibility while saving energy as the power curve of motors usually results in reduced Watts per cfm. Energy use for whole house mechanical fans of less than 0.2 or 0.3 Watts per cfm may be able to be specified in codes in the near future.
    - Be positively pressured or balanced systems. Positively pressured and balanced systems provide control of where the air entering the home is coming from and reduce risks of mold and mildew on surfaces.
    - Be installed with air intakes at proper locations. The 2014 Florida Energy Conservation Code Section R403.5.2 requirement not allowing ventilation air to come from "attics, crawlspaces, attached enclosed garages or outdoor spaces adjacent to swimming pools or spas" should be added to the IECC. Furthermore the intake should not be near insecticide spray locations, car exhaust, air conditioning condensers or dryer exhausts.
    - Have a means to remove humidity of the ventilation air. Another research project is currently exploring options (Withers and Sonne 2014).

- Consider balanced ventilation systems such as enthalpy recovery ventilation (ERV) systems. Moisture of entering air can be reduced with these systems. The systems use balanced airflow which requires two fans so they tend to use more energy than supply or exhaust only systems. ERVs are popular in the national marketplace and can be set up to meet most of the requirements listed above. In addition to the energy use and first cost, key concerns of such systems are the maintenance of two fans and the enthalpy exchange media. ERVs are not designed to maintain a specific indoor RH, but rather reduce the latent load associated with ventilation air in hot and humid climates. They can only reduce the latent load when indoor air is sufficiently cool and dry which means elevated indoor RH can occur during swing seasons.

- Supply only systems can be combined with dedicated outdoor air systems, the standard home air conditioner, and/or dehumidifiers to remove moisture and can be purchased and installed at a low first cost (albeit, the dehumidification solution may become expensive). A popular method in high efficient homes has been runtime supply ventilation systems that run only when the AC is on. They do an excellent job of bringing in air and keeping humidity under control when the AC runs frequently. However, they may also need to cycle on during other times which may include days when outside air is damp but not hot so the air conditioner thermostat does not call for cooling or dehumidification; at these times they may bring in air that will raise the humidity in the home. (For example, a late season tropical storm in November.)

- Failure rates of systems in limited field studies raise concerns about the longevity and home resident operation and maintenance of whole-house ventilation systems. If residents think they are obtaining outside air but do not know the system has failed that could be a health concern. Consideration should be given to mandating some type of alarm if there is a detected failure (much like home fire alarms).
- A research project should be initiated to study the effectiveness and failure rates of whole-house mechanical ventilation systems installed in Florida over the last 15 years.

2. INTRODUCTION

In the 1990's concerns were raised that homes were becoming increasingly airtight and that this airtightness might lead to indoor air, humidity control, and combustion safety problems. In 1995, a report was prepared by FSEC for the Florida Department of Community Affairs on the topic of building airtightness, titled "Reassessment of Airtightness Practices in the Florida Energy Code" (Cummings and Moyer 1995).

- The report indicated that Florida homes had become progressively more airtight, with home air leakage declining from about 22 ACH50 (air changes per hour at 50 pascals of pressure; a blower door test result) in the 1950's to about 4 or 5 ACH50 in 1995. The report found that residential construction had reached a point where added tightening could result in natural ventilation sufficiently small as to fall substantially short of levels needed for healthy indoor air quality.

- The report also stated that further tightening might well necessitate installation (and of course maintenance) of mechanical ventilation systems to achieve acceptable indoor air quality. It contained recommendations that the Florida Building Code should be modified to make homes more airtight between indoors and the attic, garage, and crawlspace, but less airtight at locations in the home envelope where the entering air would be of higher quality.

Since that 1995 report, residential construction codes have been modified as reflected in Section R402.4.1.2 of the 2012 IECC, which requires that a "building or dwelling unit shall be tested and verified as having an air leakage rate not exceeding 5 air changes per hour in Climate Zones 1 and 2…", which would cover all of Florida (IECC 2012). Additionally, building practices have continued to change over time and a number of groups and programs have also begun pushing to simultaneously make homes much tighter and to require mechanical ventilation. The saying "Build tight, ventilate right" represents a strongly held view among many within the buildings community. While this concept is appealing, there can be significant problems with making the house envelope very tight. Underlying this issue is the concern that when the house envelope is made very tight and mechanical ventilation systems are essential to achieving desired ventilation levels, the question arises, "Who will maintain the ventilation system and what happens to indoor air quality when the system fails or is turned off?"

One problem is that a tight house envelope creates the necessity of mechanical ventilation. The corollary to this is that when the mechanical system fails, is turned off, or diminishes in performance (such as a dirty filter or a slipping belt), the occupants of the tight home will likely suffer from poor indoor air quality. Field observations have repeatedly found that mechanical ventilation systems fail at alarmingly high rates due to motor burnout, dirty filters, slipping belts, and systems being turned off. In addition to a shortfall in outside air, failure of the mechanical system can lead to moisture problems such as elevated indoor relative humidity and mold growth during cold weather (Vieira et al. 2013).

A second problem relates to combustion safety. When a house is very tight, various forms of unbalanced air flow (such as exhaust fans without make-up air, unbalanced return air, and/or duct leakage) can lead to excessive depressurization of the indoor space which can lead to spillage or back-drafting of vented combustion devices (hot water heaters, furnaces, boilers, and fireplaces) (CMHC 1999). This can introduce combustion gases, including carbon monoxide, into the home and create a significant health risk. Negative pressure can also produce flame roll-out and the potential for a house fire.

A third problem relates to humidity in homes, which is a special concern because of the Florida climate.

- The most widely encouraged and employed method for providing mechanical ventilation in homes across the United States is continuous exhaust. Throughout much of the United States, exhaust ventilation does not create major problems. But this approach is generally questionable in Florida because it creates negative pressure. Combined with other factors beyond the control of the building code, such as homeowner thermostat set point and impermeable interior wall coverings, negative pressure has been found to cause mold growth in Florida homes and buildings (Moyer et al. 2001).

- Alternative methods of providing mechanical ventilation can produce positive pressure in homes. These systems involve a supply fan and duct, a balanced system or possible additional cooling systems. As such they are generally more complicated and more expensive than a simple exhaust system.

This report focuses on airtightness and ventilation of living spaces. Air tightness of adjacent spaces such as attics is not directly covered in this report. The airtightness of the home is dependent first on the tightness of the barrier between the conditioned envelope and outside or adjacent unconditioned spaces. In cases where there is significant leakage between the conditioned space and the adjacent unconditioned spaces, the airtightness of the adjacent space could play a role in the heat and moisture load of the house. Other research has been conducted indicating the effect of sealed and ventilated attics; see an earlier FSEC report, “Literature Review of the Impact and Need for Attic Ventilation in Florida Homes” (Parker 2005).

This report does not cover duct tightness. There are reports (e.g. Cummings et al. 1991, Swami et al. 2006) that discuss the airtightness of ductwork and the role it can play on the energy impacts of the home, including increased air leakage due to pressure differences in the home caused by duct leakage.

3. TASK 1

Task 1 involves a literature review, examination of experimental data, and calculations of energy impacts of using or not using various types of ventilation systems.

Over 40 articles, research reports, presentations and code documents were reviewed. Information sources included the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Building Science Corporation (BSC), Florida Solar Energy Center (FSEC), International Code Council (ICC), Lawrence Berkeley National Laboratory (LBNL) and the US Environmental Protection Agency (EPA).

One thing that is clear from the research is that this is not a simple, straightforward undertaking. A 2012 LBNL publication (Sherman and Walker 2012) summarizes the current state of affairs:

> *The ongoing challenge with airtightness is balancing the need to make buildings tighter to save energy and for improved comfort, with the need to provide sufficient air flow to*

maintain indoor air quality and avoid other issues such as natural draft combustion appliance backdrafting. Where this balance is to be struck is an ongoing topic of debate in the US.

3.1 Measured Airtightness Data

As documented in the 1995 FSEC study, even at that time new Florida home construction was rather airtight. How tightness of that era compares to the tightness of homes built prior to 1995 is not known as few Florida house were tested for airtightness prior to 1990. Some studies have tested old and new homes and found the older homes as currently tested to be leakier than newer homes:

- A 2012 FSEC Code study (Withers et. al. 2012) found a sample of 31 Florida homes built to the 2009 Florida Energy Code to have an average ACH50 of 5.6 compared to a sample of 47 homes built to the 1984 Florida Energy Code which had an average ACH50 of 9.1 (all homes were tested in 2011 - 2012 so some or all of the difference may be due to failures over time of the older homes).
- Recent FSEC analysis of data from mainly central and some south Florida homes showed an average ACH50 rate of 9.7 for a sample of 13 homes built between 1975 and 1984 compared with 7.5 for 16 homes built between 1985 and 1994, and 5.9 for a sample of 16 homes built between 1995 and 2006
- A 2003 FSEC study (Cummings 2003) found a sample of 11 central Florida homes built in 2001 to have an average ACH50 of 5.7.

3.2 Airtightness and Whole House Ventilation Requirement Trends

Different standards for air tightness exist in the residential marketplace. Home airtightness requirements ranging from the 2012 International Energy Conservation Code (IECC) level of 5 ACH50 to Passive House's 0.6 ACH50 were found. As noted in the introduction, "Build it tight, ventilate it right" is advocated in a number of publications with some looking at energy savings and other considerations for specific airtightness levels.

In general, there is a definite trend toward tighter homes:

- While the 2009 IECC provides two airtightness options, either a visual inspection using a provided checklist or tested ACH50 < 7, the 2012 IECC requires both a visual inspection and a tested ACH50 <= 5 in Climate Zones 1 and 2, which includes all of Florida (IECC 2009 and 2012).

- The US Environmental Protection Agency's ENERGY STAR Homes program version 3 prescriptive path requirement for Florida is an ACH50 <= 7 while the new version 3.1 Florida prescriptive requirement is an ACH50 <= 5 (EPA 2014).

- The US Department of Energy's Zero Energy Ready Home (formerly Challenge Home) program which starts with ENERGY STAR qualification as a baseline, requires an ACH50 of <= 3 for prescriptive compliance in Climate Zones 1 and 2 (US DOE 2014).

Even tighter requirements are found in the 2012 edition of Canada's R-2000 Standard (NRC 2014) which stipulates an ACH50 of <= 1.5 and, as noted above, in the Passive House criteria (Passive House Alliance 2014) which stipulates a maximum air leakage equivalent to 0.6 ACH50.

There are also a number of residential mechanical ventilation rate requirements. Four of the commonly referenced requirements are:

- ASHRAE Standard 62.2-2010: Continuous ventilation Rate (cfm) = (CFA * 0.01) + (7.5*Nbr+1), where CFA is the conditioned floor area in square feet and N_{br} is the number of bedrooms. The 2010 Standard assumes infiltration at 2 cfm per 100 square feet of conditioned area. There is also an intermittent option.
- ASHRAE Standard 62.2-2013: Continuous ventilation Rate (cfm) = (CFA * 0.03) + (7.5*Nbr+1), where CFA is the conditioned floor area in square feet and N_{br} is the number of bedrooms. For the 2013 Standard, no infiltration is assumed, but ventilation "credit" can be taken for calculated infiltration that is based on blower door measurements. There is also an intermittent option.
- 2012 IMC: Outside of an exception for engineered ventilation systems provided by registered design professionals, ventilation is required for any home that has less than 5 ACH50 in the 2012 International Mechanical Code. The IMC sets the continuous ventilation at 0.35 ach (air changes per hour) but not less than 15 cfm/person, where the number of persons equals the number of bedrooms plus 1.
- 2012 IRC: The 2012 International Residential Code sets continuous ventilation at a rate provided by Table M1507.3.3(1). It also has an intermittent option via multiplier factors provided in Table M1507.3.3(2).

The new 2014 Florida Mechanical Code will also require that mechanical ventilation be provided for any home that has less than 5 ACH50. The Code will use the same language as Chapter 4 of the International Mechanical Code (IMC 2012), which states that mechanical ventilation must be provided by "a method of supply air and return or *exhaust air.*" It also requires that the amount of supply air be approximately equal to the amount of return and exhaust air. The IMC-required continuous ventilation rate for private dwellings or IRC Table M1507.3.3(1) rate will be required by Florida as well.

The new Florida 5th Edition (2014) Energy Conservation Code will follow the 2012 IECC requirement that newly constructed houses be tested for envelope air leakage, not permitting leakage in excess of 5 ACH50 , which means that most new homes will require mechanical ventilation in order to comply with the combination of the energy and mechanical portions of the Code. Additions to the 2012 IECC were made in the Florida 5th Edition (2014) Energy Conservation Code to limit maximum mechanical ventilation to ASHRAE 62-2 levels, prevent ventilation air being supplied form attics, crawlspaces, garages, or swimming pool areas, and if air is drawn from an enclosed space, the space be insulated [Section 403.5.2].

Due to Florida's relatively small infiltration driving forces (most notably the lack of a significant stack effect), typical annual average total air exchange rates have been about 0.20 ach or less. Even so, historically Florida has not had a requirement for residential mechanical ventilation. It is also noteworthy that the IMC mechanical ventilation requirements are normally somewhat greater than the ASHRAE 62.2-2013 requirements, which generally average between 0.25 and 0.30 ach rather than 0.35 ach and do not require "approximately equal amounts of supply and exhaust air."

3.3 Airtightness and Whole House Ventilation Trends Discussion

While, as seen above, Code and program requirements are moving toward more airtight homes with mechanical ventilation, there are several important factors to consider as these changes are made including energy use and moisture impacts, which will be addressed here. Another important factor, combustion safety, will be addressed later in this report.

3.3.1 Airtightness and Whole House Ventilation Energy Use Considerations

One of the important considerations in determining airtightness and ventilation recommendations is energy use impacts. Research summarized below suggests only slight energy use impacts from airtightening in our climate in summer, and more significant impacts in winter. Ventilation will be discussed later in this section.

EnergyGauge USA modeling for a 2,000 square foot, 2010 Florida Code level home run for Orlando without mechanical ventilation and starting from an ACH50 of 10, showed annual energy savings of 333 kWh, 498 kWh and 661 kWh when ACH50 values were reduced to 5, 3, and 1 respectively.

An FSEC conducted multi-variate regression conducted for this project of monitored summer data from 58 mainly central Florida existing homes without mechanical ventilation indicated that at an 81% confidence level, for each additional ACH50, air conditioning energy use increased by about 0.5 kWh/day, or about 2% of total cooling energy use.

A recent monitored FSEC study (Parker et. al. 2014) of two side-by-side, central Florida non-mechanically ventilated lab homes did not find significant summertime energy savings from a tight (ACH50 ~2.2) central Florida lab home compared with an otherwise identical less airtight home (ACH50 ~8.0):

> *The comparative summer testing showed that tighter buildings…had little if any air conditioning (AC) energy savings…. The lack of energy savings in the tighter home was largely because the outdoor temperature was nearly as often below as above the desired thermostat set point. Thus, increased air infiltration during nighttime hours when the temperature outside is lower than the desired cooling set point actually reduces the AC load.*

While there is some difference in these two results, both indicate very small ACH50 influences on summertime energy use. The 81% confidence level of the 58-home study indicates that the true influence in a large sample of homes would likely still show up, but could be very small in terms of magnitude.

Turning to wintertime research, a multi-variate regression of winter data from the 58 non-mechanically ventilated home analysis for the three coldest days in January showed that at a 90% confidence level, heating energy use for heat pump homes increased by about 1.8 kWh/day or about 8% of total heating energy use for each additional ACH50. Winter results from the FSEC side-by-side lab home study (while the homes were not mechanically ventilated) showed a reduction in energy use for the tighter home in the range of 15.8%–18.6% relative to the leaky home (Vieira et al. 2013).

When mechanical ventilation is added there are a number of affects. First, outside air is brought in that needs to be conditioned. Second, the mechanical ventilation system uses energy. Third, depending on the system type, heat from the fan of the mechanical ventilation system is added to the space reducing heating needs but increasing cooling requirements. Thus, much or all of any savings from reducing air infiltration is used by the mechanical ventilation.

EnergyGauge USA modeling results for the same 2,000 square foot, 2010 Florida Code level home discussed above, but this time with energy (enthalpy) recovery mechanical ventilation using 0.75 W/cfm and maintained at 2013 ASHRAE Standard 62.2 levels are provided in Table 1, which shows minimal savings from increased airtightness.

Table 1. Modeled Annual Energy Use Savings for Various House Airtightness Levels with Mechanical Ventilation

ACH50	***EnergyGauge USA*** **Annual Clg+Htg+Vent (kWh)**
10	3,854
5	3,835
3	3,806
1	3,797
0.6	3,786

A different result was found however in a 2013 modeling study using an incremental ventilation energy (IVE) model (Logue et. al. 2013) showing significant airtightening energy savings (on the order of 1,000 kWh/yr going from typical DOE Weatherization Assistance Program level airtightness to ACH50 5) in our Florida climate with ASHRAE 62.2 levels of ventilation. Details as to power of the ventilation system and starting air tightness as an ACH50 level are not given by the study. The modeling was for older housing that had received typical weatherization program tightening.

The monitored FSEC side-by-side lab home study discussed above found significant increases in summertime cooling energy use when a supply-fan system was employed to provide mechanical ventilation to the tight (ACH50 2.2) home:

> *Unlike natural infiltration, mechanical supply ventilation revealed much more significant changes to energy use…when added to the tight home. Cooling energy increased by 20%–38% or about 4 kWh/day. Part of this increase resulted from the mechanical ventilation system fan itself, which added 1.8 kWh/day of energy use to the cooling system energy use.*

Another recent FSEC monitoring study involving six Gainesville Florida homes (Martin et. al. Pending Publication 2014) found that continuous exhaust ventilation (CEV) at approximately ASHRAE 62.2-2010 increased summertime cooling energy use by approximately 9% compared with runtime only, central fan integrated supply (CFIS) ventilation that provided approximately 20% of ASHRAE 62.2-2010 requirements (see Figure 1).

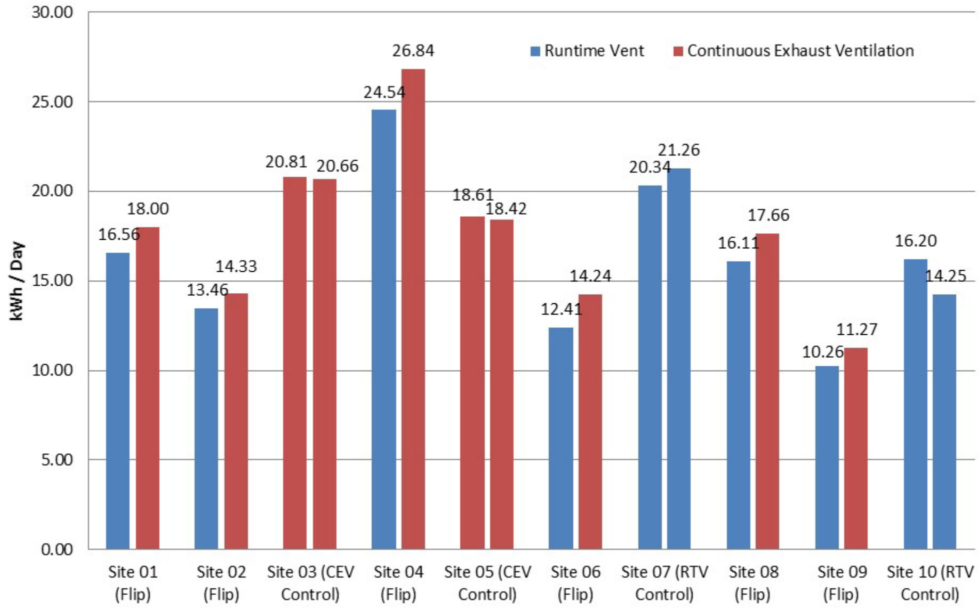

Figure 1 (figure and caption from Martin et al. publication pending 2014). Average HVAC energy use per day, broken into runtime vent (left bar) and continuous exhaust (right bar) periods. Sites 3 and 5 always operate with continuous exhaust, and sites 7 and 10 always operate with runtime vent.

As reported above, winter results from the FSEC side-by-side lab home study without ventilation showed a 15.8%–18.6% reduction in energy use for the tighter home relative to the leaky home, but when supply only mechanical ventilation was added to the tighter home, its heating use was 15% higher than the leaky home (Vieira et al. 2013). The increase in heating energy use for the tight home with ventilation prompted the researchers to note that heat recovery ventilation may have application to offset the increase.

While summertime results from the FSEC Gainesville study noted above showed energy savings for runtime only, central fan integrated supply ventilation compared to continuous exhaust ventilation, initial analysis of December 2013 through February 2014 data performed for this study indicate that the 100% ASHRAE 62.2-2010 continuous exhaust ventilation used for this study is consuming slightly less energy than the 20% ASHRAE 62.2-2010 runtime strategy in the winter. These results are being investigated further.

In a presentation at a 2012 Building America Expert Meeting (Cummings 2012), Jim Cummings provided an analysis comparing the costs and benefits of an ERV ventilated ACH50 5 Orlando home to that of an ERV ventilated ACH50 1 home in the same city. Both homes had ASHRAE 62.2-2013 ventilation, the

ACH50 home requiring 37 cfm of outdoor air and the ACH50 home requiring 79 cfm of outdoor air. With all costs other than maintenance and repairs considered, including the cost of additional air tightening and a more expensive ERV for the tighter home, Cummings calculated a net savings of $50 per year for the tighter home and a simple payback of 50 years.

3.3.2 Airtightening and Whole House Ventilation Moisture Considerations

In addition to energy savings, another important consideration in determining airtightness and ventilation recommendations in our Florida climate is moisture. Summertime research summarized below shows that moderate differences in airtightness don't have a large impact on indoor moisture, but mechanical ventilation impacts can be more significant**.** In winter, the results below show definite moisture benefits from ventilation of tight homes.

In addition to a small amount of energy savings, summertime results for the recent FSEC side-by-side lab home study also found the tighter (ACH50 ~2.2) unventilated home had "only modest differences in moisture content under natural infiltration" compared with the less airtight (ACH50 ~8.0) but also unventilated home. Adding supply only mechanical ventilation to the tight house increased summertime moisture levels by 2% - 5%.

A 2014 Building America Expert Meeting summary (Rudd 2013) reporting on modeling work also concluded mechanical ventilation causes increases in indoor RH:

> *…mechanical ventilation, operated at the ASHRAE 62.2-2010 addendum r rate, in a 3 ach50 house, raises the annual median indoor RH by almost 10% RH compared to a 7 ach50 house without mechanical ventilation in Orlando. That is because infiltration drivers are generally weak in that climate during floating hours (when it is still humid outside and the cooling system is not removing moisture), but mechanical ventilation forces a minimum air exchange.*

An earlier monitored study involving 43 existing homes in warm-humid and mixed-humid climate regions of the United States (Rudd and Henderson 2007) also found continuous whole-house ventilation during periods of infrequent cooling demand to cause high humidity levels as after long cooling cycles the interior dew point would slowly approach the outdoor dew point.

While moisture issues may often be associated with summertime in Florida, winter conditions can also be problematic, particularly for tight homes.

The FSEC side-by-side lab home study, while noting some differences in the lab homes compared to typical Florida homes (little moisture capacitance, no window operation and the homes were only one year old), found higher wintertime dew points and moisture problems (see Figure 2) inside the tighter home (without mechanical ventilation) compared with the leaky home. Each home started with typical internal moisture gains for normal occupancy, but even with reduced internal gains the tight home had humidity issues:

> *Window condensation and mold growth occurred inside the tight home. Even cutting internal moisture gains in half to 6.05 lb/day, the dew point of the tight home was more than 15°F higher than the outside dry bulb temperature.*

Figure 2 (figure from Vieira et al. 2013). Condensation on north-facing window in unventilated tight lab house January 23, 2013.

Figure 3 further illustrates these moisture issues, showing an example January day where the dew point temperature is 10+ degrees higher in the tight house than the leaky house and is higher than the north-facing window temperature during the nighttime and morning hours.

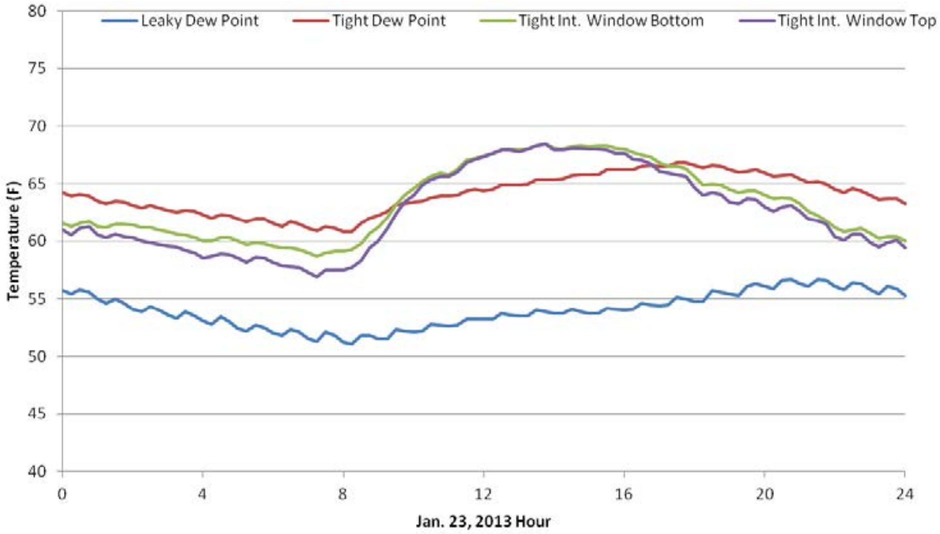

Figure 3 (figure from Vieira et al. 2013). Unventilated tight house dew point and interior window temperatures January 23, 2013.

As noted earlier, adding mechanical ventilation to the tight FSEC lab home raised heating energy use by 15%, but it also resolved winter moisture issues:

> *Winter condensation was observed again when the supply ventilation fan was off. Inside window temperatures (measured for the second winter collection period) were lower than the inside dew point on cold winter nights. However, condensation was not observed when the ventilation fan was on, or in the leaky home.*

With the winter results from the FSEC lab home study indicating a risk of window condensation and high interior humidity levels in mind, the researchers also provided guidance for older Florida homes that are air tightened:

> *To reduce condensation potential there are steps practitioners may take coincident with tightening an older home. If the efficiency measures include window replacement, a low U-value for the window can be selected to avoid condensation. Also, mechanical ventilation can be introduced, which will likely reduce humidity in the home during winter. Judicious use of operable windows during mild periods with no space conditioning will also likely be helpful in reducing moisture problems.*

3.4 Whole House Ventilation Options

As discussed earlier, the 2012 IMC, and by adoption the new 2014 Florida Mechanical Code, stipulate that ventilation air must be provided by "a method of supply air and return or exhaust air" and that the amount of supply air be approximately equal to the amount of return and exhaust air. Then Section R403.5.2 of the 2014 Florida Supplement (DBPR 2013) requires that residential buildings designed to be operated at a positive indoor pressure or for mechanical ventilation have a design ventilation rate of no more than the "design air change per hour minimums for residential buildings in ASHRAE 62, *Ventilation for Acceptable Indoor Air Quality*." Other than these requirements the new (2014) Florida Code does not address how the ventilation air is to be provided.

As noted in the introduction, the most widely encouraged and employed method for providing mechanical ventilation in homes across the United States is continuous exhaust. Throughout much of the United States exhaust ventilation does not create major problems. But this approach is generally not recommended in Florida because it can create excessive negative pressure which pulls warm moist air through the building's envelope. When this air is cooled while passing through the assemblies, condensation can occur on impermeable surfaces. **Combined with other factors beyond the control of the building code, such as homeowner thermostat set point and interior impermeable wall coverings, negative pressure ventilation has been found to cause mold growth in Florida homes and buildings** (Moyer et al. 2001). Figure 4 shows a mold covered wall that resulted from several factors including negative pressure bringing moist outdoor air into a wall cavity and impermeable wall coverings.

Figure 4. Mold covered wall resulting from a combination of factors including negative pressure and impermeable wall coverings.

Alternative methods of providing mechanical ventilation can produce positive pressure in homes. These systems involve a supply fan and duct, a balanced system or possible additional cooling systems. As such they are generally more complicated and more expensive than a simple exhaust system.

Table 2 provides a summary of whole-house mechanical ventilation options. Each can be used with humidity control strategies which are discussed in a parallel DBPR report (Withers and Sonne 2014).

Table 2. Whole-house Mechanical Ventilation Options

Ventilation Option	Description	Pros	Cons
Supply Only	Outdoor air is supplied into home via a small fan and single duct or multiple ducts to zones.	Potentially low first and operation cost (depending on fan power use). Positive pressure drives conditioned air through envelope cracks and holes. Outdoor air can be filtered and conditioned (e.g. if dropped near air handler return).	Heat and/or energy (enthalpy) recovery not possible. Poor outdoor air distribution if single duct; also seasonally elevated RH where air is delivered.
Exhaust Only	Air is exhausted from home via single duct and small fan.	Low first and operation cost.	Negative pressure in home brings unconditioned outdoor air into home through building envelope; can lead to significant moisture related problems. Can also bring in air from undesirable locations such as the attic and garage. Heat and/or energy (enthalpy) recovery not possible.
Balanced with or w/o	Supply duct brings outdoor air into home	Balanced or positive house pressure possible. Outside	Energy recovery not effective at times in swing seasons.

Recovery	while exhaust duct remove indoor air.	air can be conditioned via heat or energy (enthalpy) recovery.	Uses two fans so twice as much energy use for ventilation. Higher first cost than exhaust or supply systems.
Runtime	Duct supplies outdoor air to return side of air handler.	Control strategies can limit excessive outdoor air and provide outdoor air at times where there is no call for cooling or heating.	Energy use of large air handler fan used to provide relatively small amount of air (can be minimized with variable speed air handler fan and high efficiency motors).

A 2014 ASHRAE humidity control options report (Henderson and Rudd 2014) provides an analysis of TRNSYS modeling results completed for the study:

> *Different ventilation systems have different impacts on relative humidity Levels. It is generally understood that different types of ventilation system (exhaust, AHU supply, and balanced) combine with infiltration to provide different overall ventilation impacts. We confirmed this finding here and also quantified the impact that different ventilation approaches had on the prevalence of elevated relative humidity. Exhaust ventilation was considered to be the baseline approach in this study. Central fan integrated supply (CFIS) slightly reduced high humidity hours compared to exhaust ventilation in Orlando and Atlanta. However, CFIS ventilation slightly increased high humidity hours in Miami and Houston because it provided more fresh air and because the part-time off-cycle operation of the AHU fan sometimes resulted in increased evaporation from the cooling coil.*

Recent FSEC work, described above and also discussed in FSEC's concurrent 2014 DBPR report on indoor humidity levels (Withers and Sonne 2014), compares indoor humidity levels for approximately ASHRAE 62.2-2010 continuous exhaust ventilation (CEV) with those of runtime only, central fan integrated supply (CFIS) ventilation that provided approximately 20% of ASHRAE 62.2-2010 requirements (Martin et al. publication pending 2014). In addition to the energy use results reported above, the monitored FSEC study involving six Gainesville Florida homes found continuous exhaust ventilation run at approximately ASHRAE 62.2-2010 rates raised summertime indoor RH by 5% compared with runtime only ventilation at approximately 20% of ASHRAE 62.2-2010 requirements.

Figure 5 from this Gainesville study shows that during periods when ASHRAE 62.2-2010 continuous exhaust ventilation was in use (right bars for sites 1, 2, 4, 6, 8 and 9) there were significantly more hours of indoor RH > 60% than during 20% of ASHRAE 62.2-2010 runtime ventilation periods.

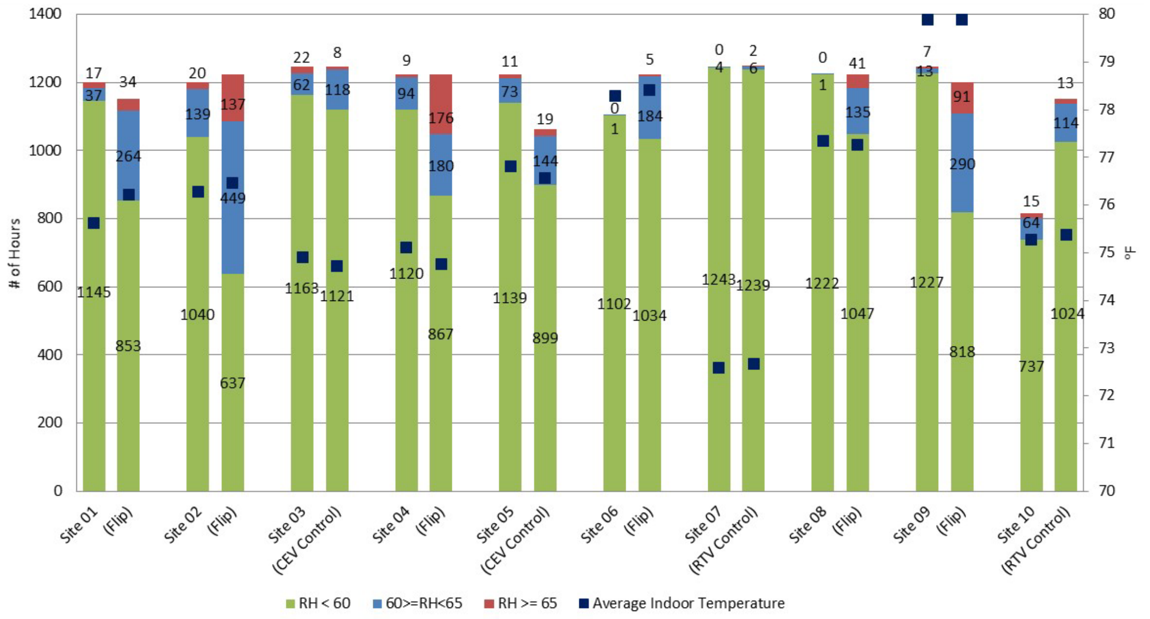

Figure 5 (figure and caption from Martin et al. publication pending 2014). Distribution of hours at various % RH ranges, separated into runtime vent (left bar) and continuous exhaust vent (right bar) periods, each corresponding to the left axis (# of hours). Numeric labels correspond to hours, black squares correspond to the right axis (average indoor temperature). Sites 3 and 5 were always operated with continuous exhaust ventilation, and sites 7 and 10 were always operated with runtime ventilation.

It is also informative to look at energy use of various levels of ventilation. A 2014 FSEC Building America program study (Martin 2014) modeled energy performance as a function of ventilation rate for a DOE Challenge Home level efficiency home for a number of US cities including Orlando Florida. *EnergyGauge USA* (EGUSA) runs were made with RH controlled to <60%. Figure 6 shows the energy use costs for

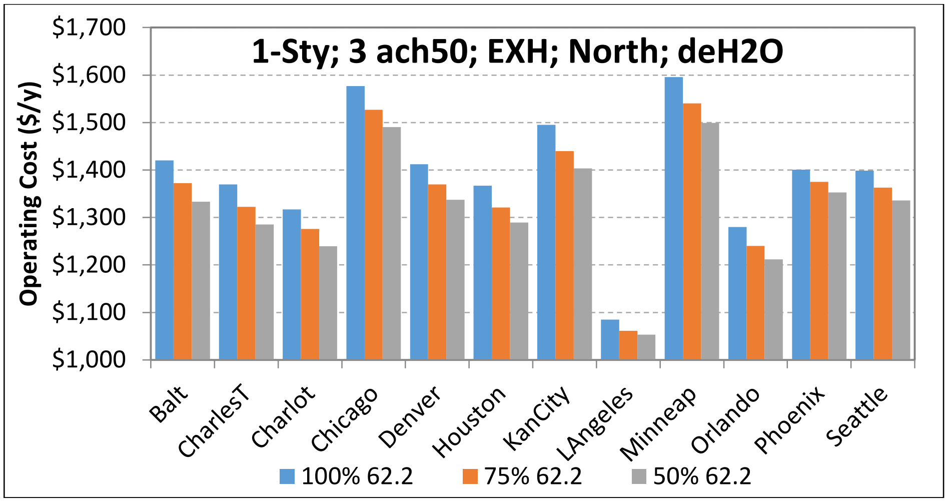

Figure 6 (figure and caption from Martin 2014). Total annual operating cost for a DOE Challenge Home controlled to <60% RH over a range of ventilation rates.

100% of ASHRAE 62.2-2013 ventilation and comparative costs when the ventilation rate is reduced to 75% and 50% of ASHRAE 62.2. Savings averaged over all the climates modeled were estimated at $45/year going from 100% of ASHRAE 62.2 to 75% and an additional $35/year going to 50%. Orlando savings are slightly less than the averages of the entire group.

3.5 Industry Airtightness and Whole House Ventilation Recommendations

A number of airtightness and ventilation practices and recommendations were found via the literature review.

The 2014 FSEC Building America program report noted above (Martin 2014) provided a summary of Building America teams' experience with ventilation approaches which is quoted extensively here:

> *Building Science Corporation (BSC) experience with whole-building controlled mechanical ventilation in tens of thousands of high performance homes in locations all across the United States has shown that drawing outdoor air from a known fresh air location, conditioning that air by filtration and sometimes heating or cooling, tempering that ventilation air by mixing it with central system return air, and fully distributing that air on at least an hourly average basis is a practical and effective way to mitigate odor complaints in all climates and an effective way to mitigate moisture buildup in mixed and cold climates. For more than 15 years, BSC builder partners have been installing systems capable of meeting more than ASHRAE Standard 62.2 ventilation rates, but typically running those systems at one third to one half that rate, resulting in satisfied builders and homeowners in both production and custom housing (Rudd and Lstiburek 1999, 2001, 2008). BSC attributes that satisfaction at the lower ventilation rates to the full distribution and whole-house mixing of outdoor air drawn from a known fresh air source with filtration (Hendron et al. 2006, 2007; Rudd and Lstiburek 2000; Townsend et al. 2009a, 2009b).*
>
> *BA-PIRC (formerly BAIHP) worked with site and factory builders constructing custom, production, affordable, and multifamily homes to implement supply-based mechanical ventilation through the introduction of outdoor air into the return side of centrally ducted, forced-air, space conditioning systems. This approach, combined with rightsized heating/cooling systems and properly operating bathroom and kitchen exhaust fans (ducted to the outdoors) has been implemented in thousands of homes, primarily in the southeastern United States, since 1997 and has effectively controlled odors, maintained comfort, and proven effective at minimizing wintertime moisture buildup (Chandra et al. 2008). Similar to BSC's approach, these systems draw outdoor air from a known fresh air location, filter the air, temper the air by mixing it with central system return air, and fully distribute the air. Systems have been commissioned to deliver approximately 30%–70% of ASHRAE Standard 62.2-2010 rates, enough to create a slight positive pressure in the home with respect to outdoors; however, only while the central HVAC system is running to satisfy a heating or cooling requirement. Therefore, operation of the ventilation system is intermittent, especially during periods of limited to no HVAC runtime. In the Southeast, these periods typically coincide with increased*

> *natural ventilation through more frequent window operation, and the system has gained the acceptance of homeowners and builders alike in terms of comfort, durability, energy consumption, and perceived odor and moisture control. However, most of these systems do not meet the whole-house mechanical ventilation requirements of ASHRAE 62.2-2010.*

While concluding that “building tight and ventilating right remains the best advice,” a 2012 BSC article (Straube 2012) also states:

> *A tight house is better than a leaky house, with a caveat: A tight house without a ventilation system is just as bad as a leaky house with no ventilation system—maybe worse.*

The 2012 LBNL paper (Sherman and Walker 2012) continues this theme, adding recommendations as to when ventilation is necessary:

> *New homes are typically three times tighter than the existing stock and are sufficiently tight that new homes need designed ventilation systems in order to meet acceptable indoor air quality requirements. In new homes airtighness can be designed-in and energy efficient homes are at about 1 Air Change per Hour at a typical test pressure of 50 Pa (ACH50h^{-1}]) compared with about 3-5 ACH50 for typical new construction. At these tightness levels some sort of mechanical ventilation is required to provide acceptable indoor air quality.*

The same LBNL paper (Sherman and Walker 2012) concludes:

> *Production builders in the US regularly build homes with leakage below 5 ACH50. Current construction techniques can get this as low as about 1 ACH50, but achieving lower levels, such as those required for Passive House require considerable extra effort and expertise and are unlikely to become common any time soon. Furthermore the energy benefits of achieving such levels may be minor, while the system robustness decreases.*

Martin Holladay, in the 2013 Green Building Advisor web article (Holladay 2013), after stating that more research is needed in this area, still concludes:

> *I think it’s wise for builders to install equipment that allows occupants to ventilate their homes at the rate recommended by ASHRAE 62.2 (7.5 cfm per occupant plus 3 cfm for every 100 square feet of occupiable floor area). However, that doesn’t mean that every home in the U.S. needs to be ventilated at that rate.*

A ventilation standard counterpoint is provided by Max Sherman of LBNL in another comment he made in the discussion section of the 2013 Green Building Advisor article:

> *Current ventilation standards are set based on engineering judgment by a room full of “experts”, but some of us would like to see that transition to be based on a bit more causality and science. That is the direction my research has gone in the last few years.*

The Future Ventilation Directions section at the end of this report provides additional information on this approach.

3.6 Whole House Ventilation Failure Concerns

As noted in the Introduction and in the above industry references, there are concerns related to mechanical ventilation failure in very tight houses. Mechanical ventilation system failure can create a number of potentially serious problems:

1) Decrease indoor air quality
2) Lead to moisture problems such as elevated indoor relative humidity and mold growth during cold weather (e.g., Florida in the winter)
3) Create unbalanced air flow causing combustion safety problems: when a house is very tight, various forms of unbalanced air flow (such as exhaust fans without make-up air, unbalanced return air, or duct leakage) can lead to depressurization of the interior space which can lead to spillage or back-drafting of vented combustion devices (hot water heaters, furnaces, boilers, and fireplaces). This can introduce combustion gases, including carbon monoxide, into the home and create health and death risk. Negative pressure can also produce flame roll-out and the potential for a house fire.

A 1999 Canada Mortgage and Housing Corporation (CMHC) field study (CMHC 1999) provides an example of the problems depressurization can cause:

> *In one house, the supply fan was not functioning. The homeowners were not aware of the problem because they still heard the sound of the exhaust fan. The result was backdrafting of the fireplace and the potential for backdrafting of other combustion appliances.*

A 2012 FSEC research report on airflow and water vapor drivers led by Jim Cummings (Cummings et al. 2012) provides additional tight house depressurization considerations:

> *Pressure differentials produced by unbalanced airflows from mechanical systems are exaggerated when a house is very tight. Consider, for example, that a clothes dryer exhausting 200 CFM from the house would produce negative pressure of –23 Pa in a 2000 ft^2 house with an airtightness of 1.0 ACH50. This level of negative pressure can cause slamming of doors and combustion safety problems such as spillage and backdrafting of vented combustion devices (e.g., gas furnaces, gas water heaters, fireplaces, and wood stoves), incomplete combustion accompanied by high carbon monoxide (CO) production, and flame rollout from water heaters. A cook-top grille exhausting 400 CFM would produce negative pressure of about –60 Pa in that same house.*

While sealed combustion equipment is becoming more popular in northern states, atmospherically vented combustion devices are still being installed. Mild Florida winters make high efficiency sealed combustion furnaces less cost effective, so atmospherically vented combustion equipment will continue to be in use. Atmospherically vented gas water heaters are also popular in the state and operate year round. As a result, the depressurization issues described above will continue to be an issue.

3.7 Whole House Ventilation Performance and Failure Research

Some research has also started looking at mechanical ventilation performance and failure rates.

Despite a survey showing occupants to believe ventilation is important for health, a 2002 Washington State research study (Lubliner et al. 2002) found significant problems with mechanical ventilation systems:

> *Only 29% (5/17) of the systems integrated with central heating systems complied with either the prescriptive or performance requirements of the code. … The field research data reveal that the technical details of the whole house ventilation requirements are widely misunderstood. Only 32% of all systems surveyed met VIAQ performance requirements. Exhaust systems not integrated with central heating were more compliant than other systems, complying with the code 71% (10/14) of the time (all prescriptively). Only 60% of those also met the performance airflow targets of the code.*

The 1999 CMHC field study noted above found 12% of heat recovery ventilators (HRVs) to not be operational due to component failure and also noted balancing issues, installation faults and a lack of homeowner understanding as concerns.

A soon to be published report from a major University in another state indicates that significant mechanical ventilation issues continue (Unreleased study, publication pending). Out of a sample of 29 mechanical ventilation systems inspected, fourteen had control issues, eight had dirty intakes, six had been installed incorrectly, and all 29 failed to have code-required display labels.

In a 2009 BSC *Top Ten Issues in Residential Ventilation Design* web article (Rudd 2009), Armin Rudd shares the following ventilation maintenance observations and recommendations:

> *Maintenance must be easy or it won't get done. Clogged air filters are probably the most common maintenance failure. Air filters must be easy to access. They should be either washable or readily available to purchase, preferably at the common home center stores. Outside air intakes that go through the first floor band joist are items that require annual cleaning. Avoid placing outside air intakes less than 12 inches or so off the ground. Parts that are expected to wear out and need replacement, like drive belts or moisture transfer cores, often don't get noticed when broken, or replaced when needed. Homeowners are usually less aware of maintenance needs for ventilation systems that are not part of the central space conditioning system. If the central space conditioning system fan stops, the system will surely receive the needed attention.*

To help address performance and failure issues, mechanical ventilation systems could be "locked in" with the space conditioning equipment, so that if it fails a homeowner or renter would need to have the system serviced. This solution however will be somewhat intrusive and cause some level of inconvenience, and there is the possibility of life-threatening consequences specifically in cold climates or on very cold days even in parts of Florida from the living space becoming too cold before the equipment can be serviced. Another possible means of alerting homeowners to a ventilation system malfunction is an alarm type system (similar to a home fire alarm).

The above referenced 1999 CMNC study, 2002 Washington State report and 2009 BSC residential ventilation web article all recommend ventilation system maintenance education, with the CMHC study also recommending additional installer education and offering maintenance agreements to homeowners, while the Washington State report also advocated "improved code language, and education of builders, contractors and building officials."

3.8 Health-Based Ventilation Considerations

As discussed earlier in this report, exhaust whole house ventilation is generally not recommended in Florida because the negative pressure pulls warm moist air through the building's enclosure. When this air is cooled while passing through the assemblies, condensation can occur on impermeable surfaces and elevated humidity can combine with other factors to cause mold growth. Beyond this consideration though, residential ventilation-health connections don't appear to be clearly established at this time.

The summary of an LBNL web article (LBNL 2014a) on this topic states:

> *Very little research has been conducted on the relationship of ventilation rates in homes with the health of the occupants of the homes. The results of a few studies suggest that children in homes with low ventilation rates have more allergic or respiratory symptoms compared to children in homes with high ventilation rates. There is also indirect evidence that ventilation rates of homes will affect health by modifying the indoor concentrations of a broad range of indoor-generated air pollutants.*

A 2013 Green Building Advisor web article on residential ventilation rates and health by Martin Holladay (Holladay 2013) puts it in a slightly different way:

> *Since experts have posited a connection between mechanical ventilation in homes and human health for the last 160 years, perhaps it's time to ask two questions:*
>
> - *Do we have any data that show a connection between residential mechanical ventilation and occupant health?*
> - *Do we know how much ventilation is desirable for optimal occupant health?*
>
> *The answer to the first question is no, not really. And the answer to the second question is an emphatic no.*

The author later goes on to explain his "no, not really" answer to the first question by stating that inferences between residential ventilation rates and occupant health can be made based on indirect evidence, and then quotes from an LBNL article related to the one noted above (LBNL 2014b):

> *From numerous experimental studies, as well as from theoretical modeling, we know that higher ventilation rates will reduce indoor concentrations of a broad range of indoor-generated air pollutants. Because exposures to some of these air pollutants, for example, environmental tobacco smoke and formaldehyde, have been linked with*

> *adverse health…, we expect that increased home ventilation rates will reduce the associated health effects.*

Holladay then also states that limiting indoor pollutants is the most important thing to do. In a comment posting to Holladay's article, Max Sherman of LBNL shares a parallel thought:

> *Ventilation is principally about removing indoor-generated contaminants of concern. The more you can capture them at their source and the less you can distribute them to the occupants, the better it is.*

4. TASK 2

The Task 2 goal is to develop alternative approaches to achieving acceptable levels of ventilation while avoiding the risks associated with super-tight home enclosures and potential mechanical system failures.

As indicated in the Task 1 section above, there is wide consensus that both controlling infiltration and providing mechanical ventilation is necessary for homes, but determining appropriate levels for each is much more involved.

While occupant health data related to ventilation are seemingly scarce, findings to date still include a rather broad consensus that ventilation systems should be able to provide ASHRAE 62.2 ventilation rates.

4.1 Recommendations

The 2012 FSEC airflow and water vapor drivers report referenced above (Cummings et al. 2012) addresses the pros and cons of tight envelopes verses relying somewhat on natural infiltration, concluding that section with the following:

> *A compromise between the two positions seems in order. Build it "reasonably tight" and provide mechanical ventilation. "Reasonably tight" might be 5 ACH50 in Florida and 3 ACH50 in Illinois, for example. In each of these locations, natural infiltration might fall between 0.10 to 0.20 ACH during most hours of the year. In case the ventilation system stops working, the house occupants will receive a substantial portion of the ventilation that they need. On the other hand, the envelope will be sufficiently tight so that natural infiltration will not exceed the ventilation requirements of ASHRAE Standard 62.2 for very many hours per year. And by producing a "reasonably tight" envelope, pressure differentials produced by unbalanced airflows will not be excessive.*

This paragraph represented the authors' position going into this study. While, as summarized above, there are a number of factors to consider and varying industry recommendations, based on the totality of the research done for this project, the authors still maintain this original airtightness position to encourage "reasonably tight" Florida homes with neutral or slightly positive pressure mechanical ventilation.

Specific recommendations include:

- Do not require further airtightening beyond the 2012 IECC requirement for homes to have an air leakage rate not exceeding 5 ACH50 in Florida.

- Consistent with the 1995 recommendations, focus on airtightness between indoors and the attic, garage, and crawlspace instead of locations in the house envelope where the entering air would be of higher quality.

- The amount of airflow required in ventilation standards has limited health-related validation. A health metric needs to be incorporated into ventilation standards and to do that, building scientists and medical researchers will need to collaborate. Although such research will take a long time, it should be conducted as there are health consequences in the balance.

- To minimize risk of health consequences source control should be advised more regularly than present. The means of doing so is beyond the scope of this study, but the public needs better education of the risk of pollutant sources in homes. Furthermore, residents need education on storing certain materials and chemicals outside the home.

- Ventilation systems should be designed to have the following features:
    - Flexible airflow rate. As standards change and more health-related research is conducted, the recommended flow rates may change. Furthermore, a system with adjustable rates will allow for field or seasonal adjustments.
    - Highly efficient fans. The ventilation system will use power and there is a fair amount of variation in energy use of fans. Oversized fans that run on slow speed may meet the needs for flexibility while saving energy as the power curve of motors usually results in reduced Watts per cfm. Energy use for whole house mechanical fans of less than 0.2 or 0.3 Watts per cfm may be able to be specified in codes in the near future.
    - Be positively pressured or balanced systems. Positively pressured and balanced systems provide control of where the air entering the home is coming from and reduce risks of mold and mildew on surfaces.
    - Be installed with air intakes at proper locations. The 2014 Florida Energy Conservation Code Section R403.5.2 requirement not allowing ventilation air to come from "attics, crawlspaces, attached enclosed garages or outdoor spaces adjacent to swimming pools or spas" should be added to the IECC. Furthermore the intake should not be near insecticide spray locations, car exhaust, air conditioning condensers or dryer exhausts.
    - Have a means to remove humidity of the ventilation air. Another research project is currently exploring options (Withers and Sonne 2014).

- Consider balanced ventilation systems such as enthalpy recovery ventilation (ERV) systems. Moisture of entering air can be reduced with these systems. The systems use balanced airflow which requires two fans so they tend to use more energy than supply or exhaust only systems. ERVs are popular in the national marketplace and can be set up to meet most of the requirements listed above. In addition to the energy use and first cost, key concerns of such systems are the maintenance of two fans and the enthalpy exchange media. ERVs are not designed to maintain a specific indoor RH, but rather reduce the latent load associated with ventilation air in hot and humid climates. They can only reduce the latent load when indoor air is sufficiently cool and dry which means elevated indoor RH can occur during swing seasons.

- Supply only systems can be combined with dedicated outdoor air systems, the standard home air conditioner, and/or dehumidifiers to remove moisture and can be purchased and installed at a low first cost (albeit, the dehumidification solution may become expensive). A popular method in high efficient homes has been runtime supply ventilation systems that run only when the AC is on. They do an excellent job of bringing in air and keeping humidity under control when the AC runs frequently. However, they may also need to cycle on during other times which may include days when outside air is damp but not hot so the air conditioner thermostat does not call for cooling or dehumidification; at these times they may bring in air that will raise the humidity in the home. (For example, a late season tropical storm in November.)
- Failure rates of systems in limited field studies raise concerns about the longevity and home resident operation and maintenance of whole-house ventilation systems. If residents think they are obtaining outside air but do not know the system has failed that could be a health concern. Consideration should be given to mandating some type of alarm if there is a detected failure (much like home fire alarms).
- A research project should be initiated to study the effectiveness and failure rates of whole-house mechanical ventilation systems installed in Florida over the last 15 years.

4.2 Future Ventilation Directions

There is currently work underway to try to incorporate a health-based approach into ventilation specifications. In a 2013 LBNL Q and A format article by Mark Wilson and Max Sherman (Wilson and Sherman 2013), Max Sherman of LBNL provides a summary of this direction:

> Q. *Of course, ventilation is a primary method for improving indoor air quality because it can reduce or dilute environmental pollutants. However, ventilation standards such as ASHRAE 62.2 don't consider specific removal of the priority pollutants. How would we benefit from revising the ASHRAE 62.2 standards to incorporate a health-based indoor air quality standard, and how might that work?*
>
> A. *ASHRAE 62.2 provides guidance for a ventilation rate based on a particular type of building and other factors, but a health metric isn't part of that calculation. Incorporating a health metric such as DALYs [disability adjusted life years] into the standard would allow designers and builders to consider the building materials used and other factors when determining ventilation rates. If it were clear that those factors showed lower indoor emissions, then a lower ventilation rate could be used; if not, you'd use a higher rate. ...*

In the same article Sherman notes that ASHRAE Standard 62.2 revisions are made on a three-year cycle and the health-based approach will be incorporated into the next (2016) version of the Standard.

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EXHIBIT C

The History of Ventilation and Temperature Control

The First Century of Air Conditioning

This is the eleventh article in a special series that commemorates a century of innovation in the HVAC&R arts and sciences.

By John E. Janssen
Fellow/Life Member ASHRAE

The results of a 10-year study of schools in New York provided guidance on ventilation to schools throughout the United States.

When man brought fire into his abode, he discovered the need to have an opening in the roof to let out the smoke and to supply air to keep the fire burning. Control of combustion provided the first incentive for the ventilation of a space. Because the fire warmed the space to a more comfortable temperature, thermal comfort was intimately linked to ventilation.

The ancient Egyptians observed that stone carvers working indoors had a higher incidence of respiratory distress than those working outdoors did. They attributed this to a higher level of dust in the indoor workspace. Thus, control of dust was the second recognized need for ventilation.[1]

The Romans negated the need for indoor fires when they invented radiant heating. Hollow tiles under the floors of their buildings ducted hot combustion products from "stoves" around the periphery of the buildings, through the floor tiles to a smokestack.

They developed a preferred ratio of window to floor area for daylighting. Oiled parchment over the window openings led to high infiltration. Later, the Venetians devised a method for making flat glass for windows.

In the Middle Ages, people began to realize that air in a building could somehow transmit disease among people in crowded rooms. Homes and small buildings were heated with open fires in fireplaces. Smoke often spilled into the room and poisoned the air. King Charles I of England in 1600 decreed that no building should be built with a ceiling height of less than 10 ft (3 m), and that windows had to be higher than they were wide. The objective was to improve smoke removal.

Research began to address the question, "What constitutes bad air?" In the 17th century, Mayow (cited by Michael Foster, 1902) placed small animals in a confined bottle with a burning candle.[3] The candle flame was extinguished before the animal was asphyxiated. An animal survived about half again as long without the candle. He concluded that the "igneo-aerial particles of the air" were the cause of the animals' demise.

One hundred years later (1775) Lavoisier, the father of gaseous chemistry, identified Mayow's igneo-aerial particles as carbon dioxide (CO_2). Lavoisier began his study of oxygen and carbon dioxide in the air of crowded rooms in 1777. He concluded that excess CO_2—rather than a reduction of oxygen—caused the sensations of stuffiness and bad air. The hypothesis was that excess CO_2 in the lungs interfered with their ability to absorb CO_2 from the blood. The argument as to whether "bad air" was caused by oxygen depletion or excess carbon dioxide continued for many years. Pettenkofer (1862) concluded that neither oxygen nor carbon dioxide were responsible for bad air. Rather, biological contaminants were responsible for vitiation of the air.[4] He believed, as did Saeltzer (1872) and others, that CO_2 was a useful surrogate for vitiated air.[5]

About the Author

John E. Janssen chaired Standards Project Committee (SPC) 62, which developed ANSI/ASHRAE Standard 62–1989, *Ventilation for Acceptable Indoor Air Qualtiy* and also served on the SPC that wrote Standard 62–1981. Until his retirement, he was a principal research fellow at Honeywell. Janssen has authored several Journal articles, including "The V in ASHRAE, An Historical Perspective" as part of ASHRAE's Centennial series.

Minimum Ventilation

According to Klaus (1970), a Cornish mining engineer, T. Tredgold (1836) published the first estimate of the minimum quantity of ventilating air needed. He calculated from the breathing rate that a subject needed 800 in.^{3}/min. of unvitiated air to purge the CO_2 from his lungs.[4] He also calculated 5,184 in.^{3}/min. for body moisture removal and 432 in.^{3}/min. for the miner's candle giving a total of 6,415 in.^{3}/min or about 4 cfm (2 L/s). These calculations, based on measured flow rates, did not consider the CO_2 or moisture concentration exhaled by the occupants. Tredgold's estimate was intended to satisfy metabolic needs, but it erred on the side of too little ventilation for comfort.[5]

Thomas Tredgold published the first estimate of the minimum quantity of ventilating air needed.

Subsequent efforts to provide quantitative guidance for ventilation of buildings have ranged from Tredgold's estimate to more than 30 cfm (14 L/s) per occupant as shown in *Figure 1*. There was a growing dichotomy in the objectives for ventilation. Should the objective be based on physiological needs or on comfort factors?

Klaus states that the most authoritative American work just before the turn of the century was *Ventilation and Heating* by J. Billings (1893).[6] Billings, a physician, believed that CO_2 was an accurate measure of impurity emissions from the human body. He calculated that 50 cfm of ventilating air would be needed to keep the room CO_2 level to 550 ppm if the exhaled respiration was limited to a concentration of 200 ppm.

Some people believed that 10 cfm (4.7 L/s) of ventilation air was sufficient. Billings argued for a 30 cfm (14 L/s) minimum and recommended 60 cfm (28 L/s). He was concerned with the spread of disease, especially tuberculosis. According to Klauss, ASHVE in 1895, "adopted the view that engineers were ready to accept the ideas of hygienists and physiologists." They recommended 30 cfm (14 L/s) per person as the minimum ventilating rate. This required mechanical ventilation and placed responsibility for system design and construction on the engineers.

For several centuries, there had been two schools of thought with respect to ventilation. Architects and engineers were concerned with providing comfort and freedom from noxious odors and the debilitating effects of oxygen depletion and/or carbon dioxide accumulation. Physicians, on the other hand, were concerned with minimizing the spread of disease. During the Crimean War, 1853–55, and a few years later in the U.S. Civil War, it was observed that there was a greater and faster spread of disease among wounded soldiers in crowded hospitals with poor ventilation. Wounded soldiers fared better when they were housed in tents or barns. Physicians wanted more ventilation to reduce the spread of disease. Thus, Billings based his recommendation of 60 cfm (28 L/s) of ventilation air per person on his concern for disease; whereas 30 cfm (14 L/s) was adequate for comfort. Thirty cfm of outdoor air per person was written into Massachusetts law in the 1880s. ASHVE adopted a minimum ventilation rate of 30 cfm (14 L/s) per occupant in 1895 and proposed a model law with this rate in 1914.

Steam heating systems were developed after the Civil War. Ventilation to control odors and reduce disease became an integral part of heating equipment. It was becoming clear that overheating was a key part of the sense of poor ventilation. Although desired ventilation rates were being debated, suitable equipment was not yet available to provide the rate needed.

Temperature Effects

The report of the New York State Commission on Ventilation (1923) found that work by Hermans (1893) in Amsterdam had concluded that the negative reaction to poorly ventilated rooms was probably caused by thermal effects, i.e., temperature and humidity. Hermans appears to be the first to blame poor indoor air quality on thermal effects. His hypothesis was that excess temperature interfered with body heat loss and produced physiological effects on a person confined in a poorly ventilated room. This hypothesis was not widely endorsed, but Billings, et. al (l898) did find that the "two great causes of discomfort, though not the only ones, are excessive temperature and unpleasant odors."[7]

Flugge (1905) and his pupils, Heyman, Paul and Ercklentz at the Institute for Hygiene in Breslau, Germany confirmed these hypotheses through a series of experiments. This work was confirmed later in England by Hill and Haldane (1905, 1907, 1913).[8]

Flugge's endorsement of Billings' recommendation of 30 cfm (14 L/s) per occupant of outdoor air was soon adopted by state building codes. Massachusetts had already promulgated such a code in the 1880s. By 1925, 22 states required a minimum of 30 cfm (14 L/s) per occupant of outdoor air. This necessitated mechanical ventilation, which was made possible by the development of the electric power industry.

Some investigators experimented with recirculated air for part of the supply.

There was a growing resistance to heating large quantities of outdoor air for ventilation. Recommended ventilation rates sometimes failed to discriminate between the outdoor airflow rate and the total supply.

Arguments persisted as to whether the effects of poor air quality came from excess carbon dioxide, excessive temperature or biological emissions. The *Department Committee Appointed to Enquire into the Ventilation of Factories and Workshops Report* (1907) in England reported on the effects of restricted ventilation.

Seventeen subjects were kept—for periods of two hours to 13 days—in small, 189 ft^3 (5 m^3) chambers. Air was circulated slowly while temperature was controlled externally. Carbon dioxide was usually more than 3,500 ppm (0.35%). During the daytime when the subject was active, the CO_2 was more than 10,000 ppm (1.0%), and at one time it reached 23,100 ppm (2.3%).[2] Subjects felt comfortable as long as the chamber was kept adequately cool.

Other tests reported by the Departmental Committee on Humidity and Ventilation in Cotton Weaving Sheds (1909, 1911) confined subjects in an uncooled chamber of 106 ft^3 (3 m^3).[9] Carbon dioxide reached 3% to 4%, oxygen fell to 17%, and the wet-bulb temperature rose to 80°F to 85°F (27°C to 29°C). Breathing was deepened by the high CO_2. These rather bar-

baric experiments exonerated CO_2 as a contaminant of concern. However, the fact is that CO_2 is dangerous at concentrations of 3% to 4%, and it is lethal above 5%.

Chicago/ASHVE

The Chicago Department of Health succeeded, in 1910, in having a commission appointed to study ventilation of school buildings. The commission included ASHVE, the Chicago Public School System and the Chicago Department of Health. Their report (1914) concluded that carbon dioxide was "not the harmful agent of major importance in expired air or air otherwise contaminated;" that the temperature of 68°F (20°C) with proper humidity control is desired in artificially heated living rooms; that the then current state of knowledge was insufficient to designate all harmful factors; and, "that from the standpoint of health, relative humidity is one of the important factors in ventilation." ASHVE wrote a model code in 1914 with a minimum ventilation rate of 30 cfm (14 L/s) per occupant of outdoor air.[10]

New York Study of Schools

A study by the New York State Commission of Ventilation in schools began in 1913. During the next ten years various ventilation systems, occupant response and incidence of disease and fuel consumption were studied in 216 classrooms in schools in New York, Springfield, Mass., Fairfield, Conn., and Minneapolis, Minn.

The ventilating systems in two rooms in PS51, Bronx, N.Y. were modified to experiment with various methods of circulating the ventilating air. The resulting report (1923) concluded that overheating was the single most annoying factor in the indoor environment. A window-ventilated room with a natural draft (gravity) exhaust from near the ceiling of an inside wall was the preferred method. It produced substantially less than the recommended ventilation rate of 30 cfm (14 L/s) per occupant. Fan ventilation with supply at the ceiling and exhaust at the floor was the next best. Window-ventilated rooms at a temperature from 59°F to 67°F (15°C to 19°C) had the lowest rate of respiratory illness. Fan ventilation with a temperature of 70°F (21°C) produced 18% more absences and 70% more respiratory illnesses. It was postulated that the more uniform air conditions (i.e., better mixing) with fan-induced circulation increased the rate of the spread of airborne disease. Sixty-eight degrees Fahrenheit (20°C) was believed the ideal temperature for comfort and minimizing the spread of disease.

Ventilation through open windows had to be constrained by outdoor conditions. Noise, dirt, odors or other emissions from the streets could make window ventilation unattractive. Fan ventilation was preferred. In addition, window-ventilated rooms required radiation under the windows and deflectors to prevent cold drafts.

Recirculation was unacceptable because of odors, even when the recirculated air passed through an air washer. This conclusion appears to have been based on 100% recirculation. The possibility of partial recirculation with air washing was suggested as possibly acceptable.

The results of this project became a guide for schools throughout the United States. Using proper temperature control meant that the ventilating rate could be reduced below 30 cfm (14 L/s) of outdoor air per occupant. Yet in 1922, 22 states had building codes requiring 30 cfm (14 L/s).

The ASHVE Laboratory

Heating and Ventilating Magazine, April 1917, stated that, "ASHVE President Lyle appointed a committee to investigate the matter of establishing a bureau of research to be conducted under the auspices of the society," John Bartlett Pierce, a founder and vice president of the American Radiator Co. provided funds to establish the John B. Pierce Foundation for technical research in heating, ventilating and sanitation, "to the end that the general hygiene and comfort of human beings and their habitations may be advanced." These funds provided the initial support for the ASHVE Bureau of Research. The John B. Pierce Laboratory was established later at Yale University.

The ASHVE Bureau of Research was established in January 1919 at the U.S. Bureau of Mines Laboratory in Pittsburgh. At that time, some government laboratories were available for privately funded work. John R. Allen, dean of the college of engineering at the University of Minnesota, was the first director of research. He acquired a research staff and began research to establish heat transfer from radiators, heat transfer and air leakage rates through building wall sections and components, and studies of outdoor air quality in various cities, Allen died suddenly in 1920, so Dean Scipio continued as acting director for one year. F. Paul Anderson, dean of engineering at the University of Kentucky, took a leave of absence to become director of the ASHVE laboratory from 1921 to 1925.

The founders Group for ASHVE Research (from an early Society publication). Starting at the top (clockwise) John R. Allen, F. Paul Anderson, A.C. Willard, F.C. Houghten and L.A. Scipio.

He hired several outstanding research people to continue and extend the work underway. Among these was a former student from Kentucky, Margaret Ingels. She was one of the first female members of ASHVE, and one of the first American women to receive a degree in mechanical engineering.

Margaret Ingels was one of the first women to join ASHVE research.

Ingels had wanted to study architecture, but the University of Kentucky offered no courses in this field. Instead, she opted for mechanical engineering, and graduated with a bachelor's degree in 1916. She joined Carrier Engineering in Newark, N.J.

They were pioneering the air conditioning of buildings. Carrier was developing the technology of humid air and had air conditioned a printing plant in 1902. Carrier had published a pioneering ASME paper on psychometrics in 1911. Ingels received a master's degree in 1920 on the basis of her experience and a thesis. One of the main air contaminants of concern was dust. Ingels worked on filtration of dust from air. She left the ASHVE Laboratory and joined her old boss at Carrier in 1929. There she worked on the marketing of air conditioning. This was directed at home air conditioning after World War II.

The laboratory, under the direction of John Allen, had hired F.C. Houghten, O.W. Armspach, Louis Ebin and Percy Nichols. Houghten went on to become a director of the lab. Armspach helped develop the dust spot meter and measured human body heat loss rates. Ebin published tables on heat transfer rates for radiators and also determined steam flow rates in one- and two-pipe steam heating systems. Allen contracted with F.B. Rowley and A.B. Algren, professors at the University of Minnesota, to measure wall heat transfer factors and air leakage rates through walls and building components. A heat flow meter invented by Percy Nichols was used in this work. These data that were published in the ASHVE Guide and Handbook are still used today. From 1921 to 1925, C.P. Yaglou worked at the lab on problems of ventilating spaces and the interaction of human occupants with their environment. He continued his work as instructor in ventilation and illumination at the Harvard School of Public Health.

Lemberg/Yaglou Research

In a laboratory environment, W.H. Lemberg, et. al. (1935), under contract from ASHVE, measured the minimum ventilation requirement using the human nose as the sensor. The olfactory nerves of the nose are exceedingly sensitive.[11] Pierce (1935) reported that a concentration of 5 × 10^{-7} mg of oil of rose per cm^3 of air can be distinctly smelled.[12] The odor of butyric acid can be detected at a concentration of 9 × 10^{-6} mg/cm^3 of air. When exposed to an odor, the olfactory sensors rapidly become saturated and lose sensitivity. It is necessary, therefore, to precondition the judge in clean air before he briefly sniffed the unknown atmosphere to be measured. Under these conditions, human judges using their sense of smell became reliable instruments for measuring odor level. The response to odor was found to be logarithmic—as is the response of the human ear and eye.

Lemberg, Brandt and Morse, all graduate students at Harvard devised an odor intensity scale ranging from zero—no perceptible odor to five—overpowering (nauseating). An index number of two was defined as a moderate odor and was deemed to be acceptable.

A box 20 in. by 20 in. by 6 ft long (0.5 by 0.5 by 1.8 m) long was used as a test chamber. It was ventilated by temperature controlled air entering at one end and exiting at the other end. Judges sampled the odor through holes in the exhaust pipe.

Ten subjects were placed in the box, one at a time, and 15 trained judges performed experiments at ventilating rates ranging from 1 cfm to 50 cfm (0.47 L/s to 24 L/s) per occupant. They found the odor to be acceptable (index no. 2) at 65°F to 72°F (18°C to 22°C) and 20 cfm (9 L/s) per person. When the temperature was raised from 79°F to 86°F (26°C to 30°C), the ventilation had to be increased to 30 cfm (14 L/s).

Yaglou, Riley and Coggins (1936) continued a more exhaustive study at Harvard.[13] A room having a floor area of 155 ft^2 (14 m^2) and a ceiling height of 9 ft, 2.5 in. (2.8 m) was used. An adjoining room of identical dimensions was used as a judge's control room. All windows were weather stripped and cracks were sealed. The judge's room was ventilated at a rate of 50 cfm (24 L/s) per occupant to precondition the judges' sense of smell. A judge entered the test room with a "clean" nose, sniff the air in the test room to measure its odor, render a judgment, and return to the odor-free preconditioning room where his sense of smell was restored.

The test room was occupied by 3, 7 or 14 subjects giving an air space of 470 ft^3, 200 ft^3 or 100 ft^3 (13 m^3, 6 m^3, 3 m^3) per occupant respectively. The ventilation airflow was varied from 2 cfm to 30 cfm (0.9 L/s to 14 L/s) per occupant. The temperature and humidity of the two rooms were kept the same, but it was necessary to keep the ventilation rate of the preconditioning room at 50 cfm (24 L/s) per occupant to approximate a zero odor condition.

Men and women within an age range of 16 to 60 years, grade school children 7 to 14 years of age, laborers, school children of lower socioeconomic class and children of a higher class comprised the groups studied.

Yaglou and his associates found a strong correlation between the required ventilation rate and the net air space per occupant. For example, at 150 ft^3 (4 m^3) per person, 20 cfm (9 L/s) of outdoor was needed to control the perceived body odor to an acceptable level of 2 on Lemberg's scale. If the occupant density was reduced to the equivalent of an air space of 300 ft^3 (8 m^3) per occupant, ventilation was reduced to 12 cfm per occupant for sedentary adults. Grade school children required 25 cfm (12 L/s) at 150 ft^3 (4 m^3) per child and 17 cfm (8 L/s) at 300 ft^3 (8 m^3) per child. Fifty percent more ventilation was required if children had gone 6.5 days without a bath and change of underwear. Only a 33% increase in ventilation was required for adults a week after a bath.

Untreated recirculated air was found to have no effect on odor density, but washing, humidifying, cooling and dehumidifying recirculated air were all beneficial in reducing the outdoor air requirement. Twelve cfm of outdoor air in the total supply of 30 cfm (14 L/s) was acceptable for sedentary adults if there was at least 200 ft^3 (6 m^3) of air space per person. There were significant differences due to children vs. adults, socioeconomic class, and air space per occupant. Subsequent research by Cain, et. al. (1983)[14] and Berg-Munch, et. al. (1984)[15] confirmed most of Yaglou's work except for the effect of air space per occupant. This difference has not been fully explained.

Ventilation Code

W.H. Carrier's work in building air conditioning, beginning in 1902, generated a need for thermal comfort and ventilation requirements by 1920. Measurements of occupant response to their environment by Yaglou, Houghton, Riley, Coggins and others provided a growing body of knowledge. A code of "Minimum Requirements for Heating and Ventilation of Buildings" was published in the ASHVE Guide in 1925. The code was updated as new data became available, especially in 1938. Yaglou began to develop the comfort chart in 1925. The code provided a minimum ventilating rate of 10 cfm (4.7 L/s) per person for the 1946 American Standards Association (ASA) lighting standard.

ASHRAE Standards

The ASHVE research yielded a body of knowledge that led to ASHRAE Standard 55 for thermal comfort and Standard 62 for ventilation. The first, ANSI/ASHRAE Standard 62-1973, *Standards for Natural and Mechanical Ventilation,* presented minimum and recommended ventilation rates for 266 applications and became the basis for most state codes. The standard was updated in 1981 and again in 1989. A conflict with the Tobacco Institute and the Formaldehyde Institute concerning the way the standard treated tobacco smoke and formaldehyde vapor prevented its adoption. Subsequent research on odor made it necessary to raise the minimum ventilation rate so that these conflicts disappeared in the 1989 issue. Standard 62-1989, *Ventilation for Acceptable Indoor Air Quality* is widely used.

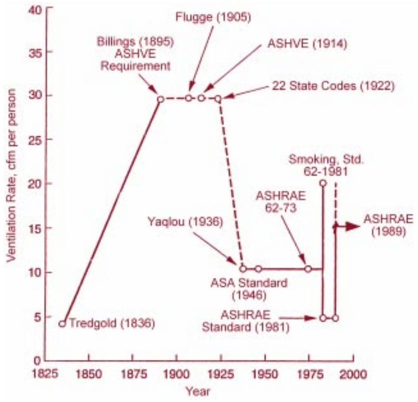

Figure 1: Minimum ventilating rate history.

ASHVE research led to a comfort chart that correlated temperature, humidity and comfort response. It was first published in the *ASHVE Guide* in 1924, and it continued to be published in the guide until 1974 when ASHRAE published Standard 55-1974, *Thermal Comfort*. Subsequent editions of that standard were published in 1981 and 1992. The comfort chart has been modified to reflect the response due to clothing, heating/cooling system designs, and living habits.

Many papers have argued the cost/benefit of outdoor air for ventilation. T.R. Tiller (1973) of Kohloss and Tiller argued this point from an Australian point of view.[16] A high dust content in desert climates sometimes makes return air preferable to outdoor air. Indeed, Standard 62-1989 says that the outdoor air should meet the U.S. Outdoor Air Quality Standard or be treated to do so. The standard mainly is concerned with dilution of indoor-generated contaminants.

W. Cain, et. al (1983) and P.O. Fanger, et. al, (1983) published results of new studies that generally confirmed Yaglou's early results. Cain working at Yale University and Fanger at the Technical University of Denmark both agreed that 15 cfm (7.5 L/s) of outdoor air was needed to dilute occupant odors to a concentration acceptable to 80% (20% dissatisfied) of the "visitors" entering an occupied space. These new data did not, however confirm Yaglou's dependence on air space. Thus, Standard 62-1989 adopted 15 cfm (7.5 L/s) per occupant of outdoor air as the minimum (see *Figure 2*).

Janssen (1986)[17] found, based on work by Leaderer and Cain (1983) [18] and Thayer (1982) [19] that 15 cfm (7.5 L/s) of outdoor air per occupant was sufficient to reduce the concentration of tobacco smoke to a level acceptable to 80% of the population at today's reduced smoking rate. Thus, Standard 62-1989 did not discriminate between smoking allowed and smoking prohibited. The new standard did, however, require more ventilation for applications such as bars, cocktail lounges, and smoking lounges where smoking activity is expected to produce higher levels of tobacco smoke.

Whether or not carbon dioxide is a surrogate for occupant odor, a health risk, or of no concern is not adequately answered today. Should the CO$_2$ level be limited by comfort or only by health risk? Early investigators thought CO$_2$ was a useful surrogate but not a health risk. Yaglou thought it was a poor indicator because of its non-linear response with odor. Ernest B. Sangree, M.D. (1894) reported that when out walking on a cold day he restored warmth to his body, his hands, and his feet by breathing deeply and holding his breath as long as possible. One may speculate that this increased the CO$_2$ in his lungs. Carbon dioxide is known to influence metabolic rate and is a vasodilator that dilates the capillaries in the skin. Thus, it increases the heat available and circulate it to the extremities.

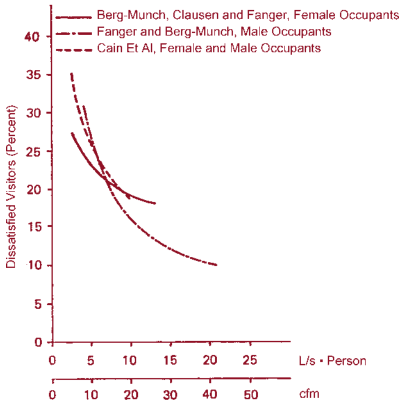

Figure 2: Odor acceptance.

Janssen, et. al (1984) studied the response of school children to CO$_2$-controlled ventilation. A polarized questionnaire devised by Woods, et. al (1982) was used.[20] When the CO$_2$ in the room rose to 1,600 ppm (0.16%) the children (ages 12 to 15) voted the air more "stuffy," more stagnant, about 2°C (3.6°) warmer, and their hands and feet warmer with respect to their bodies. No correlation existed at 1,000 ppm (0.1%) when the outdoor air was raised to 15 cfm per student. Standard 62-1989 accepted 15 cfm (7.5 L/s) as the lowest permissible ventilation rate under the Ventilation Rate Procedure. Some believe (ASHRAE/ANSI Standard 62-1989) that carbon dioxide is a useful surrogate for occupant-generated biological contaminants. Some stress may exist in concentrations of 1500 ppm (0.15%), but it is not known if this is harmful.

One problem not yet adequately solved, is the ventilation of schools in warm, humid climates. The high latent load on cooling systems poses a cost penalty. Efforts are under way to determine what degradation of the indoor environment occurs if the ventilating rates are reduced.

Kansas State Laboratory

The ASHRAE Board of Directors decided (1961) that it would be more economical to move the research lab to Kansas State University and contract for work at Kansas State or other laboratories. The temperature-controlled room was moved from Cleveland to Manhattan, Kan. and placed under the direction of Professor Ralph G. Nevins. Technical management of projects was placed under a new society Research and Technical committee. This has worked well.

Summary

Natural ventilation through operable windows was the only means of ventilating buildings prior to the development of the electric power industry in the late 19th century. The B.F. Sturtevent Co. of Boston did develop a steam engine-powered centrifugal blower in the 1880s, but this was useful only during the heating season. Overheating of buildings was recognized as the single most critical problem. Proper distribution of heating and ventilating air exacerbated the overheating problem.

Thermostatic controls were invented in the 1880s, but these also suffered from the lack of a power source. Thus, it was not until electric power became generally available early in the 20th century that the desired ventilating rates and temperature control could be achieved. As late as 1920, the relative location of open windows and room exhausts were still studied. The expansion of air conditioning in the 1930s made natural ventilation obsolete.

We now have a good idea of what ventilation rates should be and what the desired temperature and humidity conditions are. The oil embargo of 1974 has brought attention energy use. Today systems must be designed and operated to achieve a proper balance among therma1 comfort, air quality and energy consumption.

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EXHIBIT D

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ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Review of Residential Ventilation Technologies

Marion Russell, Max Sherman and Armin Rudd

August 2005

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Abstract

This paper reviews current and potential ventilation technologies for residential buildings with particular emphasis on North American climates and construction. The major technologies reviewed include a variety of mechanical systems, natural ventilation, and passive ventilation. Key parameters that are related to each system include operating costs, installation costs, ventilation rates, heat recovery potential. It also examines related issues such as infiltration, duct systems, filtration options, noise, and construction issues. This report describes a wide variety of systems currently on the market that can be used to meet ASHRAE Standard 62.2. While these systems generally fall into the categories of supply, exhaust or balanced, the specifics of each system are driven by concerns that extend beyond those in the standard and are discussed. Some of these systems go beyond the current standard by providing additional features (such as air distribution or pressurization control). The market will decide the immediate value of such features, but ASHRAE may wish to consider related modifications to the standard in the future.

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Introduction

The purpose of ventilation is to provide fresh (or at least outdoor) air for comfort and to ensure healthy indoor air quality by diluting contaminants. Historically people have ventilated buildings to provide source control for both combustion products and objectionable odors (Sherman, 2004). Currently, a wide range of ventilation technologies is available to provide ventilation in dwellings including both mechanical systems and sustainable technologies. Most of the existing housing stock in the U.S. uses infiltration combined with window opening to provide ventilation, sometimes resulting in over-ventilation with subsequent energy loss; sometimes resulting in under-ventilation and poor indoor air quality. Based on the work of Sherman and Dickerhoff (1998), Sherman and Matson (2002) have shown that recent residential construction has created tighter, energy-saving building envelopes that create a potential for under-ventilation. Infiltration rates in these new homes average 3 to 4 times less than rates in existing stock. As a result, new homes often need provided ventilation systems to meet current ventilation standards. McWilliams and Sherman (2005) have reviewed such standards and related factors.

According to ASHRAE standard 62.2-2004, published by the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE, 2004), single, detached residential buildings are required to meet a whole house ventilation rate based on the number of bedrooms in the house, the number of occupants, plus an infiltration credit (3 cfm per 100 sq. ft plus 7.5 cfm per additional occupant which includes a 2 cfm per 100 sq. ft allowance for infiltration). There are a variety of ways to meet this standard either through mechanical systems or via natural forces.

According to Home Energy Magazine May/June 2000, "<u>good ventilation system should:</u>

- Provide a controlled amount of unpolluted outdoor air for both comfort and dilution
- Have at least a 15 year life
- Be acceptable to operate by occupants (low noise, low cost)
- Not detract from the safety and durability of the house."

This paper will review both mechanical and sustainable ventilation technologies and the factors that affect their effectiveness. Mechanical technologies must include:

- Continuous exhaust systems
- Intermittent exhaust systems
- Exhaust with make-up air inlets
- Intermittent or continuous local exhaust with make-up air from inlet in return
- Continuous supply
- Intermittent supply with inlet in return side of HVAC System
- Combined exhaust and supply (Balanced)

Sustainable technologies, which are those whose motive forces are principally temperature difference and wind, are reviewed in the second section and include:

- Infiltration with operable windows
- Passive Stack Ventilation
- Solar Chimney
- Hybrid Systems

The effects of incidental ventilation provided by infiltration and operable windows are discussed. Finally, a variety of factors that can affect the ventilation effectiveness are discussed in the third section including cost and energy use, air cleaning and filtration, construction quality, control systems, and duct systems.

Mechanical Whole-house Ventilation

There are a variety of mechanical whole-house ventilation systems including exhaust, supply and balanced systems. Any of these may be in continuous operation or operate intermittently, they may be single-port or multi-port, or the system may be integrated into an existing HVAC system. Mechanical ventilation strategies provided more uniform ventilation rates than natural ventilation (Hekmat, Feustel and Modera, 1986). Properly designed mechanical systems provide good control over ventilation rates when compared to most other ventilation systems; however, additional energy is required to operate the system. Holton, J.K., M.J. Kokayko, and T.R. Beggs (1997) compared ventilation systems in new production built homes and found infiltration rates ranging from 0.1 to 0.07 air changes per hour in the summer and 0.35 to 0.15 ACH in the winter. As a result, they recommend modern houses include a mechanical ventilation system. Researchers have studied various configurations of exhaust, supply, and balanced ventilation systems, with and without whole-house re-circulation by the central heating and cooling air handler fan.

Continuous exhaust

A continuous whole-house exhaust system provides ventilation by using a single-point or multi-point central fan to remove air from the building (Concannon, 2002). Supply air enters the building envelope through gaps or provided vents (see Figure 1). If the building envelope is tight, there is a possibility that negative pressure can be created inside the building leading to back drafts from combustion (open flue) appliances. Often these systems incorporate a pressure relief damper to alleviate pressure imbalances. Supply air enters the building in an uncontrolled manner and may be pulled in from relatively undesirable areas such as garages, musty basements (or crawlspaces) or dusty attics (Barley, 2002). Whole-house exhaust systems may not be appropriate in areas where levels of outside environmental contaminants are high. In the case of radon, researchers have found that exhaust systems may actually increase the indoor levels of contaminants. (Bonnefous, Gadgil, and Fisk, 1992). In severe climates, very cold supply air may create drafts, while in moist humid climate zones, exhaust only systems can cause moisture damage to the building structure. Filtration cannot be sensibly added to an exhaust only ventilation system, unless one considers the building envelope as part of the filtration system.

Heat recovery can be added to exhaust systems. Passively, the building envelope itself can provide some heat recovery (Walker and Sherman, 2003), and is also partially effective at removing ozone. More actively, an exhaust air heat pump can be used to recover the energy in the exhaust air stream.

The Home Ventilating Institute(HVI) lists a large variety of fans that can meet current ASHRAE standards for ventilation rates if properly installed. However, several factors (such as the tightness of the building envelope, size, quality of ductwork, and placement of ducting, among others) can have a significant effect on whether the installed fan can provide the indicated ventilation rate. These fans can potentially provide ventilation rates from 50 to over 5000 cfm. Most of the operating costs result from conditioning the supply air rather than the energy to operate the fan. The HVI directory lists the energy use for only a small percentage of the fans, with typical power consumption of about 3.5 cfm/W. Wray (2000) found that from most perspectives exhaust-only mechanical ventilation systems are the most inexpensive of mechanical systems to operate .

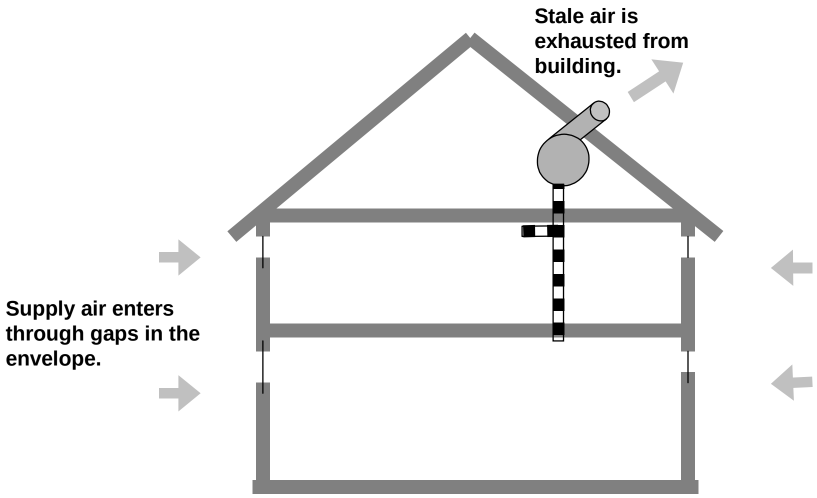

Figure 1. Mechanical exhaust system with supply air entering through the building fabric in an uncontrolled manner.

Single-point exhaust systems

A single point exhaust system is often an upgraded bathroom fan (e.g. Figure 2). Construction and installation costs are the lowest of mechanical systems. (Concannon, 2002) Only one fan and possibly some simple ducting are required to exhaust the air to the outside. In some cases, the fan can be installed in an exterior wall eliminating the need for extensive ductwork. Single-point ventilation systems suffer from a non-uniform distribution of fresh air especially to closed rooms. (Rudd, A. 2000.) In an evaluation of five mechanical ventilation systems, Reardon and Shaw (1997) found local exhaust only strategies that depended on kitchen and bathroom fans to provide whole-house ventilation provided only marginally better performance than infiltration alone. This simple system suffered from a poor distribution of supply air; the lower room received all the supply air while the upstairs rooms (bedrooms) did not receive enough air to meet the applicable ventilation code. Standard 62.2, however, has no distribution requirement; so this is not an issue for a minimally compliant system, but it is nevertheless a consideration.

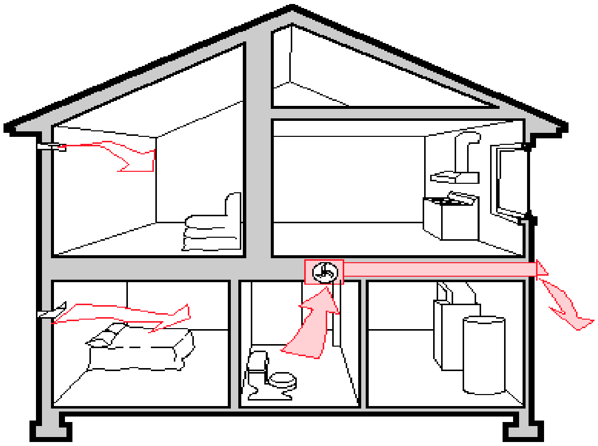

Figure 2. Example of a single-point local exhaust system with makeup air inlets (Oikos Green Building Source, 1995). Air inlets are needed only for tight building envelopes.

Multi-point exhaust systems

Multi-point exhaust systems are an improvement over single-port exhaust systems in that they improve the room-to-room uniformity of the whole-house ventilation, but there is the extra cost of installing the ductwork (Rudd, 1999). One exhaust fan is ducted to many rooms of the house and may be remotely installed to reduce noise levels. In a comparison of ventilation systems, Reardon and Shaw (1997) found that if a centralized exhaust system is used with pick-up grilles in each room of the house instead of a local exhaust system, air was distributed evenly throughout the house even to closed bedrooms.

Intermittent exhaust

An intermittent exhaust system is installed similar to a continuous exhaust system; generally it consists of one central fan to remove stale air from the building, but may also incorporate several fans in areas of high sources (*i.e.* bathrooms and kitchens). In this case, the fan(s) runs only part of the time at a higher rate and are sized to provide the necessary ventilation. The rate of ventilation when the system is operated intermittently must be larger than if it were operating continuously (Sherman, 2004). There are several advantages for using intermittent ventilation systems. The occupant can reduce the amount of outdoor air entering the building during periods of the day when the outdoor air quality is poor. Peak load concerns may make it advantageous to reduce ventilation for certain periods of the day. When the ventilation system is integrated with the heating and cooling system, cyclic operation may also make more sense.

A timer can be used to control the fan which usually has a switch for the occupant to turn on when needed. The disadvantage here is that the occupant controls the ventilation and must be relied on to know when ventilation is needed. If the fan is noisy[1], the occupant may chose not to operate the system, which could result in under-ventilation. Many systems use a timer to automatically run the fan for a certain amount of time each day so that the occupant is not relied on to sense when ventilation is needed. However, the occupant often has control over a switch to turn the fan on high when extra ventilation is needed. More sophisticated (and costly) control systems are available including: CO_2 sensors, occupant sensors and humidity sensors. CO_2 and occupant controlled systems do not meet the current 62.2 unless those features are used to raise the ventilation over and above the minimum rates required by 62.2.

Our own experience has shown that installation and operating costs are similar to the continuous exhaust systems, but may exceed them if sophisticated control systems are installed. As with continuous exhaust systems, most of the energy requirements are for conditioning the supply air rather then fan operation. The potential exists to reduce energy consumption when compared to the continuous exhaust system if the intermittent system is used in conjunction with natural driving forces to provide adequate ventilation while reducing the energy required to condition outside air. For example, running the fan at night could reduce cooling costs. Also, the fan could be programmed to run during times when outside pollutant levels are low or alternatively to shut down the system when outside particulate or ozone levels are high. If time-of-use utility rates are locally in use, it may be possible to reduce operating costs by ventilating more during low-cost periods to allow reduced or even zero ventilation during high-cost periods.

Exhaust with make-up air inlets

This ventilation system uses fans as described above, but controls the entry of supply air into the dwelling by providing openings specifically for air supply (see Figure 3).

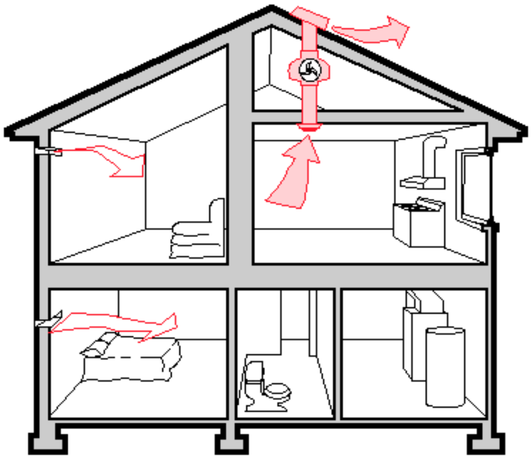

Figure 3. Inline exhaust fan with make-up trickle vents. (Oikos Green Building Source, 1995.) Trickle vents are needed when the building envelope is tight.

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[1] If the system is Standard 62.2 compliant, ventilation fans should meet sound requirements and noise should not be a substantial issue.

These trickle vents or louvers can be located in rooms that need extra ventilation such as the bathroom. Again, filtration of the supply air is not possible with this system; however the entry point of the supply air can be controlled to provide cleaner air by installing trickle vents away from polluted areas such as garages, musty basements or dusty attics.

Trickle vents are not necessary to meet 62.2 per se, but may be needed in exceptionally tight construction to reduce depressurization and related issues. They are commonly used as part of European systems both because of the tight construction and to assure that habitable rooms have individual air supplies.

Local exhaust with make-up air integrated in HVAC system

This method builds on the exhaust systems described above, but uses an air inlet in the return duct system of the air-handling unit of the HVAC system. This would use the existing duct system to extract air from individual areas of the building. Because existing ductwork would be used, marginal installation costs can be kept very low. This system can provide uniform ventilation throughout the house and may be operated intermittently or continuously. There is the added operating expense running the central fan when heating or cooling is not needed, which depends on climate and system sizing.

From the perspective of Standard 62.2 it is usually the exhaust system which is intended to comply with the standard. The make-up air system is intended to supply air distribution and reduce depressurization—both of which are beyond the minimum requirements of 62.2, but are often desirable. In principle, however, the make-up air system could be designed to meet 62.2 and the exhaust system used as a source control enhancement.

Continuous supply

Air is supplied by a central fan ducted to some or all of the rooms of the dwelling forcing stale air out through leaks in the building envelope. Continuous supply systems allow the occupant to control the location of the supply air to maximize air quality and give the occupant the option of filtering and/or conditioning the supply air (Building Science Corporation). This system creates a positive pressure inside the building, which has both advantages and disadvantages. The size of the pressure depends on the supply flow and the tightness of the envelope. A positive pressure prevents outside contaminants from entering the building, but it also can force moisture-laden air through the building fabric. In cold climates the moist air may condense in the walls of the building creating an environment for mold growth. Various studies have considered the use of whole house fans to provide night ventilation for cooling purposes (Santamouris, 2005). In these systems, air conditioning loads may be reduced up to 56% depending on the thermal preferences of the occupants.

Because outdoor air is often not in the thermal comfort zone, the temperature of supply air is a design concern for supply systems. Supply systems need to address this concern by conditioning or tempering the air in some way, during the periods when it would be perceived as unacceptable. One method, for example, is to mix the supply air with indoor air before it reaches the occupants. Standard 62.2, however, has no requirements for tempering.

Single-point Supply
In this strategy a supply fan provides fresh air via a small amount of ducting to a main room of the house. The air is distributed about the house by natural process. Often there is a return duct in a separate room. This system has low equipment costs; only the fan and a small amount of ducting are needed. However, the system suffers from a poor distribution of supply air especially to closed rooms in the house (Rudd, 2000) even compared to single-point exhaust. Tempering or conditioning of this air is almost always needed, if one wishes to avoid comfort complaints.

Multi-point supply
The multi-port system having the advantage of improving ventilation uniformity throughout the house, but with the extra installation cost of the ductwork. Because each supply is of a lower flow the needs for tempering or conditioning may be reduced. From the perspective of 62.2, however, there are no differences between single and multi-point supply systems.

Intermittent supply with inlet in return side of HVAC System

This system uses the existing central forced air system to supply fresh air in a distributed manner through the building's ducting. An inlet is placed in the return of the HVAC system to allow fresh air to enter when the air handler fan operates (see Figure 4). Integrating the supply air into the existing HVAC system provides a low cost option to supply and distribute fresh air through the existing duct system and is the ventilation system most acceptable to large production home builders (Rudd and Lstiburek, 2001). All mechanical ventilation systems benefited from intermittent operation of the central fan. This resulted in more uniformity of ventilation air distribution among the various rooms of the house (Rudd and Lstiburek, 2000).

By operating the system intermittently as opposed to continuously, Rudd (1999) estimated a 28% annual savings in total energy use. Computer modeling studies showed the cost-effectiveness of this system when compared to a separate supply ventilation system as well as the marginal costs of operation compared to no mechanical ventilation ($3 to $27 per year) (Rudd, 1998). They estimated it would take 10 years to recover the initial costs of a separately ducted supply ventilation system. The continuous and intermittent simulated systems had average outside air exchange rates of between 40 and 50 cfm, including the combined effects of ventilation and infiltration. These rates met 62-89, but would not meet the 62.2-2004.

These systems can create positive pressure in the house, so a pressure relief vent is often included. We (Rudd) more often see pressure relief achieved through the backdraft dampers of bathroom and kitchen exhaust fan ducting, as well as incidental leakage sites around windows and doors or other building enclosure penetrations. It is possible to add filtration to the supply air to remove contaminants. Installation costs are minimal for the return inlet itself; only a small amount of extra ducting and possibly a damper are required. Depending on the design, extra costs may be incurred for control devices and/or dampers.

Heat recovery potential for intermittent supply is low since heat exchange only occurs as the exhaust air exits via exfiltration through the building fabric. Currently available air handler fans are available to meet air flow rate standards in an energy efficient manner. Simple control systems are available to operate the system when the HVAC system is heating or cooling or to operate the system on a timer so that fresh air is supplied when heating or cooling are not required. (Walker and Sherman, 2003.) Energy efficiency is maximized when the entire air distribution system is airtight and located in a conditioned space (Rudd, 1998).

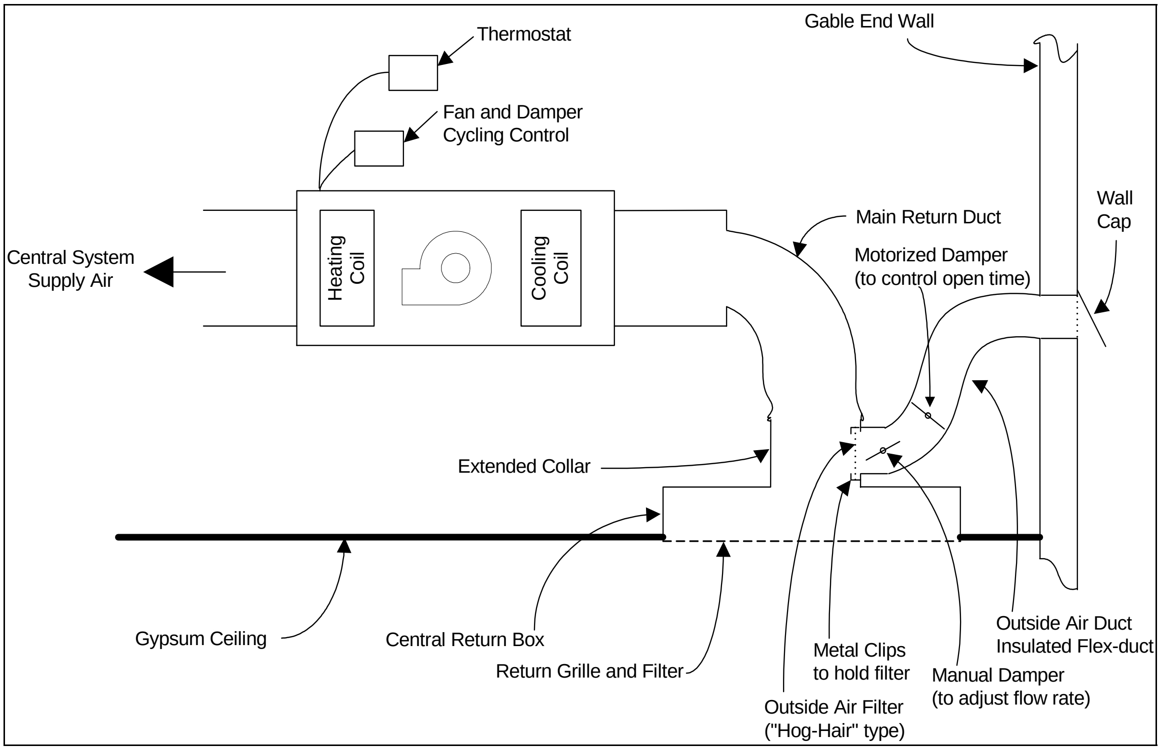

Figure 4. Example of supply ventilation integrated into the return side of an existing HVAC system (Building Science Corporation).

Combined exhaust and supply (Balanced)

A balanced ventilation system uses two fans with separate ducting systems, one to supply fresh air and one to remove stale air from the building (see figure 5). The system should not affect the pressure balance of the interior space unless the return path between the supply and exhaust is blocked. This ventilation strategy can be used effectively in any climate. It is possible to include a heat exchanger (or heat pump) to recover heat from the exhaust air and use it to precondition the supply air. Extensive ducting is used to supply fresh air to living and sleeping rooms, while a separate exhaust system removes stale often moist air from the kitchen and bathrooms. Advantages include pre-filtration of the supply air and energy savings from the heat recovery of the exhaust air. Some disadvantages include installation costs, maintenance costs (because there are multiple fans) and fan noise—for fans not meeting 62.2 noise requirements. Noise generated from the fan(s) and ducting system can be transmitted to each room of the house and reach 30 to 40dB. Veld. and Passlack-Zwaans (1998) describe various strategies for soundproofing including insulating ducts and preventing fan vibrations. Reducing noise from ventilation systems has a positive impact on indoor air quality by reducing the likelihood that occupants will block vents or turn off the system.

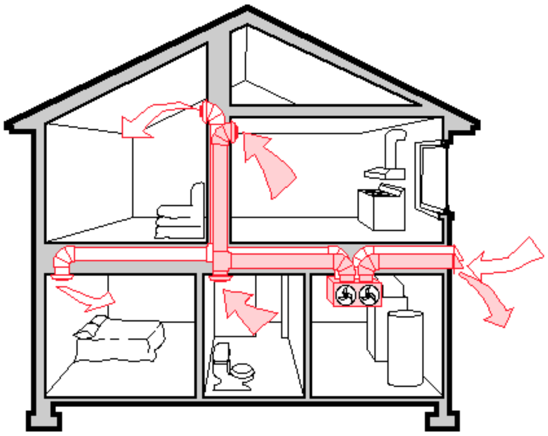

Figure 5. A Balanced ventilation system (Oikos Green Building Source, 1995).

Supply integrated into HVAC system with continuous exhaust
If the house has an existing central forced air system, it is possible to save on installation costs by integrating the supply inlet into the return of the HVAC system. A separate exhaust fan would run continuously to remove the stale air. This system can sometimes be problematic in humid climates where moist air is injected into cool supply air ducts resulting in condensation and independent humidity control may be required.

Supply integrated into HVAC system with intermittent exhaust
In this strategy (similar to the above) the exhaust fan would operate intermittently. Advanced control strategies can in principle be used to operate the exhaust fan only as needed to supplement the supply air to the return.

Houses Without Forced-Air Distribution Systems

Most new homes in the U.S. are built with forced-air systems, but not all. Houses with radiant, hydronic and/or baseboard systems may not have any central air distribution system and cannot use any of the HVAC-integrated systems discussed above. Any of the other systems, however, can be used to meet 62.2.

If air distribution is a concern, however, some systems may perform better than others for houses without forced air systems. If the building envelope is tight an exhaust system with trickle vents/air inlets can be used to assure that each room gets some outdoor air. Supply or balanced approaches require a dedicated distribution system (i.e. multipoint supply) in order to get good air distribution.

Sustainable Ventilation

Most of the systems described above focus on a mechanical ventilation solution. ASHRAE Standard 62.2 does not mention any other way to provided ventilation to new construction, but it does allow (section 4.1.2) alternative approaches if approved by a licensed design professional. There are, a variety of potential ventilation options that do not require fans. Here we examine such *sustainable* technologies with the understanding that they do not meet 62.2-2004, but they allow advanced solutions in the future.

Tradition: Infiltration with operable windows

Many existing homes rely on infiltration through a porous building envelope for background ventilation with operable windows to provide increased ventilation when needed. Natural climatic forces create differences in air pressure between the outside and inside of the building that can ventilate a building. Pressure differences depend on changes in temperature and wind speed. Wind causes a positive pressure on the windward side of the building and a negative pressure on the leeward side of the building (see figure 6). The resulting amount of ventilation is dependent on the placement and number of openings in the building envelope and on wind direction and speed. This makes the ventilation rate unpredictable and uncontrollable since the driving mechanism is variable over the year and the flow paths are diffused over the building envelope. (Allard, F. and Ghiaus, C. 2005.) The average ventilation rate my be predictable, but the average ventilation rate itself is not the key factor.

Sherman and Matson (1997) have shown that typical existing homes have an annual average air change rate of over one air change an hour due to infiltration; and this high rate can satisfy existing ventilation standards so that many existing homes do not need any extra ventilation system. Dwellings in cold, harsher climates and new residential construction are 3 to 4 times tighter, creating a tight building envelope and the potential for under-ventilation. (Sherman, M. and Matson, 2001.) .

This most basic ventilation system has no extra construction costs or explicit operating costs; however, there is poor control over ventilation rates when the envelope is leaky. The energy implications are almost exclusively from the need to condition the outdoor air. The system relies on the occupants to open and close windows to provide adequate ventilation when the envelope is tight. The lack of control can result in energy loss due to high air change rates especially in winter when temperature differences and wind speeds are high. Alternatively, the system may under-ventilate during the hot summer months. When climatic conditions are favorable, natural ventilation can be used for cooling and can replace air conditioning systems for part of the year.

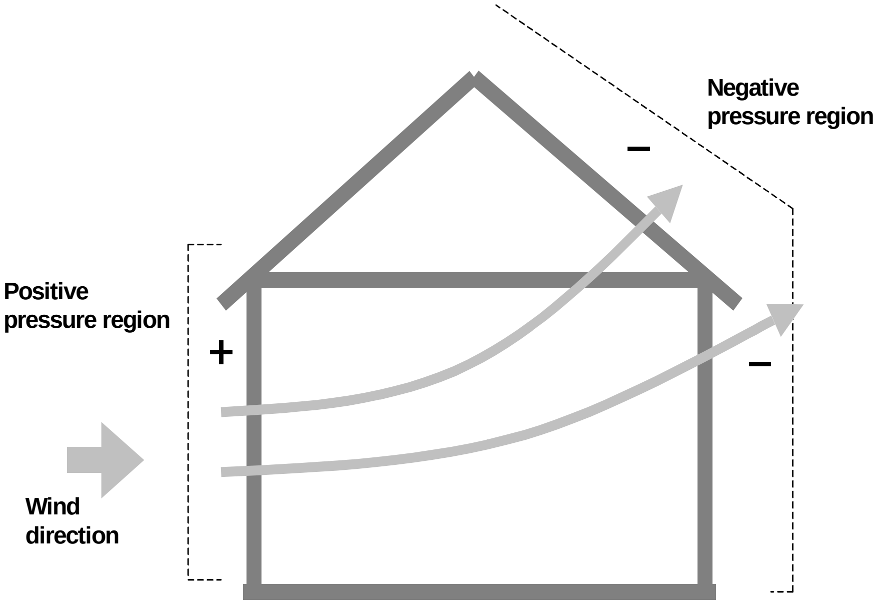

Figure 6. Wind speed/direction on a building creates positive and negative pressures.

But in urban settings there are considerable limitations to such an open ventilation system including noise, security, and pollution. (Santamouris, M. 2005.) Additional limitations arise from the unique climatic conditions of cities. Both the higher temperatures (the heat island effect) and the decreased wind speeds in urban canyons can decrease the potential of natural ventilation systems. Geros *et. al.* (2001) studied the reduction of air flow in naturally ventilated buildings in ten urban canyons in Athens and found that because of the reduced wind speed, the air flow through the buildings decreased up to 90 %. A few strategies exist for reducing noise in buildings using operable windows and they are capable of reducing traffic noise by 7.5 to 8.5 dB without compromising the airflow path resistance. (Oldham *et.al.*, 2004)

Since climate plays an important factor in the effectiveness of natural ventilation, many groups have analyzed the suitability of various climatic conditions. The potential of natural ventilation depends not only of the outdoor climate, but also the building site and the design of the building site. Yang *et. al.* (2005) have created a model to evaluate the potential of a particular site to provide the natural forces necessary to meet ventilation standards with only natural ventilation. It is clear that many climates are too harsh for infiltration to be used as a primary source of ventilation. Conversely there are climates where the driving forces are too weak for infiltration to be a practical source of primary ventilation. All of which leads Wilson and Walker (1992) to conclude “There is no hole for all seasons.”

Infiltration does provide ventilation automatically without using any transport energy; but it almost always requires more space conditioning energy to supply the equivalent ventilation as a constant mechanical system. Infiltration can provide some heat recovery and filtration through the building envelope, but unless it is well designed (e.g. the "dynamic insulation" used in Scandinavia) it is not likely to provide much. Infiltration depends on whether so there is no "right" amount of air leakage. Infiltration will always provide more ventilation than is needed during extreme periods in order to meet average demands.

For more information on operable windows and infiltration, see the "Incidental Ventilation" section below.

Passive Stack Ventilation

Passive stack ventilation is designed to provide more control over ventilation rates than natural ventilation by incorporating one or more stacks or towers into the building structure to extract stale air while fresh air enters through provided openings such as trickle vents or louvers. Passive stack air flows are created from a combination of two climatic forces: differences between the inside and outside temperature and wind. The negative pressure at the stack top is often the critical factor. (Wind pressures are mostly negative on the sides of buildings rather than the "leeward" side in many situations; see figure 7).The combination of pressures from warmer indoor air and negative wind pressure at the top of the stack result in air being exhausted from the stacks.

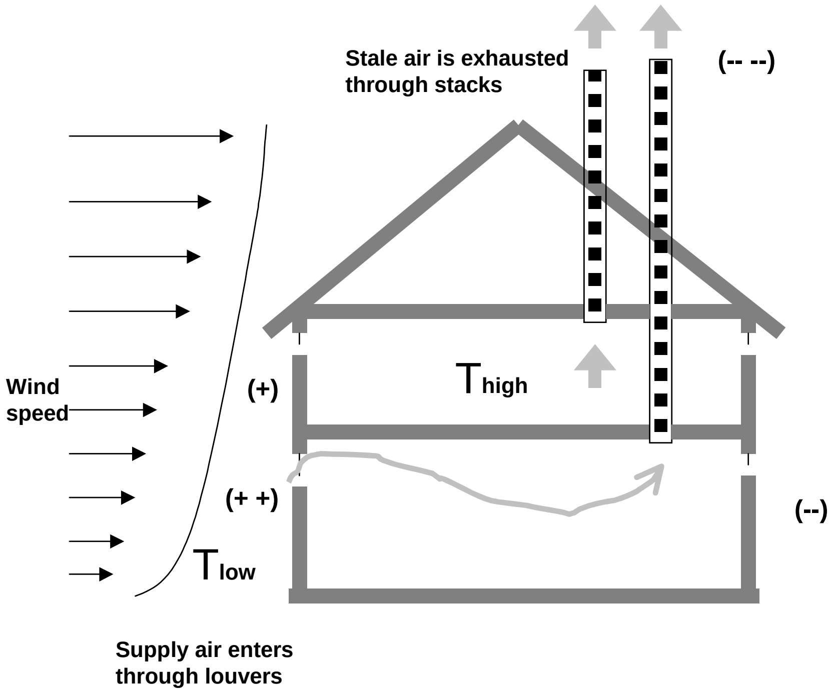

Figure 7. Stack forces are created with both wind speed and indoor/outdoor temperature differences.

Although rare in the United States, passive ventilation systems are widely used in the European Union. Axley (2001, in AIVC TN 54) found that in England 90%, and in the Netherlands most single-family dwellings use passive ventilation (90% and 65% respectively). Emmerich and Dols (2003) have used some of Axley's approach to create a passive ventilation design and analysis tool for use in a multizone environment.

Stack height and position are important in maintaining a negative pressure at the stack terminus and preventing back flows into the building. A taller stack is less sensitive to wind speed and wind direction. Installation guidelines and building codes reflect the importance of stack position relative to the roof[2] A variety of terminal caps are available that are designed and located to provide consistently negative pressures (independent of wind direction) at the stack exit. (Axley, J. W. 2001.) Stacks need to have a larger diameter than mechanical ducting systems to reduce flow resistance for low pressure drop conditions.

Ventilation flow rates can vary significantly from room to room. Upper, leeward rooms in particular may be under ventilated and can easily have not outdoor air. Careful design measures can be taken to control and distribute flow rates. Typically systems are designed with trickle vents or louvers which can be manually adjusted to control the flow rate, but these work best when uncontrolled infiltration rates are low (and building envelopes are tight). Each room must have a transfer grill or vent to allow free distribution of the air. While these same criteria are relevant for mechanical ventilation, the issue is often more critcal for passive ventilation because of the lower driving forces.

Many anecdotal cases indicate that passive ventilation systems have shown the capability of providing adequate long term ventilation, but fall short when required to provide short term high ventilation during peak episodes of contaminant production (*i.e.* bathing or cooking). Because they are similarly designed as mechanical systems, but without mechanical components, passive stack ventilation systems can reduce construction and operating costs of residential buildings. Careful design of internal spaces should be considered during the construction to allow air to flow between the rooms of the building and from the supply openings through the exhaust spaces. Relatively larger ducts are required than a mechanical system should flow resistance be an issue. Operating (air transport) costs are non-existent; however, there are usually some days of the year when weather conditions (low wind speed and/or small indoor/outdoor temperature differences) create insufficient airflow.

There is inherently some uncertainty in any system performance that is dependent on natural driving forces. Under ventilation or over ventilation can be expected at certain times of the year. (Yoshino, H., Liu, J., et. al., 2003.) Wilson and Walker (1992) showed

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[2] At present there is insufficient information to recommend specific minimum or maximum values for performance parameters, but there are references worth considering including those in the AIVC database and **IP 13/94 Passive stack ventilation systems: design and installation** by R K Stephen, L M Parkins, M Woolliscroft; 1994] A draft European Standard for testing cowls and roof outlets is in preparation (prEN 131415).

that even with several large passive ventilation openings, single family residences could not be adequately ventilated (relative to 62-89) during periods of light winds (less than 10 km/h) or small temperature differences (Δ10°C). These conditions are common in the spring and fall. At these times proper ventilation may only be attained if the occupant opens a window or otherwise supplements the system.

Usually natural forces are highest on cold days creating over-ventilation, cold draughts and energy loss. Self-regulating vents are available that can reduce or control over-ventilation. Pressure sensitive ventilators are available that can provide constant ventilation rates over a wide range of pressures, but these passive control units are relatively scarce (Axley, 2001 in AIVC Tech Note 54).

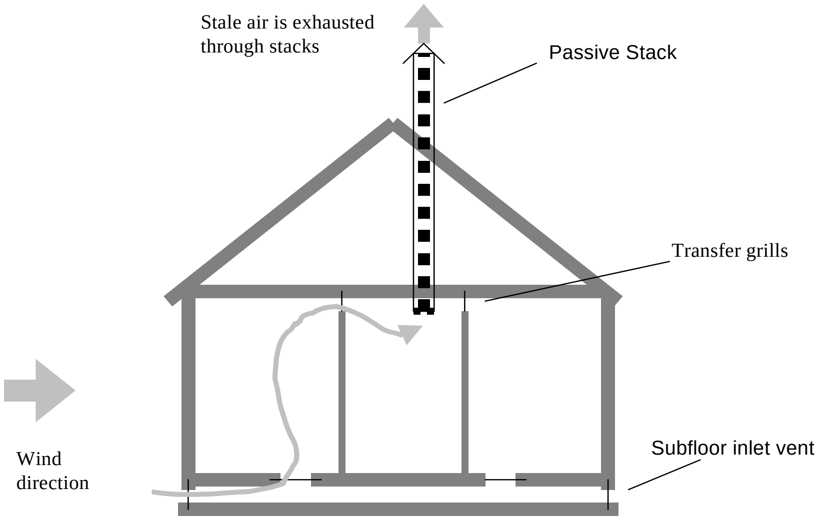

Figure8. Using sub-floor inlet vents can temper cold supply air and provide some heat recovery.

Passive systems fall short when compared to mechanical systems in the areas of filtration and heat recovery. Filtration of the supply air in not feasible and heat recovery is also relatively uncommon. Shao et. al. (1998) has shown that heat pipes can be used with a 50% heat recovery efficiency. Another strategy for heat recovery is to install inlet vents into the sub-floor (See figure 8.). This strategy will temper cold supply air and help avoid cold drafts and will also reduce the sensitivity of the ventilation rate to wind direction (Hayashi and Yamada, 1996).

Solar Chimney

A solar chimney is a passive stack system fitted with a solar collection panel (or often glazed walls on the south side of the building) used to heat the air in the stack resulting in an increased buoyancy of the air in the stack. By increasing the temperature differential between the inside and outside of the stack, ventilation rates are substantially improved on warm sunny days with low wind speeds. (Bansal et. al., 1994.) This would increase the year round effectiveness of the passive stack ventilation system. Airflow rates can be increased 20% over passive stacks without solar chimneys. (Jaros, M., Charvat, K. 2004.)

Khedari et al, (2003) studied the performance of solar chimneys in air conditioned buildings and reported that the solar chimney could reduce the load on the air conditioning system, using ventilative cooling, resulting in an average electrical savings of 10-20 %. The advantages of this system are the increase in reliability of the passive stack system and, also the system is silent and transparent to the occupant. The disadvantages are the extra design, installation and cost of the solar glazed panels. This system would be most appropriate for a sunny, warm climate.

Hybrid Systems

Hybrid systems are passive systems with a low-power fan to boost the flow of air through the stacks or vents thus combining the advantages of a passive system with the reliability of a mechanical system. The combination of the two systems improves the indoor air quality while reducing energy demand through an intelligent controller. (Heiselberg, 2005.)

There are a number of ways the two systems may be combined. The building may have two independent systems linked by a controller to switch from one to the other (a mechanical exhaust fan for the summer and winter and natural ventilation for the moderate seasons, for example). Another combination is fan-assisted natural ventilation where the main ventilation is provided by natural forces, but a low power fan can be switched on to assist ventilation during periods of weak natural forces. A third similar strategy is to include a small fan in a passive stack system to assist in creating optimal pressure differences in the stack. Yoshino et. al. (2003) has shown that a hybrid system can provide adequate ventilation rates even when weather conditions created poor ventilation in the passive system. By using a fan to boost stack ventilation during times of low wind speed under ventilation was prevented. And by using damper control at the vents, over ventilation was pre-vented when temperature differences were large.

Often, these systems incorporate the use of sophisticated control systems such as CO_2 sensors, room temperature, air flow sensors, motorized windows and even a weather station. Filtration of supply air is not common. The main disadvantage of hybrid systems is the complex control system. They add an extra cost to the installation in terms of expensive parts and trained personnel to install them. Most occupants feel comfortable with (or prefer) a simpler user interface.

Incidental Ventilation

Incidental (or adventitious) ventilation refers to features or effects that were not designed to provide whole-house ventilation, but in fact may. When they are truly incidential one does not “count” them in the ventilation design, but one may need to take account of them in order to determine the actual energy and indoor climate impacts of a specific design.

For example, an air-to-air heat exchanger can only recover the energy of the air that goes through it. If the building is leaky and a significant fraction of the actual ventilation air by-passes the exchange energy performance will be severely compromised. By contrast the performance of an exhaust air heat pump is less dependent on envelope air tightness, although not completely independent.

Infiltration

Air leakage through the building envelope can have a detrimental effect on ventilation effectiveness regardless of the ventilation system. Infiltration rates are not constant since they are dependent on the weather. Both mechanical and passively ventilated leaking homes will lose energy when infiltration rates are high during the heating season. Very little heat recovery occurs in the building envelope (Walker and Sherman, 2003) which generally results in a loss of energy used to condition the infiltrating air. Balanced ventilation systems will also suffer a reduction in performance when air by-passes the heat recovery unit. However, buildings that are too tight may also suffer from a reduction in indoor air quality. Mechanical exhaust systems can create a negative pressure inside the dwelling when infiltration is low. This can lead to back drafts from combustion appliances, poor indoor air quality, and high fan power requirements.

There are several methods available to measure leakage of the building envelope (Sherman 1990, Sherman and Chan 2004, Ask 2003, Dorer 2004). Ideally a building would leak no more than the air required for healthy indoor air. The amount of infiltration will depend on the air tightness of the building, the difference in indoor and outdoor temperatures, and the wind pressure. A tight building envelope will provide very little ventilation from infiltration and will require a provided ventilation system. Infiltration rates need to be taken into consideration when designing a HVAC system.

Sherman (1995) has created a map of infiltration zones required to meet ASHRAE 62-89 ventilation standards based on the climate data of each zone. In mild climates (such as the coast of California) infiltration alone is not enough to provide adequate ventilation in newer well-insulated homes. While in harsher climates, infiltration rates may be so high as to cause over ventilation, energy loss and comfort issues due to draughts. This zone would require the tightest home construction.

Operable Windows

Most homes are required to have operable windows in each room of the house. Occupants are more likely to feel comfortable when they have control over the ventilation system and windows provide a familiar system of ventilation. If used on a daily basis, windows can provide the ventilation necessary to meet current codes. Liddament (2001) reviewed several studies on occupant behavior and ventilation, and found that windows were most likely to be opened under the following conditions: sunny days, higher occupant density, higher outdoor temperature, low wind speed, during cleaning or cooking activities, and when smoking. However, there are many circumstances when opening a window is not practical such as noise, rain or high winds, outdoor pollutants, cold drafts, privacy, security and safety issues, energy loss, or the window may be difficult to operate. These observations suggest that window opening or closing is not always in response to ventilation needs.

Local exhaust fans

Local exhaust fans are often used in rooms with high moisture to provide source control when needed—most commonly kitchens and bathrooms, but laundries, utility rooms and lavatories may also have local exhaust fans. Local exhausts fans are not intended to dilute contaminants, but rather to remove them while they are still concentrated. As such, they are source control measure rather than ventilation in the normal sense.

While doing their source removal job, they may also increase the overall ventilation of the building and in that sense are incidental ventilation. For example, a high capacity kitchen exhaust of 400 cfm assures that the overall ventilation rate will be (temporarily) at least 400 cfm which is well above minimum 62.2 rates. Because the duty cycle of these local exhaust fans is determined by the occupants and presumably related to a source-generating activity, one cannot count on them towards meeting minimum ventilation requirements.

A notable exception to that last statement is the “double duty” bath fan. In this design a continuously operating local exhaust fan simultaneously meets the need for local exhaust and also whole-house ventilation. Provided the fan meets the appropriate requirements (e.g. sizing, noise) 62.2 allows this approach.

Real World Factors

Standard 62.2—or any other ventilation standard or code—is a set of minimum requirements that, if followed, will provide a certain minimum level of indoor air quality. In deciding how to apply such requirements, however, a variety of real-world factors need to be considered. Often these decisions are determined by the needs of the client (or builder) more so than the requirements of the standard. (Rudd and Lstiburek, 2001)

Construction and Installation Issues

A potential problem exists when technologies are not properly installed or designed (Dorer, 1998). Any ventilation system will not reach its performance potential if components are poorly manufactured or installed improperly. In 2001 a group of recently constructed homes in Minnesota were examined for various performance measures. Sheltersource, Inc., (2002) found that the average measured bathroom fan exhaust capacity was only 71 to 75% of the total rated capacity. Several factors contributed to poor performance including long duct lengths. Compression in flexible ducts can also increase pressure drops up to a factor of nine. This resulted in a loss of ventilation rate and a significant increase in power and energy consumption by the HVAC system. (Abushakra, Walker, and Sherman, 2003). Building air tightness is another area where the quality of the construction and the design of the building are as important as the materials in determining the desirable air tightness of the building envelope (Sherman and Chan, 2004).

Energy and Costs

Ventilation requires energy to move the air and to condition the supply air. Plus, it requires costs for purchasing designing and installing the equipment. Energy use for ventilation and infiltration is significant and can account for one third to one half of the total space conditioning energy (Sherman and Matson, 1993). Building energy uses account for approximately 40% of total primary energy use in developed countries. Of this, the residential sector uses 60 to 70% for space conditioning (Orme, 1998). Practical measures can be taken to conserve energy while still providing healthy ventilation rates. These include avoiding unnecessary air changes (due to leaky buildings), using good control strategies (not opening windows during periods of heating and cooling), and optimizing fan and equipment efficiencies. Orme (2001) has indicated that energy losses from air change are as important as conduction and equipment losses.

Sherman and Matson (1993) estimated that 2.1 EJ per year could be saved by tightening the existing US housing stock. Most of the US housing stock uses infiltration as the ventilation system. The average ventilation rate has been estimated at more than 1 air change an hour with an estimated energy load of 4EJ annually. If the existing housing stock was tightened and a continuous mechanical ventilation system was installed to provide an national average air change rate of 0.52 ACH, the researchers estimated the energy load to be 1.8EJ with a cost savings of $2.4 billion (Sherman and Matson, 1997).

Mechanical ventilation systems can save energy used to condition supply air if the building envelope is tight and infiltration is limited. Energy consumption can be reduced 9 to 21% by installing a mechanical ventilation system with heat recovery (Hekmat, Feustel, and Modera, 1986). There is the extra cost of purchasing, installing, and operating the equipment. Table 1 (Rudd, 2005) summarized the costs for various supply and exhaust mechanical systems.

All systems are run continuously, but a cost estimate is made for running the central fan for mixing purposes if this would be an option for some houses. The results show that a single port exhaust system is the least expensive to purchase and install with an estimated cost of $70. This is supported by Wray et al. (2002) who also found a mechanical exhaust system to be the least expensive to operate. While a 4 point energy recovery ventilation system would be the most expensive to purchase and install ($1720), the benefits of improved air distribution, filtration opportunities and energy savings may outweigh the initial costs. As expected, retrofitting an existing house is more expensive than new construction and multi-point distribution systems were more expensive than a single point system. If the house has an existing central fan system, than it need not be cost prohibitive to integrate a supply ventilation system with a single point exhaust.

Table 1. Equipment and installation costs for new and retrofit mechanical ventilation systems (Rudd, 2005).

Ventilation System Description	***Central fan use****	***Equipment Costs ($US)***	***Installation Costs ($US)***	***Total Costs ($US)***
Single-point Exhaust, new construction	Off 10min/hr	70 125	0 20	70 145
Single-point Exhaust, retrofit	Off 10min/hr	100 155	200 240	300 395
Multi-point Exhaust, new construction, 2 bath fans	Off 10min/hr	140 195	0 20	140 215
Multi-point Exhaust, new construction, remote fan	Off	450	3 points, 400 4 points, 500	850 950
Multi-point Exhaust, retrofit, remote fan	Off	450	3 points, 800 4 points, 1000	1250 1450
Single-point Supply, new construction, remote fan	Off 10min/hr	350 405	350 370	700 775
Multi-point Supply, new construction, remote fan	Off	350	3 points, 550 4 points, 650	900 1000
Single-point HRV, new construction	Off 10min/hr	800 800	550 570	1350 1370
Multi-point HRV, new construction	Off	800	3 points, 750 4 points, 770	1550 1570
Single-point ERV, new construction	Off 10min/hr	800 800	550 570	1350 1370
Multi-point ERV, new construction	Off	950	3 points, 750 4 points, 770	1700 1720
Central-fan integrated supply with continuous single-point exhaust	Off 15min/hr 15min/hr with damper	125 125 180	100 100 120	225 225 300
Central-fan-integrated supply with intermittent single-point exhaust	Off 15min/hr	160 160	100 100	260 260

*The central fan was used to mix and distribute the air.

Even though such cost estimates are available, they are not necessarily sufficient to enable optimal selection of the ventilation system. Individual users may place high values on criteria that were not considered or heavily weighted. To optimize such a multi-objective system sometime requires exotic optimization approaches. For example, Roberson, *et.al.*, (1998) developed such an unusual optimization for overall cost effectiveness (which included considerations for installation costs, operating costs, distribution effectiveness, and the potential for depressurization and for condensation) a multi-point supply system was found to be the best system overall. In cold climates, the group recommended a balanced system (mult-port supply with single-port exhaust) to prevent moisture problems in the building walls. In most of these cases, however, a simple continuous exhaust system would have proven to be more cost effective if the only objective were meeting Standard 62.2

Climate can have a large impact on energy use. In hot, humid climates dehumidification is necessary in houses with controlled ventilation systems. According to Rudd et.al.

(2003), mechanical ventilation with a separate dehumidification system provided the best overall value, including humidity control, installation costs, and operating costs. Some key factors contributing to the energy savings were locating the ducts inside the conditioned space, using insulation and installing high-performance windows.

Controls

A variety of control systems from the simple to the complex are available to adjust the ventilation rate to achieve comfort and energy savings. A variety of systems are available including timers, occupant sensors, CO_2 sensors, outside temperature, or humidity sensors. The least reliable system is relying on the occupant to open and/or close windows. The occupant will respond to odors, drafts, noise or a need for privacy rather than the need for a certain ventilation rate.

The area of residential ventilation controls will continue to grow as users wish to take advantage of intermittent ventilation options, to have pollutant or weather sensitive mechanical systems, etc.

Distribution Systems

A distribution system provides uniform ventilation and is an important component of all ventilation systems. In general, central exhaust systems, natural and passive ventilation systems do not distribute the fresh air as well as a multi-point supply system, or a mechanical system that uses the ductwork of an existing HVAC system (Rudd and Lstiburek, 2000). These systems allow the supply air to enter the building envelope in a rather uncontrolled manner and inevitably some rooms don’t receive enough air while others are over ventilated.

The distribution system is an integral part of many mechanical ventilation systems. The distribution system can have a significant effect on the ventilation rate and efficiency of a building. Leaky ducts are a source of energy loss, ventilation rate loss, and in the case of return ducts, a source of indoor pollution (Delmotte, 2003). In particular the location of the ductwork is important. Modera (1993) has shown an energy loss of 30 to 40% when ductwork installed in unconditioned spaces. He also showed through field testing and modeling that leakage through the average duct system was 37% higher than infiltration through the building envelope. Houses with leaky ductwork and air handlers located outside the conditioned space are at risk for increased infiltration rates especially in hot, humid climates This has large impacts on the actual ventilation rate found in the average house. The ventilation rate in many houses may not meet ASHRAE standards even though the equipment was designed to provide adequate ventilation since leaky duct-work can prevent effective distribution of the supply air.

One strategy to save conditioning energy is to close the registers or grilles in rooms that are not being used. This strategy can increase the pressure in the entire duct system and increases the leakage rate in the ducts. A recent study found that the energy saved due to conditioning the air was only partially offset by increased duct system losses (Walker, 2003).

Indoor Air Quality

Exposure to indoor pollutants can pose a serious health risk especially for sensitive populations such as the young, asthmatic, or elderly. (Sherman and Hodgson, 2004 and Seppanen, 2004.) Indoor pollution originates from both indoor and outdoor sources and may be in the form of suspended particulates, volatile organic chemicals (VOCs), human bio-effluents and microbiological contaminants. Occupant activities such as cooking, bathing, smoking, vacuuming, using cleaning products, painting, as well as chemical emissions from building materials, electrical equipment and appliances are all examples of indoor sources. Outdoor sources primarily result from vehicle exhaust, but also agricultural activities, construction, manufacturing activities, ground sources (radon), and allergens (Levin, 2004). The most effective method for controlling pollutants is by reducing or eliminating the source of the emission, but this is not always possible for some pollutants (Sherman and Matson, 2003, Levin, 2004). A number of strategies exist for improving indoor air quality including increasing ventilation rates to dilute the pollutant, filtration to remove particulates, or air cleaning to capture VOCs, or a combination of all three strategies. Diluting pollutants with more fresh air has historically been the function of ventilation; however, it is not a pollutant specific strategy and not all pollutants can be treated the same way. Proper maintenance and operation of the ventilation system, appropriate building design to limit sources of pollution, avoiding excessive depressurization, providing local ventilation at sources that produce pollution (combustion appliances) and moisture control are all important strategies in controlling indoor air quality (Hadlich and Grimsrud, 1999).

Dilution Ventilation

Appropriate whole house ventilation can dilute the level of indoor pollutants with fresh outdoor air (assuming the outdoor air in not more contaminated than the indoor air). Almost all of the ventilation technologies described can provide the necessary ventilation rates for effective dilution. For natural ventilation and/or passive systems there is some inherent lack of control of ventilation rates which may result in times when indoor pollution is high. Although these systems may provide an annual average acceptable ventilation rate, they cannot effectively deal with peak periods of pollution (Sherman and Wilson, 1986). On the other hand, all mechanical systems offer high levels of ventilation rate control so that indoor pollutants can always be diluted. Plus, many mechanical systems also include local fans in areas where production of pollutants is high, such as bathrooms and kitchens, in order to minimize the spread of pollutants into other parts of the house. Also, ventilation rates required to dilute VOCs, such as formaldehyde, is more than that needed to control human bio-effluents, such as CO_2 (Sherman and Hodgson, 2004).

Filtration

Sherman and Matson (2003) have shown that dilution ventilation is not always effective at reducing particle concentrations. Effective filtration can reduce the concentration of particulates that can not be reduced at the source; this can also reduce the need for ventilation dilution. Filtration is most commonly used in mechanically ventilated buildings with supply systems and can be used to filter re-circulated air or to filter the incoming supply air.

Particle filters are rated by the ASHRAE (52.2) MERV (Minimum Efficiency Reporting Value) scale. Typical furnace filters are rated at MERV 4 or lower and are not effective at removing respirable particles, but can remove large pollens and visible dust particles. MERV filters rated 6 to 8 can remove smaller particles in the range of 10μm (PM_{10}) and filters with a MERV rating of 9 to 13 can remove fine respirable 2.5μm ($PM_{2.5}$) particles. Currently ASHRAE standards recommend using A MERV 6 filter to protect the HVAC system from accumulating particles and becoming itself a source of indoor pollutants. In order to reduce human exposure, particle filtration requires high efficiency filters, continuous operation, and tight building envelopes and distribution systems to be effective. This comes at a high energy cost.

Outdoor pollution presents a serious limitation for naturally (or passively) ventilated buildings especially in urban areas. Researchers have shown that outdoor particles penetrate fully (almost 100%) into the indoor environment of houses with very leaky building envelopes and /or open windows that do not provide much opportunity for interaction between the air stream and the envelope. (Thatcher, 1995 and 2001, Partti-Pellinen, 2000). In a comparison of mechanical ventilation systems with and with out filtration, however, the Canadian Mortgage and Housing Corporation (CMHC, 2003) found that unfiltered exhaust systems provided some protection from outdoor particles when compared to unfiltered supply or balanced ventilation systems. These provided no protection from the ingress of outdoor particles. Emmerich and Nabinger (2001) found penetrations fround penetration factors of 60-80% in test houses.

These studies suggest that the building envelope offers some protection from pollen, allergens, nitrogen oxides, diesel particles, etc. Ventilation systems that move the supply air through the building envelope (such as natural infiltration, passive systems, and mechanical exhaust systems) can provide some filtration from these types of outdoor particles. The CMHC found that the best protection from outdoor particles was provided by a ventilation system that positively pressurized the house and used a high efficiency filter (HEPA), which can be expensive. In this case, a HEPA filter supply ventilation system was able to remove 99% of the outdoor particles.

However, in the case of radon, mechanical exhaust systems cannot always reduce the indoor radon concentration and may even increase it (Bonnefous, *et.al*, 1994). This result may apply to other soil gas contaminants as well. The researchers recommend a balanced ventilation system with heat recovery for low radon concentrations and an expensive subslab ventilation system to reduce radon flow into the building. Sherman (1992a) has shown that supply ventilation is generally superior for radon control, but that other types can work quite well depending on the climate and construction type.

Filtration performance is selective; it often has poorer efficiencies for the finest of particle sizes and will fail unless care is taken in the installation and maintenance of the system. (Liddament, M. W. 2001) If the building is tight and the filtration system is maintained, there is a potential to reduce both indoor particulate levels and ingress of outdoor particulates into the indoor environment. According to Sherman and Matson (2003) a MERV 11 filter installed in a supply ventilation system can reduce cat and dust mite allergens 30 to 40%); they recommend installing a MERV 9 to 12 filter and reducing duct leaks, preventing filter by-pass reducing infiltration, and running the fan continuously to maximize the filtration efficiency. For comparison ASHRAE 62.2 requires a MERV 6 filter.

Particulates can be reduced by filtration, electrostatic precipitators, and simply by deposition that occurs in the HVAC system. Wallace, *et.al*. (2004) showed that the use of a central fan in a forced air system alone could reduce the whole-house particle concentration (PM2.5) by 14% and that installing an in-duct mechanical filter could reduce the levels of particles by 23%. An electrostatic precipitator could reduce particles especially fine particles, by 51%, but these are more expensive than mechanical filters and require maintenance. Thatcher, *et.al*.(1995) have shown that the shell of the building offers little if any filtration of total particles and that indoor particle concentrations are significantly impacted by the activity level of the residents in the house. Even light activity, such as walking, can significantly increase the suspended particulate concentration for supermicron particles. Since residential HVAC systems operate cyclically, filters used as part of the HVAC system perform better when the fraction run-time is high. Fugler and Bowser (2002) showed that high-efficiency furnace filters have a minimal effect on indoor particulate (PM10) levels when the occupants are active, but during low activity times (sleeping), PM10 could be reduced 70%.

Summary

In this report we have reviewed the literature and used our expertise to evaluate technologies for meeting residential ventilation requirements. Our principle focus was on meeting ASHRAE Standard 62.2, but in doing so we found that there are a lot of other issues that influence the actual decisions about what gets installed in houses.

There are a wide variety of systems currently on the market that can be used to meet ASHRAE Standard 62.2. While these systems generally fall into the categories of supply, exhaust or balanced, the specifics of each system are driven by concerns that extend beyond those in the standard.

Some of these systems go beyond the current standard by providing additional features (such as air distribution or pressurization control). The market will decide the immediate value of such features, but ASHRAE may wish to consider relevant modifications to the standard in the future.

ASHRAE may also wish to consider expanding the standard to allow sustainable technologies—that is, passive or hybrid technologies that principally rely on natural driving forces rather than fans to transport the air. Such systems have been used for millennia and are currently used in Europe to satisfy ventilation requirements. R&D is necessary to develop such systems for the US, but they have great potential for green buildings.

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EXHIBIT E

RM 24-15

M1507.3, M1507.3.1, M1507.3.2, M1507.3.3, Table M1507.3.3(1), Table M1507.3.3(2), M1507.3.4 (New), Table M1507.4.4, M1507.3.5 (New), M1507.4, Table M1507.4

Proponent: Craig Conner, representing self (craig.conner@mac.com); Joseph Lstiburek, representing self (joe@buildingscience.com)

2015 International Residential Code

Revise as follows:

M1507.3 Whole-house mechanical ventilation system. Whole-house mechanical ventilation systems shall be designed in accordance with Sections M1507.3.1 through ~~M1507.3.3~~ M1507.3.6.

M1507.3.1 System design. *No change to text.*

M1507.3.2 System controls. *No change to text.*

M1507.3.3 Mechanical ventilation rate. The whole-house mechanical ventilation system shall provide outdoor air at ~~a continuous~~ an average rate of not less than that determined ~~in accordance with~~ by Equation 15-1 or ~~TableM1507.3.3(1)~~ Table M1507.3.3.

$$Q_r = (0.01 \times A_{floor}) + [7.5 \times (N_{br} + 1)] \qquad \textbf{(Equation 15-1)}$$

where:

Q_r = ventilation flow rate, cubic feet per minute (cfm)

A_{floor} = floor area in square feet (ft^2)

N_{br} = number of bedrooms, not less than one

~~Exception: The whole-house mechanical system is permitted to operate intermittently where the system has controls that enable operation for 25-percent of each 4-hour segment and the ventilation rate prescribed in Table M1507.3.3(1) is multiplied by the factor determined in accordance with Table M1507.3.3(2).~~

TABLE M1507.3.3 ~~(1)~~
~~CONTINUOUS~~ WHOLE-HOUSE MECHANICAL VENTILATION ~~SYSTEM~~ AIRFLOW RATE ~~REQUIREMENTS~~

DWELLING UNIT FLOOR AREA (square feet)	NUMBER OF BEDROOMS				
	0 – 1	2 – 3	4 – 5	6 – 7	> 7
	Airflow in CFM				
<1,500	30	45	60	75	90
1,501 – 3,000	45	60	75	90	105
3,001 – 4,500	60	75	90	105	120
4,501 – 6,000	75	90	105	120	135
6,001 – 7,500	90	105	120	135	150
> 7,500	105	120	135	150	165

For SI: 1 square foot = 0.0929 m^2, 1 cubic foot per minute = 0.0004719 m^3/s.

Delete without substitution:

~~TABLE M1507.3.3(2)~~

~~INTERMITTENT WHOLE-HOUSE MECHANICAL VENTILATION RATE FACTORS~~[~~a, b~~]

Portions of table not shown for clarity

~~a. For ventilation system run time values between those given, the factors are permitted to be determined by interpolation.~~

~~b. Extrapolation beyond the table is prohibited.~~

Add new text as follows:

M1507.3.4 Ventilation quality adjustment The required whole house ventilation rate from Section M1507.3 shall be adjusted by the system coefficient in Table 1507.3.4 based on the system type using Equation 15-2.

$Q_v = Q_r \times C_{system}$ **(Equation 15-2)**

where:

Q_r = ventilation rate in cubic feet per minute from Equation 15-1

C_{system} = system coefficient from Table M1507.3.4

TABLE M1507.3.4

SYSTEM COEFFICIENT

SYSTEM TYPE	**DISTRIBUTED**[a]		**NOT DISTRIBUTED**[a]	
	MIXED[b]	**NOT MIXED**[b]	**MIXED**[b]	**NOT MIXED**[b]
Balanced[c]	0.75	1.0	1.0	1.25
Not Balanced[c]	1.0	1.25	1.25	1.5

a. "Distributed" shall apply where outdoor ventilation air is supplied directly to each bedroom and the largest common area; otherwise "not distributed" shall apply.

b. " Mixed" shall apply where not less than 70% of the whole building air volume is recirculated each hour by one or more mechanical systems, otherwise "not mixed" shall apply. Where a central heating or cooling air handler fan is used to provide the mixing, the design heating or cooling airflow rate shall be used to determine the operation time setting required.

c. "Balanced" shall apply where two or more fans simultaneously supply outdoor air and exhaust air at approximately the same rate; otherwise "not balanced" shall apply. Where outdoor air is supplied by a central forced air system, "balanced" shall apply only where the fan for such system operates simultaneously with the exhaust fan(s) .

M1507.3.5 Intermittent operation Systems controlled to operate intermittently shall operate for not less thant one hour in each four hour period. The ventilation rate provided by systems controlled to operate intermittently shall be computed as the average ventilaton provided including both times of operation and non-operation.

Revise as follows:

~~M1507.4~~M1507.3.6 Local exhaust rates. Local exhaust systems shall ~~be designed to~~ have the capacity to exhaust the minimum air flow rate ~~determined~~ in accordance with Table ~~M1507.4~~M1507.3.6. Fans required by this section shall be provided with controls that enable manual override, such as an on and off switch. Fan controls shall be provided with ready access from the room served by the fan.

~~TABLE M1507.4~~ TABLE M1507.3.6

MINIMUM ~~REQUIRED~~ LOCAL EXHAUST RATES ~~FOR ONE- AND TWO-FAMILY DWELLINGS~~

AREA TO BE EXHAUSTED	EXHAUST RATES
Kitchens	100 cfm ~~intermittent or 25 cfm continuous~~
Bathrooms-Toilet Rooms	~~Mechanical exhaust capacity of~~ 50 cfm ~~intermittent or 20 cfm continuous~~

Reason: This proposed change adds the equation to compute minimum ventilation rates, adjusts airflow rates based on the effectiveness of the ventilation system type, more clearly states that the occupants shall have controls to adjust the ventilation, and makes several changes to clarify the ventilation section.

The equation on which Table M1507.3.3 is based is added explicitly as Equation 15-1. The equation is an alternative to the ventilation rates in Table M1507.3.3. The rate computed by Equation 15-1 is often lower than the table because the rates in the table have been rounded up to the largest floor area and highest number of bedrooms for each cell in the table.

Some types of ventilation work better than others. The proposal adds a ventilation quality adjustment (new M1507.3.4) based on the type of ventilation system.

This change improves on the code language; for example, although Section M1507.3.3 says the requirement is for a continuous rate, it is clear the section also allows intermittent ventilation. Unneeded words are eliminated. For example the existing Table M1507.3.3(2) and the discussion on "intermittent" in the exception is a long-winded ways of saying rates that are averaged over 4 hour periods also work.

This change makes it clear that occupants can control kitchen and bath fans, allowing them to increase the ventilation when needed. For example, increasing the ventilation if food is burned in the kitchen, or odors in the bathroom suggest higher levels of ventilation.

Some argue ventilation rates need to be substantially increased, but they do not provide evidence that existing rates are inadequate. The existing ventilation rates in the IRC have been used in many programs over the past two decades: Environments for Living program, Engineered for Life program, Energy and Environmental Building Association (EEBA) building recommendations, DOE Building America program experience, Canada's R-2000 program and Canada's Energy Star program.

Excess ventilation causes problems. Excess ventilation causes part load humidity problems in humid climates, which can lead to mold. Excess ventilation causes buildings to get overly dry during the winter leading to problems with wood finishes and furniture. Excess ventilation can cause discomfort to occupants leading to the installation of humidifiers which can be sources of indoor pollutants, leading the occupants to turn off the ventilation system which defeats the purpose of providing ventilation. Finally excessive ventilation leads to big energy costs.

Cost Impact: Will not increase the cost of construction

Overall costs should not increase. The required ventilation airflow rates are based on the same equation as the existing code. Ventilation rates required by the Equation 15-1 option are the same or slightly less than in the existing Table M1507.3.3(1). There will be some increases or decreases in cost depending on the system type, with the code change encouraging the use of the more effective systems. Some options, such as providing ventilation air through a central forced air system, are an inexpensive way to provide ventilation that is both "distributed" and "mixed". Most builders are already using the larger fans in Table M1507.3.6. Operating costs should go down due to encouraging the use of more effective ventilation system types and letting the occupant control ventilation to use it when most needed.

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