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Ventilation in US Manufactured Homes: Requirements, Issues and Recommendations

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SYNOPSIS: US Manufactured homes are required to be built to Department of Housing and Urban Development's Manufactured Home Construction and Safety Standards (MHCSS.) The National Fire Protection Association recently updated ventilation standards for manufactured homes (NFPA501-1999.) HUD will review and consider adopting the NFPA501-1999 ventilation standards for their revisions to the MHCSS. Both the NFPA and HUD standards process received input from staff involved with energy efficient manufactured housing programs such as The Super Good Cents™/Natural Choice™ program (SGC/NC), USDOE Building America Industrialised Housing Partnership (BAIHP), and EPA's Energy Star program. Members of ASHRAE and the National Institute of Standards and Technology (NIST) provided contributions as well. NIST and Forest Products Lab provided HUD with research assistance on the 1994 revisions to the MHCSS ventilation standards *(Burch/TenWolde.)* In 1999, HUD requested that NIST conduct CONTAM modeling research to evaluate ventilation requirements for the future revisions to MHCSS *(Persily.)*

The modeling found that:

- The assumption of 0.25 air changes per hour (h^{-1}) for infiltration is problematic given the dynamics of infiltration.
- Operation of kitchen or two bath fans typically increases ventilation rates to 0.7 h^{-1}.
- Forced air-system duct leakage typically increases infiltration rates to 0.55 h^{-1}.
- Exhaust fans and supply duct leakage draw moisture into the home in hot humid climates.
- Energy use and duct leakage of ventilation systems connected to forced-air systems is considerable.
- Passive inlet window vents provide little improvement in ventilation effectiveness.
- Exhaust fan location has little impact on ventilation rates, outdoor air distribution or home pressures.
- Improved control strategies are needed to reduce energy use and improve ventilation effectiveness.
- Additional CONTAM research is needed on pollutant exposures, parametric studies, windows and controls.
- There is a need to perform in-situ field data collection to validate the modeling conclusions.

The following author recommendations were provided to both NFPA and HUD and are based on experiences from the construction of over 90,000 SGC/NC and BAIHP energy efficient manufactured homes, and on the NIST research findings:

- Controls to optimize air change rates and minimum energy cost should be considered.

- Use envelope and ductwork fan pressurization and ventilation system flow rate testing.
- Tighten floors, ceilings and ductwork to prescribed levels.
- Utilize air inlets only when needed.
- Combine whole house and bathroom exhaust fans when ductwork, undercut doors or grills connect rooms together.
- Define de-pressure limits that minimize fireplace back-drafting and moisture condensation problems.
- Consider the impact of kitchen and bathroom exhaust fan damper leakage on reducing pressure imbalances and distribution of outside air.
- Use quiet, durable and energy efficient ventilation fans.
- Educate occupants on operation of ventilation system using homeowner manual, labels, brochures and videos.

1.0 HUD – MHCSS:

Overview: In the United States, 15-20% (200-300,00) of new single family dwellings are built in manufactured housing plants. These homes are usually built in 1-3 sections and transported up to 500 km (300 miles) to a site where the axles and wheels are removed and the sections connected.

Gaskets and/or caulking are used to seal the ceiling, floor and wall "marriage-line". A 6m (20 ft), 30 cm (12 in) diameter insulated plastic flexible "crossover duct" in a vented crawlspace connects to the HVAC ductwork located below the floor and above the floor insulation in the "belly."

The construction and installation of these manufactured homes must meet requirements contained in the U.S. Department of Housing and Urban Development's (HUD) Manufactured Home Construction Safety Standards (MHCSS.) MHCSS address structural, fire safety, energy efficiency issues, and has requirements for providing outdoor air ventilation. MHCSS supersedes local and state building codes. HUD provides interpretive bulletins to MHCSS.

1.1 MHCSS 1994 Requirements and Issues: The requirements and relevant issues to the 1994 revisions to MHCSS (MHCSS94) are as follows:

- **Occupant Control:** MHCSS requires an occupant controlled whole house ventilation system. The typical system uses an outside air duct to the return side of the forced-air system which brings in 63 –104 l/s (30-50ft^3/min) on thermostat demand or when the occupant turns the thermostat fan switch from "auto" to "on". Experience has shown that these systems tend to only operate in thermostat demand mode, and are rarely used by occupants for supplemental ventilation. Some occupants perceive these systems as noisy, uncomfortable, and wasteful of energy *(Lubliner.)*
- **Flow Rates:** MHCSS94 requires that whole house ventilation systems be capable of providing .0068 l/s/m^2 (0.035 ft^3/min/ft^2.) However, MHCSS does not require flow rate testing to ensure adequate flow rate compliance as part of a quality assurance program *(Lubliner.)*

- **Infiltration Assumption:** The MHCSS94 requires a flow rate of .0068 l/s/m^2 (0.035 ft^3/min/ft^2.) This requirement assumes a 0.25 h^{-1} from infiltration as a single value for weather-driven infiltration rates. This approach is inherently problematic, given the strong dependence of infiltration on weather *(Persily.)*
- **Balanced Ventilation:** MHCSS requires systems be "balanced", but provides no quantifiable definition of "balanced". Perfect balancing cannot be achieved due to building envelope, HVAC, occupants and weather dynamics *(Lubliner.)*
- **Pressure Relief:** Originally, the MHCSS94 required pressure relief vents for forced-air intake systems because of concerns about "positive pressure." In fact, field tests confirm that supply duct leakage creates negative, not positive pressure whenever the forced-air system operates *(FSEC, Palmiter.)* This is clearly due to the presence of supply ductwork leakage and lack of return ductwork outside the building pressure envelope. MHCSS94 no longer requires "pressure relief" vents in cases where kitchen and bathroom exhaust fan damper leakage is shown to reduce pressure imbalances. Many of the industry standard bathroom and kitchen exhaust fans provide sufficient pressure relief, provided they are used as intermittent spot ventilation devices. Dampers around standard industry bath fans have Equivalent Leakage Areas (ELAs) comparable to the outside air intake forced-air systems and greater than window air inlet vents *(Lubliner.)*
- **Outside Air Source:** MHCSS94 also states that the ventilation system cannot draw or expel air into the floor, wall, or ceiling/roof systems, even if those systems are vented. In reality, when HVAC equipment operates, most outside air enters through leakage in the building envelope, kitchen and bath exhaust fan dampers, as well as leaks in the duct system, rather than the ducted vents or window inlets. To address this requirement, HUD required air inlet vents for whole house exhaust systems, unless it is shown that kitchen or bath fans damper leakage provide air intake comparable to that of the window inlet vents. Just like the "pressure relief vents," the initial requirement for additional air intake window vents or vents to the air-handler return ductwork provided little benefit based on the ratio of envelope ELA to air inlet vent ELA for typical envelope tightness levels.
- **Outside Air Forced-air Approaches:** One approach uses no damper. This allows conditioned air to exfiltrate when the HVAC is not operating and increases HVAC distribution system cycling losses. When the forced air system operates, the intake acts like a 12.5 cm (5inch) diameter leak in return ductwork. The other approach uses a motorized damper in the air intake duct that opens whenever the forced-air system fan operates. This approach avoids the exfiltration cycling losses, but still acts like a supply ductwork leak whenever the forced-air system operates.
- **Location of Whole House Exhaust Fan:** MHCSS94 states that the bathroom fan can not be used as the whole house fan. Because of the increased costs of adding the additional fan, most manufacturers utilize one of the two forced-air ventilation system approaches instead of the exhaust system. Those that do use a whole house exhaust fan are permitted to use a noisy, inexpensive bath fan, which are typically not designed for continuous durable operation. Since rooms in manufactured homes are typically connected by ductwork, undercut doors and transom grills, spatial ventilation effectiveness is adequate regardless of the location of the whole house exhaust fan.

2.0 NFPA Standard 501: The NFPA Manufactured Homes Technical Committee on Mechanical recently reviewed and updated Standard 501. Upon receipt HUD will consider adopting the new NFPA501-1999 as an updated MHCSS. The new proposed standard will receive public comment prior to adoption.

2.1 Improvements to NFPA Standard 501: NFPA501-1999 made progress in addressing many of the issues arising from the MHCSS94 including:

- Requiring more specific design, installation and material details for controlling building envelope and ductwork air leakage.
- Improving occupant education and labeling efforts for whole house ventilation systems.
- Requiring quieter and more durable whole house exhaust fans.
- Limiting the differential pressure caused by whole house ventilation systems to no more than 7.0 Pa (.028 in. H_2O)
- Allowing the whole house fan to be installed in the bathroom, provided that the room is connected by ductwork to the other zones of the house. It is expected that the cost savings of locating the whole house fan in the bathroom will be used to purchase quieter and more durable fans, improved controls, better occupant education and labeling efforts.

2.2 Outstanding Issues of NFPA 501 Draft: While the NFPA501-1999 improves the MHCSS94, NFPA501-1999 did not accept the following recommendations provided by committee members and building scientists during the NFPA standards process *(NFPA Draft):*

- Periodic envelope and duct performance leakage tests using blower doors and duct blasters to fully address the problems encountered with envelope and duct leakage as a result of inadequate practices and materials in both manufacture and installation.
- Address the increased energy impacts of the forced-air based ventilation systems (a 350W fan motor which supplies 63-104 l/s (30-50 ft^3/min) of outside air,) and the duct leakage energy penalties from distributing that air through the HVAC supply ductwork.
- Eliminate window and return duct inlet vent requirements, except where manufactured homes are tight enough to warrant their use. Eliminating the inlet vents provides cost savings, which can be used to limit floor, ceiling and duct leakage. The current predominant vehicle for intake air in whole house exhaust systems is the building envelope. Given current envelope and duct tightness levels, eliminating inlet vents will have little effect on the amount of airside air which is drawn in thorough the envelope. Figure A provides the results of house tightness on manufactured homes throughout the USA, and indicates that homes are not achieving desired tightness levels where inlet vents are in use. Focusing on sealing penetrations in floors, ceiling and ductwork where known pollutant sources may enter may be a more effective way to reduce outside air being drawn from the crawlspace and attic. Outside air drawn through wall envelope penetrations may increase the drying potential of homes in heating climates *(Lstiburek)*, and may filter pollen better than air inlet vents. More discussion and research is needed to determine how different ventilation systems effect pollutant sources and emission rates, since some pollutant sources may increase while others decrease. In addition, some researchers suggest that some heat recovery occurs when outside air is drawn through walls *(Nelson.)*

3.0 ASHRAE Standard 62.2: Concurrent with the NFPA501 revisions, the American Society of Heating, Refrigeration and Air Conditioning Engineers *(ASHRAE)* produced residential Standard 62.2, "Ventilation for acceptable indoor air quality." Both ASHRAE 62.2 and NFPA501 are fairly consistent in terms of requirements, although the approaches vary. Some of the ASHRAE 62.2 committee members provided useful comments to the NFPA501 development, review, and comment processes *(NFPA Draft.)*

4.0 SGC/NC: Significant input to the ASHRAE 62.2 and NFPA 501-2000 standards processes came from lessons learned from the U.S. Northwest region's Super Good Cents™/Natural Choice™/Energy Star (SGC) energy efficiency construction program for manufactured homes. The SGC program has resulted in the construction of 90,000 energy efficient homes over a ten-year period.

4.1 SGC Specifications Versus MHCSS94: SGC does not allow forced-air fans to be used as the whole house ventilation systems, thereby avoiding parasitic energy losses from the forced-air fans. In cooling climates these losses increase cooling loads, while in heating climates they offset some heating load.

- SGC requires quieter (1.0 - 1.5 sone) whole house exhaust fans.
- SGC employs periodic in-plant and in-field random performance testing of building and duct tightness, and is working on improved duct sealing and installation techniques that employ mastics and gaskets instead of tapes.
- SGC has effective occupant education brochures and labeling materials to help occupants understand their ventilation system and the importance of operation during occupancy periods.

4.2 Existing and Future SGC/NC Specification

Fan Noise and Operation: The SGC program requires a 1.0 sone fan running constantly or a 1.5 sone fan set to run for at least 8 hours per day during occupancy periods. A proposal to eliminate the 1.5 sone fan option has been approved, along with improvements to the occupant ventilation brochure, suggesting operation of the system whenever the home is occupied.

Inlet Vents via window frames or return ductwork: Another requirement is either air inlet window vents in each bedroom and one in the main living area, or ducted intake to allow some outside air to enter when the whole house exhaust fan runs, regardless of the forced-air fan operation. There are two ducted intake air systems: one uses a motorized damper that only opens when the whole house exhaust fan is operating. This system, called the "Northwest Timer kit" cycles the whole house exhaust fan on for 20 minute per hour. The other system has no damper and acts like a return duct leak, increasing cycling losses as described above in the discussion of MHSCC. A proposal to eliminate requiring inlet vents, focussing on tighter ducts and floor/ceiling envelopes has been approved by SGC manufacturers.

5.0 DOE BAIHP: The US Department of Energy's (DOE) Building America Industrialised Housing Partnership (BAIHP) is providing building science training, testing, and general technical assistance to manufacturers throughout the USA. This includes monitoring of energy use, indoor air quality and HVAC system performance. Current BAIHP activities include:

Moisture Investigations: Testing of standard practice and energy efficient manufactured homes in the warm humid Southeast USA have found mold due to condensation behind vinyl-covered drywall, primarily due to a combination of air infiltration from HVAC induced negative house pressures (cause by supply duct leakage), and cold-side vapor barriers. BAIHP is focusing on cost effective ways of tightening supply ductwork to reduce moisture condensation on cold side vapor barriers (vinyl-covered drywall) in hot humid climates. Tightening ducts/building envelopes and eliminating cold side vapor barriers seems to be effective in reducing moisture condensation problems *(FSEC.)*

Combustion spillage: FMCSS requires that combustion air be supplied directly from outside. However, some wood fireplaces with loose operable access doors have been observed "back-drafting" smoke into the homes under excess negative pressures caused by the HVAC equipment *(Boe.)* BAIHP is investigating the frequency of back-drafting occurrences in SGC/NC homes in the Pacific Northwest.

Ventilation Controls: BAIHP also helped to develop a new control called the Air Recycler™. This controller adjusts the ventilation rate based on operational time of the furnace and occupancy level *(Rudd.)* The Air Recycler™ has had limited use in manufactured housing. One concern is that it typically relies on the operation of an inefficient furnace fan for ventilation. Suggestions to overcoming this problem include the use of a low-wattage whole house exhaust fan instead of the forced-air fan *(Lubliner.)* Another solution is to use a variable speed high efficiency fan motor; this may be first-cost prohibitive to an industry that typically pays less than $200 for an electric forced-air furnace. NIST and WSU are currently developing a new control system, which would adjust the ventilation system run-time based on an estimate of the infiltration rate.

Performance Monitoring: BAIHP is monitoring the energy and HVAC performance in new current practice and energy efficient manufactured homes in the US. The monitoring results are helping to support recommendations to improve ventilation system performance.

Energy Star Technical Assistance: BAIHP staff provide field testing and other technical assistance to manufacturers interested in building homes to the Energy Star Manufactured Home program standards. Energy Star homes are built 30-50% more efficient than current practice. Energy Star is currently working on energy efficient ventilation specifications, and recognizes energy savings in SGC manufactured homes associated with low wattage exhaust ventilation systems *(EPA.)*

6.0 HUD/NIST/CONTAM: In 1999, HUD directed NIST to employ CONTAM, a multi-zone airflow and indoor air quality computer program, to simulate airflow in a 99 m^2 (1063 ft^2) double-section home under several different scenarios. These scenarios included envelope infiltration only, infiltration plus the effects of local exhaust and forced-fan operation, an outdoor air intake duct installed on the forced-air return, and whole house exhaust with and without passive inlet vents. Simulations were performed to predict outdoor ventilation rates into the house due to infiltration and mechanical ventilation, inter-zone airflow rates between the rooms, building air pressures, and ventilation air distribution.

6.1 Summary of findings

Validity of the 0.25 h^{-1} assumption for infiltration: Using a single value for a weather-driven infiltration model is inherently problematic, given the strong dependence of infiltration on weather. Infiltration rates vary by as much as 5:1 in these simulations, based on weather conditions alone. Impacts of the exhaust fan and forced-air system more than double these variations. Nonetheless, when considering predicated infiltration rates on an annual basis, the air change rate is below 0.25 h^{-1} for about one-third of the year in Albany, NY and Seattle, WA, and for 70% of the year in Miami, FL. Note that if there were no duct leakage in these homes, these percentages would be significantly higher. The assumption of 0.25 h^{-1} in modern manufactured homes may be high; more importantly, it ignores the variation due to weather and HVAC operation (see Figures B1 and B2.)

Impact and effectiveness of outdoor air inlets on the force-air return ductwork: Employing an outdoor air intake on the forced-air return duct is effective in raising air change rates and distributing ventilation air throughout the home. However, the overall impact on the home's air change per hour is a function of the operating time of the forced-air system, which in turn depends on the extent of system over-sizing and the use of other control strategies, such as manual switches and timers. While increased forced-fan operation provides higher ventilation rates, there is an energy cost associated with increased fan operation. Also given the existence of significant duct leakage, this scenario creates excessive air change rates, particularly when weather-driven infiltration is high (see Figures B1, B2, and D.)

Impact and effectiveness of whole house exhaust fan with and without passive inlet window vents: A whole house exhaust fan with passive inlet vents provides adequate ventilation and reasonable distribution, but again is highly dependent on the fan operation schedule. As implemented in the house model, these vents themselves are not particularly effective in ventilating the home. Based on the magnitude of the vent openings relative to house tightness, their installation basically corresponds to a 15% leakier envelope than a designed air intake system. Such a system would presumably require a tighter envelope than is typically achieved in practice. Furthermore, under the conditions in these simulations, outdoor air did not necessarily enter the building through these vents; when they did indeed act as inlets, the amount of outdoor air entering through them was not significant (see Figures B1, B2, and C.)

Locating the whole house exhaust fan in the main living area versus the bathroom: In this model, the impact of the whole house fan did not greatly depend on its location. Whether the fan was in the main living area or a bathroom off the main living area did not have a significant impact on the air changes per hour, outdoor distribution or building pressure (see Figure C.)

7.0 Recommendations: Key recommendations for MHCSS include:

- ❖ Consider system design and control impacts on ventilation effectiveness and energy use.
- ❖ Utilize fan/duct pressurization testing for quality assurance.
- ❖ Conduct flow rate testing for quality assurance.
- ❖ Improve occupant education and labeling efforts.
- ❖ Define de-pressure limits to minimize back-drafting in heating climates.
- ❖ Consider how kitchen and bathroom fan leakage may reduce negative pressure and impact distribution of outside air.
- ❖ Define de-pressure and perm rating limits, tighten ductwork and building envelope and prohibit cold side vapor barriers to minimize moisture condensation in hot humid climates.
- ❖ Define de-pressure limits or improve systems to reduce back-drafting of fireplaces with leaky doors.
- ❖ Require quiet, durable and energy efficient ventilation fans, and improve occupant use of systems through education.

- Eliminate the requirements for outside air intakes on exhaust systems in heating climates and use cost savings to tighten floors, ceilings and ducts.
- Allow whole house fans to be located in bathrooms, provided the bathroom is connected to the house by ductwork, undercut doors or grills.
- Conduct additional CONTAM research, including pollutant modeling, parametric studies on key variables and operable window impacts. After CONTAM modeling, validate assumptions and results through field research.

8.0 Figures:

Figure A - House Tightness Research

Blower Door Tests of U.S. Manufactured Housing					
Project Name	**Data Source**	**Test #**	**EE/CP***	**Year Built**	**ACH****
BPA	Eck	21	CP	65-80	14.3
RCDP-CTRL	Davis	29	EE	89	8.8
RCDP-MCS	Davis	131	CP	89	6.1
MAP	Davis	162	EE	94	5.5
Comfort Seal/OR	EWEB	1253	CP	59-89	12.1
Comfort Seal/OR	EWEB	187	EE	90-97	10.1
SGC/ID	Ecotope	25	EE	97-98	4.6
SGC/WA	Ecotope	11	EE	97-98	4.8
WSU/BA	Lubliner	1	EE	96	2.4
FSEC/BA	Chandra	6	CP	99	5.5-7.5
FSEC/BA	Chandra	2	EE	99	5.5
FSEC/BA	Cummings	21	CP	74-86	12.6
NY	AEC	6	CP	94-95	10.2
NC	AEC	8	CP	94-95	12
CONTAM	Persily	1	CP	99	6.5

*CP = Current Practice EE = Energy Efficient
**ACH = air changes per hour (h^{-1}) at 50 PA

Figure B-1 - Summary of Annual ACH during occupancy

Case/Condition	ALBANY			MIAMI			SEATTLE		
	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}
1/Envelope leakage only	0.23	55	87	0.09	100	100	0.20	72	99
2/Scheduled exhaust fans	0.30	43	70	0.18	79	87	0.28	57	79
3/Forced-air operating on outdoor temperature	0.37	29	48	0.20	76	86	0.35	27	64
4A/Intake on forced-air, operating on outdoor temperature	0.40	27	41	0.21	73	86	0.37	24	54
4B/Intake on forced-air, occupancy schedule	0.72	0	0	0.67	0	0	0.69	0	0
5A/Passive inlets and whole house exhaust on exhaust schedule	0.45	24	38	0.28	68	78	0.43	18	46
5B/Passive inlets and whole house exhaust on occupancy schedule	0.58	7	18	0.40	28	61	0.56	2	12
6A/ Whole house exhaust (no inlets) on exhaust schedule	0.41	29	47	0.25	76	79	0.39	27	64
6B/ Whole house exhaust (no inlets) on occupancy schedule	0.54	10	21	0.38	36	68	0.52	4	14

Figure B-2 – Summary of Annual ACH at Heating and Cooling

	ALBANY			MIAMI			SEATTLE		
Case/Condition	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}	Mean air change rate (h^{-1})	Percent of hours < 0.25 h^{-1}	Percent of hours < 0.35 h^{-1}
1/Envelope leakage only	0.27	39	83	0.14	100	100	0.23	67	99
2/Scheduled exhaust fans	0.32	33	71	0.19	87	89	0.27	57	84
3/Forced-air operating on outdoor temperature	0.42	13	38	0.29	64	87	0.36	17	66
4A/Intake on forced-air, operating on outdoor temperature	0.46	10	28	0.31	49	87	0.38	13	52
4B/Intake on forced-air, occupancy schedule	0.64	4	11	0.49	20	46	0.58	4	18
5A/Passive inlets and whole house exhaust on exhaust schedule	0.49	6	25	0.35	30	82	0.43	6	42
5B/Passive inlets and whole house exhaust on occupancy schedule	0.57	2	9	0.41	10	56	0.52	2	11
6A/ Whole house exhaust (no inlets) on exhaust schedule	0.44	13	39	0.31	64	87	0.38	17	66
6B/ Whole house exhaust (no inlets) on occupancy schedule	0.53	5	15	0.37	30	65	0.48	6	23

Figure C– Summary of Inverse Age of Air Values

House conditions	Wind speed (m/s)	Inverse age of air (h^{-1}) KLA	MBED	BED2	BED3
All fans off	0	0.16	0.17	0.18	0.18
	5	0.17	0.19	0.18	0.19
Forced-air fan on; all exhaust fans off; interior doors open	0	0.19	0.19	0.19	0.19
	5	0.53	0.53	0.52	0.52
Forced-air fan on; all exhaust fans off; interior doors closed	0	0.24	0.24	0.24	0.24
	5	0.55	0.55	0.57	0.57
Intake on forced-air return; interior doors open	0	0.32	0.32	0.32	0.32
	5	0.63	0.64	0.62	0.63
Intake on forced-air return; interior doors closed	0	0.38	0.38	0.38	0.38
	5	0.65	0.63	0.65	0.65
Whole house exhaust in KLA zone; passive inlet vents; interior doors open	0	0.40	0.37	0.31	0.35
	5	0.55	0.42	0.39	0.44
Whole house exhaust in KLA zone; passive inlet vents; interior doors closed	0	0.40	0.33	0.31	0.35
	5	0.55	0.41	0.39	0.44
Whole house exhaust in BATH1 zone; passive inlet vents; interior doors open	0	0.40	0.37	0.31	0.35
	5	0.54	0.42	0.39	0.44
Whole house exhaust in BATH1 zone; passive inlet vents; interior doors closed	0	0.39	0.32	0.30	0.30
	5	0.51	0.39	0.39	0.41
Whole house exhaust in KLA zone; no passive inlet vents; interior doors open	0	0.36	0.33	0.28	0.32
	5	0.47	0.37	0.31	0.37
Whole house exhaust in KLA zone; no passive inlet vents; interior doors closed	0	0.36	0.29	0.27	0.30
	5	0.47	0.34	0.30	0.36

All values correspond to 20 °C (36 °F) temperature difference. The values for nonzero wind speed are averages over winds from the north, south, east and west.

Figure D – Summary of Energy Consumption and ACH

CASE/CITY	ANNUAL ENERGY CONSUMPTION							
	Heating		Cooling		Fans		Total	
	MJ	kWh	MJ	kWh	MJ	kWh	MJ	kWh
Envelope leakage only (Case #1)								
Albany	10200	2834	172	48	0	0	10372	2882
Miami	189	53	2012	559	0	0	2201	612
Seattle	6150	1708	14	4	0	0	6164	1712
Scheduled exhaust fans (Case #2)								
Albany	11781	3273	263	73	184	51	12228	3397
Miami	243	68	2843	790	184	51	3270	909
Seattle	7392	2053	26	7	184	51	7602	2111
Forced-air fan operating on outdoor temperature (Case #3)								
Albany	15139	4206	393	109	2927	813	18459	5128
Miami	328	91	4422	1228	1080	300	5830	1619
Seattle	9634	2676	36	10	2521	700	12191	3386
Intake on forced-air, operating on outdoor temperature (Case #4A)								
Albany	16799	4667	414	115	2927	813	20140	5595
Miami	342	95	4686	1302	1080	300	6108	1697
Seattle	10228	2841	38	11	2521	700	12787	3552
Intake on forced-air, occupancy schedule (Case #4B)								
Albany	22334	6204	565	157	8440	2345	31339	8706
Miami	628	174	7273	2020	8054	2237	15955	4431
Seattle	15329	4258	54	15	8275	2299	23658	6572
Passive inlets, whole house exhaust on exhaust schedule (Case #5A)								
Albany	17697	4916	475	132	3045	846	21217	5894
Miami	407	113	5310	1475	1198	333	6915	1921
Seattle	11385	3163	44	12	2639	733	14068	3908
Passive inlets, whole house exhaust on occupancy schedule (Case #5B								
Albany	20573	5715	509	141	3564	990	24646	6846
Miami	511	142	6056	1682	1716	477	8283	2301
Seattle	13786	3830	47	13	3157	877	16990	4720
Whole house exhaust on exhaust schedule (Case #6A)								
Albany	15888	4414	428	119	3045	846	19361	5379
Miami	367	102	4731	1314	1198	333	6296	1749
Seattle	10246	2846	41	11	2639	733	12926	3590
Whole house exhaust on occupancy schedule (Case #6B)								
Albany	18984	5274	465	129	3564	990	23013	6393
Miami	479	133	5569	1547	1716	477	7764	2157
Seattle	12822	3562	44	12	3157	877	16023	4451
Constant air change rate of 0.35 h^{-1}								
Albany	11604	3224	439	122	2927	813	14970	4159
Miami	368	102	5362	1490	1080	300	6810	1892
Seattle	9002	2501	34	9	2521	700	11557	3210

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10.0 - References

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