Manufactured Housing Research Alliance

Whole House Ventilation Strategies

January 2, 2003

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January 2, 2003

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The purpose of this research was to provide a baseline for evaluating whole house ventilation strategies for manufactured homes.

The first step was to conduct a literature search and review to investigate whole house ventilation requirements and design strategies for manufactured homes. The findings of the literature review were debated among, and analyzed by a Steering Committee of industry representatives.

In general, airflow through homes, and its impact on building performance and homeowner comfort, is one of the most difficult building science phenomenons to quantify and predict. ASHRAE recommends a minimum whole house ventilation equal to 0.35 air changes per hour for residences. Previous studies of manufactured homes indicate that approximately 0.25 air changes per hour are provided by natural infiltration. In order to turn the ASHRAE recommendation and the estimate of natural infiltration into a prescription suitable for inclusion in the Manufactured Housing Construction and Safety Standards, HUD calls for all manufactured homes to include a ventilation system with the capacity of 0.035 cubic feet per minute per square foot of floor area. This aligns with the recommendation of the NFPA 501 Committee.

It is unclear how whole house ventilation systems currently in use in manufactured homes perform with respect to the HUD requirements, including this static ventilation rate. Research is proposed to establish whether or not existing whole house ventilation systems, once installed and operating in typical manufactured homes, exchange air with the outdoors at the rate that is specified in the HUD code and to consider options to improve system performance and cost efficiency. The development of a "best practices" manual for whole house ventilation systems design, installation and operation is also proposed. Finally, follow-up research is proposed to correlate the newly developed ventilation system design(s) against the target ventilation rate of 0.35 air changes per hour to determine if ventilation targets are being met.

2

CURRENT STATE OF KNOWLEDGE

Whole-house ventilation is the process of supplying fresh air to a living space and exhausting stale air, either by natural or mechanical means in order to maintain an acceptable level of air quality. Normal human activities such as cooking, bathing, breathing, and maintaining house plants introduce indoor pollutants (including excessive levels of water vapor) into the home. Additionally, building materials and furnishings can contribute to indoor pollution through outgassing of chemicals used in their manufacture. Finally, appliances such as heaters and fireplaces can add harmful combustion byproducts to the air in the home. Pollutants can build up to levels that may negatively impact human health unless they are removed or diluted with fresh outside air.

Ventilation acts to either dilute pollutants (including excessive levels of humidity) or flush them from the home. Residential construction traditionally has relied on infiltration to provide ventilation. Infiltration is the leakage of air through the building envelope through unintended gaps in walls, roofs, windows, doors and other construction elements. Improvements in construction, however, have resulted in more airtight buildings and hence the need for dedicated mechanical or passive devices to satisfy ventilation needs. Furthermore, infiltration has been shown to vary with environmental conditions such as wind and temperature differentials, and for significant periods these driving forces may not be sufficient to achieve adequate natural infiltration.

In general, airflow through homes, and its impact on building performance and homeowner comfort, is one of the most difficult building science phenomenons to quantify. Ventilation system performance involves much more than simply air exchange. Ventilation systems can induce pressure differentials, add or remove humidity beyond desirable levels, affect comfort, add to space conditioning costs, over- or under-ventilate depending on seasonal driving forces, and may distribute ventilation unevenly throughout the home. Ventilation systems add to the cost of housing; besides the capital costs, ventilation accounts for a portion of the total energy load on the home. Thus efforts to characterize different ventilation strategies and to optimize their performance in various climates are important research areas.

The goal of this effort was to define a series of research questions whose results:

1. update the foundation upon which recommendations to the ventilation standards for HUD-code homes are made, and
2. guide the industry towards improved, more efficient and cost-effective practices to achieve the desired ventilation level. An important part of this second goal is to identify effective whole-house ventilation strategies and provide a baseline for evaluating ventilation products and practices.

2.1 UNDERSTANDING AIR FLOW CHARACTERISTICS

2.1.1 Quantifying Whole House Airflow

Much effort has gone into attempts to quantify airflow within a home and the rate of air changes with the outside. A number of field studies conducted from the late seventies through early nineties attempted to quantify the average natural infiltration rate for typical manufactured homes. These studies established an approximate average rate of 0.25 air changes per hour (ACH) under natural conditions (3, 13, 14, 35). This data formed the foundation upon which the MHCSS whole-house ventilation standards are now based.

While two of these studies monitored homes in the field over long periods, they were all conducted on a limited number of homes (two homes in Indiana for 16 months (13); 35 homes in the northwest over a winter (14); one home in a test chamber (35)) and all derived, through extrapolation, average air change rates over an extended period of time (3).

Two more recent efforts by the Manufactured Housing Research Alliance measured envelope leakage rates in 66 existing and 22 newly constructed energy-efficient manufactured homes using blower door tests[1]. Blower door tests measure envelope "leakage" rates at a given pressure (usually 50 Pascal) rather than natural infiltration rates directly. The leakage rates found translate into average infiltration rates of 0.43 ACH for the existing homes, and 0.26 ACH for the new homes, using a simplified version of the LBL Infiltration Model (see below) to estimate an average infiltration rate from the blower door measurements to an average infiltration rate. The variation within these data sets, expressed as standard deviation as a percentage of the mean value, is 36% and 23% for the existing and new energy efficient homes respectively[2]. This indicates some lack of consistency of envelope tightness for typical manufactured homes, but a trend towards improved tightness and consistency of the building envelope for current practice energy efficient homes.

2.1.2 Predicting Air Exchange With The Outdoors

Two primary methods are used to measure the leakiness, and thereby predict the natural infiltration rate, of a home's envelope: tracer gas tests and blower door tests. Tracer gas tests are more precise and can be conducted over long periods of time to measure actual air change rates either with or without ventilation systems operating. A gas is released into the home and concentrations of the gas are monitored over time to determine how quickly the gas dissipates through the home's envelope. Tracer gas tests are time-consuming and complicated to administer but are useful for measuring airflow patterns and air change rates in limited numbers of homes and for calibrating computer models.

Blower door tests are one-time assessments of a home's leakage rate measured when the home is artificially pressurized. This test is relatively simple and quick to perform and gives a good snapshot of the leakiness of a home's envelope. The standard blower door test is conducted with the ducts open to the home; therefore, leaks in the ducts are incorporated in the results of a blower door test. Blower door tests, however, do not directly measure the air movement though a home's envelope under conditions of normal pressure. Therefore, a given home's average infiltration rate cannot be directly determined from this type of test. Attempts have been made to infer the natural infiltration rate from blower-door tests by accounting for additional design and climactic factors that impact the rate such as inside-outside temperature differential, wind speed, height of the home, and construction type.

The most commonly used method for predicting the natural infiltration rate from test data is the LBL Infiltration Model, developed by researchers at the Lawrence Berkeley National Laboratory. It incorporates four factors intended to account for the additional variables of wind, construction type,

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[1] Alternatives For Minimizing Moisture Problems in Homes Located in Hot, Humid Climates, Manufactured Housing Research Alliance, 2002

[2] The standard deviation of the data sets is 0.15 for the existing homes and 0.06 for the new energy efficient homes. Expressing this number as a percentage of the mean value of the data set, reveals the consistency of the measurements, or lack thereof.

climate, and building height. Selection of these factors, particularly those for wind shielding and construction type, requires some degree of subjective interpretation.

Examining the extremes of these factors permits the prediction of the maximum variation in natural infiltration for two manufactured homes with the same blower door test results according to the model. The model's wind shielding correction factor ranges from 0.9 to 1.2. The leakiness correction factor (which accounts for the type of cracks in the home's envelope) ranges from 0.7 to 1.4. The climate factor ranges from 14 to 26. The height factor does not affect this analysis since virtually all manufactured homes are one story. Multiplying the extremes of these factors together results in a minimum overall factor of approximately nine (0.9 * 0.7 * 14 = 8.82) and a maximum of approximately 44 (1.2 * 1.4 * 26 = 43.68), a variation of up to 490%. So, applying the LBL infiltration model, two manufactured homes with equal blower door test results, may have estimated average infiltration rates that vary by nearly a factor of five depending on the homes' climate, microclimate and construction characteristics.

2.1.3 The Difficulty in Quantifying Air Flow

Developing a "typical" natural infiltration rate for manufactured homes with any degree of certainty has proven exceedingly difficult. While it is possible to measure the static leakage rates for large samples of homes using blower door tests (MHRA studies), this tells us little about how these homes perform over time under varying daily and seasonal weather conditions (17). Site factors such as temperature, wind, orientation of the home, and construction type further complicate the issue by their varying impacts on the natural infiltration in homes with equal leakage areas.

These points speak to the limits of attempting to predict airflow rates with any degree of certainty. The large body of accumulated experience does not suggest that *most* homes built to the current standards experience severe indoor air quality and building moisture control problems due to inadequate ventilation. But there is no concrete evidence one way or the other. It is also unclear to what extent homes are over-ventilated, and suffer corresponding energy penalties and moisture control problems.

2.1.4 The Engineering Community Consensus

The consensus of the engineering community, expressed through the ASHRAE process, is that a natural infiltration rate of 0.35 ACH measured using the accepted techniques will result in adequate indoor air quality most of the time for most homes. ASHRAE settled on a recommended air change rate of 0.35 ACH for residential structures as a balance of health (indoor air quality) concerns against the desire for energy conservation. It is understood to be a rough and imperfect approximation of how a healthy, energy-efficient home should perform on average. It is this static target to which the current MHCSS sets the bar, and which existing ventilation methods strive to attain.

2.2 CODIFYING VENTILATION REQUIREMENTS

2.2.1 The Current HUD-Code

In attempting to codify a target rate for whole house ventilation, HUD made the following simplifying assumptions:

1. Homes should be capable of being ventilated at 0.35 ACH. That is, the target rate does not need to be achieved on a continuous basis but under "average" conditions and with

ventilation system operating, the home would be expected to be exchanging air with the outdoors at this rate[3].

2. Of this total, 0.25 ACH is assumed to be provided by natural infiltration resulting from the construction of the home, its operation, and site factors.
3. The remaining ventilation shall be provided by a balanced mechanical, passive, or combination mechanical/passive system with a minimum capacity of 0.035 cubic feet per minute per square foot (cfm/sf) floor area. When the mechanical or passive system is activated, pressure differentials are initiated which often reduce the degree of natural infiltration. Therefore, the mechanical or passive system must make up for this reduction, in addition to the simple 0.1 ACH differential between the 0.35 ACH requirement and the 0.25 ACH assumed from natural infiltration. The formula used by HUD, which accounts for this reduction as well as typical ventilation system efficiencies, yields a minimum capacity of 0.035 cfm/sf floor area, which translates to approximately 0.20 ACH.

Several active and passive strategies have been designed to meet the MHCSS specification including supply and exhaust ventilation systems using both manual and automatic controls.

How these ventilation strategies actually perform in manufactured housing on a dynamic basis is not well understood. It is believed that many ventilation strategies over ventilate or under ventilate and do not provide a continuous exchange of indoor air. Not all approaches to whole house ventilation work equally well nor are they all intended for the same set of environmental conditions. For example, some strategies that are adequate in smaller homes may not perform as well in larger homes. Others that are suitable in heating dominated climates may add excess moisture in hot, humid climates. Current whole-house ventilation strategies are characterized in Appendix A.

2.2.2 NFPA Committee Recommendations

The issue of whole house ventilation has been considered by the NFPA Committees.

In the 2000 edition of the 501 Standard on Manufactured Housing, NFPA drops the reference to natural infiltration and the 0.35 ACH overall goal, and simply prescribes the minimum ventilation system capacity of 0.035 cfm/sf floor area as its overall air exchange requirement.

As described above in Section 1.2.1, two primary assumptions are made in order to result in the HUD/NFPA prescription of 0.035 cfm/sf floor area ventilation system capacity: the 0.35 ACH goal for an average fresh air ventilation rate and the average natural infiltration rate of 0.25 ACH for manufactured homes. It is not within the scope of this work to challenge either of these assumptions. The proposed research will investigate cost effective ways of meeting the parameters set forth by NFPA 501 (2000 edition) 2.3.2 Whole House Ventilation.

NFPA establishes the following parameters for whole house ventilation (excerpted from Manufactured Housing Standard 501, 2000 edition, 2.3.2):

1. "2.3.2 Whole-House Ventilation. Each manufactured home shall be provided with whole-house ventilation having a minimum capacity of 0.035 ft3/min * ft2 (10.8 L/min * m2) of interior floor space or its hourly average equivalent."

[3] The HUD-code also requires dedicated kitchen and bathroom ventilation fans for local moisture removal. These fans are not counted towards the whole house ventilation requirement and so are not discussed in this report. The HUD Code allows operable glazed areas in place of mechanical ventilation for toilet compartments in Uo Zones I and II.

2. "2.3.2.1 …The ventilation system or provisions for ventilation shall not create a positive pressure in Uo value Zone 2 and Zone 3 or a negative pressure condition in Uo value Zone 1 in excess of 0.03 inches of water (7 Pa)."
3. "2.3.2.2 … The ventilation system shall be designed to ensure that outside air is distributed to all bedrooms and main living areas."

This last requirement is somewhat vague. It has been demonstrated that manufactured housing can be built to perform well in terms of inter-zonal air distribution. However, it is far from certain that many homes are performing well in this regard and it is not clear what the maximum acceptable inter-zonal pressure differentials should be and what effect this has on ventilation and long term home performance.

3

FURTHER RESEARCH NEEDS

3.1 RESEARCH GOALS AND TASKS

Research is needed to establish whether or not existing whole house ventilation systems, once installed and operating in typical manufactured homes, exchange air with the outdoors at the rate that is specified in the HUD code and to consider options to improve system performance and cost efficiency.

The goal of this work is to develop design strategies that meet the HUD requirements and those proposed by NFPA in the most cost effective manner, while maximizing comfort and minimizing potential moisture problems.

This goal will be reached through the process outlined below:

3.1.1 Improve Ventilation Strategies and Publish Guidelines

Task a. Develop comprehensive system design strategies

Comprehensive strategies include the mechanical or passive ventilation system in concert with the design of the home itself. This system must function consistently well in a variety of home sizes and configurations and in a range of climates. It is relatively simple to design a fan that will move the required amount of air under laboratory conditions. It is far more complex to ensure that this system performs as intended once installed in a home. Factors that will be considered include the layout and installation of the ductwork, location of registers, location of air handler unit, shell leakage, duct leakage, the location of interior walls and doors, control systems and recommended operating profile.

Two or three system alternatives are expected to be developed in addition to the current ventilation system designs currently used by most manufacturers. These systems may include elements of fresh air inlet to furnace systems (Appendix A.1), whole house dedicated exhaust fans (Appendix A.2), heat recovery ventilators, and other ventilation systems. The designs will be investigated in conjunction with an actual home. Home manufacturers and ventilation system suppliers will be involved in the development of the new ventilation system concepts.

Task b. Evaluate the performance of the systems developed

Full scale testing and/or computer models will be used to evaluate the performance of the systems designed above in meeting the HUD performance targets.

- Each system developed will be installed in up to three homes of varying sizes and configurations – at least one single and one double section home. If possible, multiple systems will be installed in the same home and tested independently.
- Duct leakage[4] and shell leakage measurements taken with duct blaster and blower door tests will be analyzed to benchmark each home's air leakage performance characteristics.

[4] The ducts in these homes will be constructed so that they are relatively tight – a maximum of 5% cfm per sf floor area of duct leakage to the outside.

- Short-term tracer gas tests will be conducted to determine the air change rates during operation of the ventilation systems. This actual rate will be compared to name plate cubic feet per minute (cfm) flow rate of the ventilation system in use.
- Air pressures will be measured in each room of the home, comparing inside and outside pressures during operation of the ventilation system(s) to determine if positive or negative pressures are generated and the degree of those pressures.
- Interior and exterior air moisture content will be monitored to gauge how the system impacts humidity and vapor pressure.
- Tests will be repeated to evaluate the effects of a number of occupant-controlled variables such as door position and operation of spot kitchen and bath ventilation fans and clothes dryer vents. Tests will be conducted with windows closed as the prescribed ventilation requirements are in addition to window opening area.
- A cost analysis will be performed to determine the impact on home price and operating costs of the newly developed ventilation systems.

Task c. Refine designs

Designs will initially be refined based on computer simulations and/or calculations. Once installed in test homes, the systems will be modified as necessary to achieve target ventilation rates and other performance criteria such as reliability, pressure balancing, and cost. The refinement process will push the envelope of system designs in the search for optimal system performance.

Task d. Manual of best practices

The outcome of this task will be a document illustrating best practices for whole-house ventilation of manufactured homes.

3.2 DELIVERABLES

3.2.1 Technical Report of Findings

This report will discuss the design process utilized to develop the ventilation systems, the characteristics of the systems, and the homes in which they were installed. It will document the testing procedures and initial test results, as well as the redesign efforts and final testing results. It will include detailed drawings and specifications of the ventilation systems, as well as schematic drawings of the test homes and test set-ups.

3.2.2 Publish Guidelines for Whole House Ventilation in Manufactured Homes

A best practice manual for whole house ventilation will be created for the industry. This manual will address comprehensive system design and optimization of system operation, including

- Design and specifications for one to three ventilation system types suitable for manufactured homes that will meet the performance targets established by HUD and NFPA.
- Estimate of the initial and operating costs of these systems
- The optimum operating profile on a daily and seasonal basis for these systems on a climate-specific basis.
- How the operating profile should be modified by climate.
- How shell and duct leakiness and building design affect the optimum operating profile.

Consumer education is also a key component in the proper operation of whole house ventilation systems. Currently, there is confusion and a lack of understanding of the purpose and need for whole house ventilation systems. Educational materials targeted at the purchasers of manufactured homes will be created to address this need.

3.2.3 Make Substantial Recommendations For Changes in the HUD-Code

A technical report documenting the research and testing results will be written. The report will substantiate any proposed recommendations for modifying or fine-tuning the HUD-code. These recommendations may be climate-specific.

APPENDICES

A

CHARACTERIZATION OF EXISTING VENTILATION SYSTEMS

The whole house ventilation systems commonly in use today can be grouped together into two basic categories, with some options within each category. Both are active (mechanical) ventilation systems.

A.1 FRESH AIR INLET TO THE RETURN AIR COMPARTMENT OF THE FURNACE

With this system, fresh air is ducted from the outside directly into the return air compartment of the furnace. There are a few variations of this strategy:

- ✓ The inlet duct either has a gravity-damper or no damper. This system is the most common.
- ✓ The inlet duct has a motorized damper, which opens on call from the thermostat.
- ✓ A timer can be added to this system to prevent long periods of inadequate ventilation during the “shoulder” months (spring and autumn) when the air handler operates infrequently.
- ✓ A roof-mounted fan pressurizes the attic, which is exhausted through gable vents. A portion of the fresh air is directed into the furnace cabinet, where it is conditioned before being distributed to the home.

This type of system is a simple method of introducing fresh air into the home, however it does have drawbacks. Air is drawn into the fresh air duct only when there is a call for heating and cooling and the main furnace blower is activated (systems with timers are an exception). This results in inconsistent ventilation operation, particularly during the swing seasons when the air handler, and therefore the ventilation system, is not operating for long periods of time. Operational frequency will also vary greatly by climate with the operation of the heating and cooling system.

When operating, outside air enters the air handler without regard to the temperature or humidity of the incoming air. This can increase the load on the air conditioner beyond its dehumidification capacity. Gas furnaces may be able to overcome the additional heating load, but total electric systems may have difficulty, which can result in high utility bills and comfort problems. The HUD-mandated ventilation rate of 0.035 cfm/sf floor area may be more than the air conditioning system and/or furnace can satisfactorily condition in some circumstances. Although reports of this phenomenon are anecdotal and not necessarily widespread, this factor should be considered when designing whole house ventilation systems. Field technicians have been known to recommend that homeowners seal off the fresh air duct or detach it from the furnace to solve the comfort problem and reduce utility bills. This solution, however, compromises fresh air ventilation.

A.2 DEDICATED EXHAUST FAN

A dedicated exhaust ventilation fan connected to a fresh air duct to the outside is installed in a central area in the home – usually a central hallway. This fan is typically manually operated, although it is possible to connect it to a timer, humidistat, or the central heating and cooling system operation.

The advantage of this system is that a timer or humidistat control can be calibrated to provide ventilation at regular intervals or when humidity, one of the most important indoor "pollutants", is high. A dedicated exhaust fan is typically much smaller and uses considerably less energy than a furnace blower. It also provides maximum occupant control.

Occupant control can be a disadvantage if the occupants choose not to use it, as humans are poor judges of ventilation needs. As with the fresh-air to furnace system, temperature and humidity of incoming air is not controlled and can add to the latent or sensible load of the home. In this case the potential for moisture and comfort problems is even greater since the air is not pre-conditioned by the HVAC system before entering the home. The source for the make up air is not provided as part of this ventilation system, and so the exhaust fan has the potential to contribute to negative pressures within the home, which is theorized to contribute to moisture problems in hot, humid climates in particular[5].

Dedicated exhaust ventilation fans are similar to dedicated spot ventilation fans for kitchens and baths, as mentioned in Section 2.2.1. In some cases, a system may be designed as a dual-function spot and whole house dedicated exhaust fan.

[5] Minimizing Moisture Problems in Homes Located in Hot, Humid Climates: Interim Report, Manufactured Housing Research Alliance 2002

B

SUMMARY OF LITERATURE

Most of the literature reviewed for this report was based on research conducted on HUD-code homes (25 of 35 applicable articles). Natural air infiltration varies greatly on a daily and seasonal basis, as well as by local climate factors including wind and temperature, which also influence the frequency of window opening by occupants. A regular air change rate of 0.25 ACH due to natural infiltration can not be depended upon on a regular basis (3, 17, 26). Although some older manufactured homes showed leakage levels that would exceed the rate required by code, achieving acceptable natural infiltration at least some of the time (10), it is theorized that newer homes built to higher energy conservation standards do not. One researcher concludes that natural infiltration is an important component of a good whole house ventilation system, but provides an unknown level of ventilation (33). This same researcher claims that infiltration is highest during times of the year when window opening is least desirable (33), i.e. cold and windy weather. A number of researchers make the point that occupant-controlled mechanical and passive ventilation systems can not be counted on as their pattern of use is unknown, variable and inconsistent (3, 17, 26). The two most advantageous mechanical ventilation systems for HUD-code homes from a cost and operational standpoint are fresh-air-duct-to-furnace and whole-house-exhaust-fan (22). At least two studies conclude that the location of the whole house exhaust fan does not significantly affect ventilation performance in HUD-code homes (17,26), however, studies of site-built homes show that fresh air distribution is not adequate for closed rooms without fresh air distribution ducts located within them (27, 30). Two field studies claim that many whole house ventilation systems on the market do not perform up to their rated cfm specification level (14, 23).

1. **Pacific Northwest National Laboratories, June 1991. "Air Exchange Rates in New Energy-Efficient Manufactured Housing." Pacific Northwest National Laboratories, Richland, WA, at *http://mfdhousing.com/pnnl/ots.html*.**

This study describes the performance of the whole house ventilation system and presents results of the air leakage and air exchange measurements of 139 newly constructed, energy efficient manufactured homes built under Bonneville's RCDP and 35 current practice manufactured homes. Standard door fan pressurization was used to estimate shell leakiness and a passive perfluorocarbon tracer was used to estimate air exchange rates.

2. **Alternative Energy Corporation, 1996. "Air of Importance: A Study of Air Distribution Systems in Manufactured Homes." Alternative Energy Corporation, Raleigh, NC.**

ADS degrade energy performance dramatically through air leakage and conduction, mainly as a result of poor installation and set-up.

3. **Burch, D.M., May 1993. "Indoor Ventilation Requirements for Manufactured Housing." NISTIR 4574, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.**

Mathematical analysis of HUD code homes indicates that natural infiltration is not sufficient to meet the 0.35 ACH guideline/requirement. Recommendation is that 55 cfm mechanical equipment be required since occupant-operated fans and windows can not be counted on in cold or hot periods to supply the remaining ventilation. Three independent field tests also found natural air infiltration rates in the 0.25-0.28 ACH range.

4. Burch D. M., and A. TenWolde, 1993."A Computer Analysis of Moisture Accumulation In The Walls Of Manufactured Housing." ASHRAE Trans. 1993, vol.99, Part 2, Paper number DE-93-16-1, 977-990.

Abstract: A detailed computer analysis was conducted to investigate the effectiveness of three alternative practices for controlling moisture accumulation in the walls of manufactured housing during the winter. The three practices included (1) providing an interior vapor retarder, (2) using permeable sheathing and siding, and (3) providing an outdoor ventilated cavity. The current HUD Manufactured Home Construction and Safety Standards do not require a vapor retarder for practices 2 and 3. The analysis was carried out for cold winter climate (Madison, WI), an intermediate winter climate (Boston, MA), a mild winter climate (Atlanta, GA), and a Pacific Northwest climate (Portland, OR). The practice of providing a vapor retarder was found to be effective in all four climates. The moisture content of the siding was always considerably below fiber saturation. On the other hand, the practice of using permeable sheathing and siding and the practice of providing an outdoor ventilated cavity were not always effective in colder climates. Moisture accumulated above fiber saturation, and free liquid water existed within the pore structure, providing a potential for material degradation. A detailed computer analysis was also conducted of moisture accumulation in manufactured housing walls in a hot and humid climate (Lake Charles, LA). During the summer, moisture from the outdoor environment is transferred into manufactured housing by diffusion and, more important, infiltration. As a result, moisture accumulates at interior layers of the construction cooled by air conditioning. When an interior vapor retarder is used in the construction, the relative humidity at the outside surface of the vapor retarder can approach saturation, thereby providing an environment conducive to mould and mildew growth.

5. Burch, D.M., and A. TenWolde, 1993. "Ventilation, Moisture Control, and Indoor Air Quality in Manufactured Houses: A Review of Proposed Changes in the HUD Standards and a Proposal for Revised Standards." Forest Products Laboratory, Madison, WI, and National Institute of Standards and Technology, Gaithersburg, MD.

FPL/NIST proposed revisions of 3280.103:

B1) To accomplish 0.35 ach, home should be equipped with one of the following ventilation systems with a minimum continuous capacity of 0.035 cfm/sf floor area.

i. Fresh air inlet from exterior to furnace with exhaust vents to prevent positive indoor air pressure during winter.

ii. Mechanical ventilation system designed for continuous operation

iii. Passive system other than operable windows

iv. Combination of passive and mechanical system

v. Operable windows except in region 4 and Alaska

Ventilation system shall not create adverse positive indoor pressure in regions 3 & 4 or negative in southern cooling climates.

Kitchens shall have mechanical system capable of 100 cfm, bathrooms 50 cfm.

6. Conlin, F., E. Levy, and B. Warren, 1997. "Measured Air Flow Capacity Through Engineered Orifices." The Levy Partnership, New York, NY.

Many kitchen and bath vents can fulfill the requirement for sidewall vents in manufactured homes.

7. Davis, B., 1997. "Response to 'Ventilation Facts and Fallacies in Manufactured Homes'." Home Energy Magazine, Nov./Dec., at *http://hem.dis.anl.gov/eehem/97/971102.html#97110207*.

Furnace-based ventilation systems, because they operate only intermittently and use a large fan to circulate air in most homes, result in very little long-term pollutant dilution or removal in a manufactured home. Continuously operating moderate-volume exhaust fans designed to run for long periods with quiet operation do a much better job of pollution dilution and removal.

8. Devine J., R. Kunkle, and M. Lubliner, 1999. "Occupant interaction with Washington State Ventilation and Indoor Air Quality Code Mandated Whole House Ventilation Systems: Telephone Survey Results - Washington State University Energy Program." ASHRAE Transactions, Vol.105, Part 2, Paper number SE-99-11-04, 877-880.

Abstract: The Washington State Ventilation and Indoor Air Quality Code (VIAQ) has required the installation of whole house ventilation systems in all new homes since July 1991. A variety of systems are allowed by the VIAQ. In May 1998, a survey was conducted to explore occupant interaction with the code mandated systems. The survey is part of a research project designed to explore the effectiveness of the VIAQ. Examines the data collected from a survey of 235 Washington State residents living in homes effected by the ventilation requirements. During a 10 minute telephone interview, respondents were asked about repair records, alterations, inconveniences, and benefits of their whole house ventilation systems. The study reveals that people are concerned about indoor air quality, and believe fresh air is important for health. However, they do not operate their ventilation systems near as much as recommended (3.4 hours on average compared to 8 hours per day recommended) and when they adjust their systems, they adjust them to provide even less fresh air. Over 99% of the people surveyed believed the air in their homes was good or average. People who have problems with the systems, such as noise, draughts and/or energy waste, use their systems less than other people. While people who have code mandated ventilation systems are typically not aware of all the systems components, 64% of those with ventilation systems say they would install the same systems again.

9. Dorer, V., and D. Breer, 1998. "Residential Mechanical Ventilation Systems: Performance Criteria and Evaluations." *Energy and Buildings*, Vol. 27, No. 3, June. pp. 247-255.

Abstract: The performance of mechanical ventilation systems has been checked in several innovative residential houses as part of either a Swiss research or a P&D (pilot and demonstration) project. This paper gives a list of performance criteria for the ongoing comparison and evaluation of these mechanical ventilation systems. For some criteria, target values are proposed. In the second part, this paper briefly describes four residential buildings with mechanical ventilation systems where such evaluations were performed, and highlights interesting design features and results from the measurements. It then focuses on discrepancies between the design goals and what has been encountered in reality during the evaluation campaign. Problem items were, among others, commissioning, occupant acceptance and window opening behavior as well as sealing of ducts and heat exchangers.

10. Ek, C.W., S.A. Onisko, and G.O. Gregg, 1989. "Air Leakage Tests of Manufactured Housing in the Northwest USA." Symposium on Air Change Rate and Air Tightness in Buildings, ASTM, Atlanta, GA April 16-17.

93 double-wide manufactured homes from 19 manufacturers were tested via blower door tests. The average leakage rates were found to be 8.40 Pa, correlating to 0.50 ACH predicted in normal atmospheric pressure. Specific areas of leakage in the envelope were determined with smoke stick tests.

11. Pacific Northwest National Laboratories, Nov. 1996. "Energy and Indoor Air Quality Measurements from Five Energy Conserving Manufactured Homes." Pacific Northwest National Laboratories, Richland, WA, at *http://mfdhousing.com/pnnl/ots.html.*

This study attempted to determine whether manufactured homes built to the Model Conservation Standards performed according to the energy requirements of the standards. Air exchange rates in these homes and indoor air pollutants levels were measured. All analyses were made under unoccupied conditions to establish a baseline independent of occupant characteristics and behavior.

12. Feustel H. E., M.P. Modera, et al, 1986. "Ventilation Strategies for Different Climates." Proceedings IAQ 86, Managing Indoor Air for Health and Energy Conservation USA, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, Georgia, April 20-23, 342-363.

Abstract: Until recently, residential ventilation in the United States has been provided by infiltration. In this report we compare natural ventilation (ventilation by infiltration) with several mechanical ventilation strategies and examine the overall energy consumption associated with strategies in different climatic regions in the US. The strategies examined are; natural ventilation, balanced ventilation with an air-to-air heat exchanger, exhaust ventilation without heat recovery and exhaust ventilation with heat recovery via heat pump. Two strategies for utilizing the heat pump output for domestic hot water are examined. One heat pump strategy employs exhaust fan reversal to provide space cooling whenever possible during the summer months. A modified TRNSYS residential load model incorporating the LBL infiltration model, an algorithm to calculate effective ventilation and a modified TRNSYS domestic hot water model are used to simulate the energy consumption associated with each strategy. The domestic hot water model is used to determine the useful heat supplied by an exhaust ventilation heat pump as a function of daily hot water demand. The simulations indicate that the choice of ventilation strategy can have a significant impact on energy consumption. They show that total end-use energy consumption can be reduced to as much by mechanical ventilation as by super insulation of a house. The comparisons also show that for the same effective ventilation rate, houses with mechanical ventilation systems (especially those with exhaust fans) have better indoor air quality than those that rely on natural ventilation.

13. Goldschmidt, V.W., and D.R. Wilhelm, 1981. "Relation of Infiltration to Weather Parameters for a Mobile Home." ASHRAE Transactions, V. 87, Pt. 2.

Natural infiltration rates were measured in two mobile homes in Indiana for 16 months. The researchers developed a correlation for the rate of infiltration as a function of inside-outside temperature difference and wind speed. Results indicated a rate of 0.25 ACH for a temperature difference of 30 degrees F and a wind speed of 7 mph.

14. Hadley, D.L., and S.A. Bailey, 1990. "Infiltration/Ventilation Measurements in Manufactured Houses - Residential Construction Demonstration Program." Pacific Northwest Laboratory, Richland, WA, PNL-7494.

139 MCS (energy-efficient) homes and 35 current practice homes were tested. The exhaust system did not perform up to its 50 cfm rating (performance was approx. 30 cfm). The MCS homes were much tighter as tested with blower door test. In a 2-6 week "as lived in" PF tracer gas test, air infiltration rates were similar, indicating additional ventilation in the MCS house, although it is hypothesized that this was primarily due to passive ventilation since the exhaust systems were insufficient. Mean infiltration rate for the 35 homes measured with tracer gas during heating season was 0.28 ach.

15. Jewell, R.L., August, 1981. "Reduction of Manufactured Housing Formaldehyde Levels by Ammonia Fumigation." Chemistry Department, Weyerhauser Company, Federal Way, WA.

Measurements of 18 manufactured homes with tracer gas ranged from 0.1 to 0.5 ACH with mean of 0.27 ach.

16. Lee, A.D., Z.T. Taylor, G.B. Parker, G.L. Wilfert, J.W. Callaway, and S.A. Onisko, November 1986. "Energy and Indoor Air Quality, Measurements from 5 Energy Conserving Manufactured Homes." Pacific Northwest National Laboratories, Richland, WA.

Tests were performed on 5 unoccupied Model Conservation Standards (energy-efficient) HUD-code homes. Conclusions: (1) manufactured homes can be built with low air change rates (although leakage increases 20-100% with transport). Rates were 0.1 ACH or less without air-to-air heat exchangers operating. (2) Tight construction does not necessarily lead to high levels of formaldehyde or radon – both fell well below HUD targets. (3) Air-to-air heat exchangers are helpful in increasing air exchange rates, but do not perform up to designed air exchange rate calculations. In 4 homes, the air-to-air heat exchangers achieved the 0.6 ACH target.

17. Lubliner, M., and A. Gordon, September 2000. "Ventilation in U.S. Manufactured Homes: Requirements, Issues and Recommendations." Presented at 21st Annual AIVC Conference, The Hague, Netherlands.

Using a single value for weather-driven infiltration is problematic. For example, according to a computer model, the air change rate is below 0.25 ACH for about 33% the year in Albany and Seattle and 70% of the year in Miami (the percentages would be lower if duct-leakage were eliminated). Effectiveness of mechanical strategies is dependent on their operating schedule. Whole-house exhaust fan location was unimportant. MHCSS recommendations included.

18. Lubliner, M., and D. Stevens, 1997. "Ventilation Facts and Fallacies in Manufactured Homes." Home Energy Magazine, July/August, at *http://hem.dis.anl.gov/eehem/97/970704.html#97070401*.

A continuous-exhaust ventilation system with inlet vents in the window frames is more cost-effective than a furnace-based system. It offers homeowners efficient mechanical ventilation systems, maintains comfort, and reduces operating costs. These systems can thus allow manufactured homes to be made tighter without creating indoor air quality problems.

19. Lubliner M., D.T. Stevens, and B. Davis, 1997. "Mechanical Ventilation in HUD-code Manufactured Housing in the Pacific Northwest." ASHRAE Transactions 1997, Vol.103, Part 1, paper number PH-97-8-2, 693-705.

Abstract: Electric utilities in the Pacific Northwest have spent more than 100 million dollars to support energy-efficiency improvements in the Housing and Urban Development (HUD) code manufactured housing industry over the past several years. More than 65,000 manufactured housing units have been built since 1991 that exceed the new HUD standards for both thermal performance and mechanical ventilation that became effective in October 1994. All of these units included mechanical ventilation systems that were designed to meet or exceed the requirements of ASHRAE Standard 62-1989. Addresses the ventilation solutions that were developed and compares the comfort and energy considerations of the various strategies that have evolved in the Pacific Northwest and nationally. The use and location of a variety of outside air inlets will be addressed, as will the acceptance by the occupants of the ventilation strategy.

20. Ecotope, Inc., May 1992. "Measured Infiltration and Ventilation in Manufactured Homes." Item #33 at *http://mfdhousing.com/pnnl/ots.html*.

This report summarizes the results of infiltration measurements made on two groups of manufactured homes in Bonneville's service area: 131 energy efficient homes constructed under RCDP and a control group of 29 homes not participating in energy efficiency programs. Two basic techniques

were used to estimate infiltration: the perfluorocarbon tracer method and the blower door depressurization tests combined with an infiltration model developed at Lawrence Berkeley Laboratory.

21. Meier, A., 1994. "Infiltration: Just ACH50 Divided by 20?" Home Energy Magazine Online, January/February.

Discussion of how to convert one-time blower-door air leakage measurements to approximate average infiltration rates. Discusses the genesis of two methods, including the LBL infiltration method.

22. Miller, J.D., and C.C. Conner, 1993. "HUD Ventilation Standard for Manufactured. Homes: System Prototype Descriptions and Cost Information." Pacific Northwest National Laboratories, Richland, WA.

Descriptions of five prototype ventilation systems that could meet the new HUD requirements. System 1 (fresh air duct to furnace) and system 2 (house exhaust fan) offered the lowest cost and most advantages. Cost for these systems range from \$200-\$300 per home for materials and labor installation (1993 dollars).

23. Palmiter, L., T. Bond, I. Brown, and D. Baylon, April 28, 1992. "Measured Infiltration and Ventilation in Manufactured Homes; Cycle II." Ecotope, Inc., Seattle, WA.

Ventilation and infiltration measurements of 160 homes (131 of which were built to energy-efficient Super Good Cents (SGC) standards). The standard of deviation of infiltration and tightness parameters was too high (30% of the mean) for efficient operation of the mechanical ventilation equipment. Ventilation in most SGC homes failed to meet the 0.35 ACH standard. Even with fans operating 24hr/day, 0.35 ACH would not be achieved in many conditions. Most fans did not provide ventilation at the rated capacity due to system design and installation flaws. From an engineering standpoint, the optimum home is nearly airtight and has a mechanical ventilation system. If a significant component of ventilation is natural infiltration, problems with control and predictability result in either energy waste or inadequate ventilation.

24. Parks, B., 1999. "Manufactured Housing Fresh Air Ventilation System Field Test." Prepared for the Administrator of Manufactured. Homes, Office of the State Fire Marshall, Department of Public Safety and Corrections, by Parks Air & Heating, West Monroe, LA.

Field test to determine if FAVS contribute to MH moisture problems. Conclusions: (1) FAVS are ok in the north where small amounts of moisture are needed, but not in south because it adds moisture (2) central A/C unit should be toward center of home to minimize humidity problems.

25. Persily, A.K., May 1998. "A Modeling Study of Ventilation, IAQ and Energy Impacts of Residential Mechanical Ventilation." NISTIR 6162, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

Multi-zone simulations of IAQ, ventilation, and energy impacts of site-built house in Washington State. One year simulations for 4 different ventilation approaches.

26. Persily, A.K., and S.R. Martin, 2000. "A Modeling Study of Ventilation in Manufactured Houses / Ventilation Strategies for U.S. Manufactured Homes." NISTIR 6455, Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, MD.

Computer modeling of double-wide manufactured homes predicted infiltration rates lower than the assumed 0.25 ACH for many hours of the year. The supplemental ventilation systems examined meet or exceed the required 0.35 ach, but are dependant on operation schedule. Impact of whole-house exhaust fan is independent of whether located in main living area or bath off main living area. For the case of a whole-house exhaust fan, passive inlet vents are not required with the assumed levels of leakage. HUD standards changes are suggested.

27. Rudd, A.F., 1998. "Measured Air Change Rates and Distribution of Ventilation Air In A Single Family Home." Building Science Corporation, Westford, MA, at *www.buildingscience.com.*

A 1-story, 1350 sf house in Las Vegas was outfitted with two independent ventilation systems. The relative difference in air change rate and distribution of ventilation air induced by their operation was evaluated. (1) Intermittently operated central-fan-integrated supply ventilation system, wherein, 47 ft3/min of outside air was ducted into the return air side of the central heating and cooling system blower. Tracer gas test results showed excellent uniformity of ventilation air distribution, while the installed outside air duct was undersized. (2) Continuously operated separate supply ventilation system, not connected to the central air ducts, wherein, a separate fan drew 54 ft3/min of outside air and 112 ft3/min of re-circulated inside air from the master bedroom and delivered the resulting 166 ft3/min of mixed air to the main living area. Results showed poor ventilation air distribution for closed bedrooms where there was no ventilation system ducting, while the air change rate for the main living area, and to a lesser extent the master bedroom, was adequate.

28. Rudd, A.F., 2000. "Practical Approaches to Residential Ventilation for Improved Durability and Indoor Air Quality." Durability and Disaster Mitigation in Wood-Frame Housing Conference, November 8, Madison, Wisconsin.

29. Rudd, A.F., 1999 "Discussion of Ventilation System Energy Performance and Cost." Building Science Corp., Westford, MA, at *www.buildingscience.com.*

An hourly simulation study using DOE2.1E was conducted to determine the annual difference in energy consumption between various ventilation options in different climates. Comparison of central fan vs. multi-port system with ducts installed either inside or outside the conditioned space. Compares energy use and operating cost.

30. Rudd A. F., and J.W. Lstiburek, 2000. "Measurement of Ventilation and Inter-Zonal Distribution in Single Family Homes." ASHRAE Transactions, Vol.106, Part 2, paper number MN-00-10-3, 709-718, at *www.buildingscience.com.*

Abstract: Ventilation air change rate, local mean age-of-air, and interzonal ventilation air distribution were measured for two single-family homes and eight ventilation systems. A multizone, single-gas, tracer gas decay measurement technique was used. A single-story, slab-on-grade, 1350ft2 house was tested in Las Vegas, Nevada, and a two-story, 3192ft2 house with basement was tested in Minneapolis, Minnesota. The ventilation systems studied included various configurations of exhaust, supply, and balanced ventilation, with and without whole-house recirculation by the central heating and cooling air-handler unit fan. Some of the systems were independent of the central air distribution system, while others were integrated with it. In general, results showed that all ventilation systems benefited from periodic operation of the central fan, giving excellent uniformity of ventilation air distribution. Systems without central fan recirculation showed poor ventilation air distribution for closed rooms where there was no ventilation system duct.

31. Sherman, M.H., 1999. "ASHRAE's Residential Ventilation Standard: Exegesis of Proposed Standard 62.2." Lawrence Berkeley National Laboratory, University of California, Berkeley, CA.

Summary of the draft standard. Addresses questions and concerns that those affected by the proposed ASHRAE Standard 62.2 might have.

32. Sherman M.H., 2001. "Comments Welcome on Standard 62.2P." ASHRAE IAQ Applications, vol.2, no.4, 10-11.

Abstract: Reports on discussions within the ASHRAE Standards Project Committee on two issues: 1) unvented combustion appliances and 2) whether windows alone could provide whole house ventilation especially in cold climates. Compromise decisions were arrived at. The status of the various addenda to ASHRAE Standard 62-1999 is given.

33. Sherman, M., and N. Matson, 1996. "Residential Ventilation and Energy Characteristics." Lawrence Berkeley National Laboratory, University of California, Berkeley, CA.

The U.S. housing stock currently has a negligible number of houses using whole-house ventilation systems. Infiltration is the dominant ventilation system. Infiltration is often viewed as a poor ventilation mechanism because the flow paths are diffuse and unknown while the driving mechanism is both unstable and variable over the year. While these qualities do little for those who strive for certainty, they do have some advantages. Averaged over any time longer than a day, infiltration provides a floor on the ventilation rate even when no ventilation systems operate. Infiltration rates are the highest during the times of the year when window opening is least desirable. Although infiltration may have relatively low ventilation efficiency, it is at times the optimal system or, more often, a component of an optimal system.

34. Strunk, P.R., T.F. Brennan, W.R. Smith, and L.F. Kinney, 1999. "Residential Air Infiltration and Ventilation Demonstration." New York State Energy Research and Development Authority, Albany, NY, Report 99-5.

This report discusses results from eight homes in upstate New York in which continuous mechanical ventilation systems were installed. Measurements of air exchange, airflows, pressure differences, sound levels, and electrical power consumption were obtained to assess the system's performance. In addition, design and installation practices, as well as installation costs were evaluated.

Air exchange measurements under a variety of conditions indicated that natural air exchange s less than or very near 0.35 ACH much of the time in all eight homes. Four different types of ventilation systems were designed, installed, and tested in two homes each. Installation costs ranged from $1,426 to $3,398. Installed airflows at ducts and grilles were found to be within 10% of design airflows for the most part; tracer gas measurements of natural air exchange and exchange during ventilation showed average increases of 0.23 ACH and 0.41 ACH for the whole house and master bedroom, respectively. The systems were found to perform well in most respects, although several recommendations for improved performance are offered as a result of the work. Finally, the cost of ventilation in terms of extra space-conditioning energy and in electricity was evaluated at each house and found to be minimal for most of the systems.

35. Teitsma, G.J., and B.A. Peavy, 1978. "The Thermal Performance of a 2-Bedroom Mobile Home." NBS Building Science Series 102, National Institute of Standards and Technology, Gaithersburg, MD.

Air infiltration was measured for a mobile home in a test chamber. The researchers determined a correlation that resulted in a natural infiltration rate of 0.25 ACH for a temperature difference of 30 degrees F and a wind speed of 7 mph.

36. TenWolde, A., March, 1994. "Ventilation, Humidity and Condensation in Manufactured Houses During Winter." ASHRAE Transactions, Vol.100, Part 1, paper number 3746, 103-115.

Abstract: Many manufactured homes have lower natural ventilation rates than those in site-built houses. This, combined with high occupancy levels, may lead to moisture problems, which can cause

structural damage and health problems. The objectives of this study were to (1) obtain information on the moisture behavior of manufactured houses and moisture release from occupants and other sources and (2) evaluate the effect of mechanical ventilation. The ventilation and indoor humidity was measured in six manufactured houses during winter. The measurements indicate that ventilation in manufactured homes is often less than recommended. Using a mathematical model, the average moisture release and moisture storage rates were determined and the effect of mechanical ventilation with controls on humidity and comfort, condensation, and energy consumption during winter was analyzed. Results show that the average moisture release is similar to documented rates and that manufactured houses appears to store less moisture than site-built houses. However, moisture storage in manufactured houses is enough to reduce the potential for condensation during winter. To prevent significant condensation, natural ventilation is usually sufficient and mechanical ventilation is needed only in case of high occupancy and moisture loads or in an airtight house with negligible natural ventilation. ASHRAE's minimum ventilation requirements usually exceed the level needed to prevent condensation, and in cold winter climates, these minimum ventilation levels without humidification will cause the indoor air to be uncomfortably dry. To improve ventilation, manufactured houses should be supplied with balanced mechanical ventilation with an automatic control and manual override. In the absence of a better inexpensive alternative, a humidistat control may be used during winter to prevent condensation without excessive heat or comfort loss. However, a humidistat control does not ensure that ASHRAE minimum ventilation levels will be achieved.

37. Tuluca, A. N., M.H. Sherman, and M. Krati, 1990. "Reduction of the Effective Leakage Areas of Single-Section HUD-Code Manufactured Homes Due to Air Infiltration Barriers." ASHRAE Transactions, Vol. 96, Part 1, 39-45.

Abstract: This paper addresses the effective leakage area (ELA) reduction in single-section HUD-code manufactured homes due to the application of an air-infiltration barrier (AIB). The data used for the analysis were generated over a period of three seasons, through hourly measurements of air infiltration, temperature, and wind speed, at a site with two HUD-code homes, one sheathed with an AIB and the other one caulked (Wilhelm 1979). The effective leakage areas are calculated using a model (Sherman and Grimsrud 1980) that correlates the air infiltration rate in residences to (1) weather variables, (2) the effective leakage area of the house, and (3) coefficients that are determined by construction and terrain characteristics. Two sets of ELA calculations are performed for both AIB and caulked homes. In the first one, the model has the site-built housing coefficients presented in the ASHRAE Handbook of Fundamentals (ASHRAE 1989). In the second one, the construction coefficients in the model are modified to account for the particular construction characteristics of single-section HUD-code manufactured homes. The magnitude of the ELAs is discussed and recommendations are made for the value of the ELA reduction attributable to an AIB.

38. Wray, C. P., N. E. Matson, and M.H. Sherman, 2000. "Selecting Whole-House Ventilation Strategies to Meet Proposed Standard 62.2: Energy Cost Considerations." ASHRAE Transactions, Vol.106, Part 2, paper number MN-00-10-1, 681-691.

Abstract: ASHRAE Standard 62.2P is being proposed to address residential ventilation issues. As housing, especially new housing, gets more airtight and better insulated, it has become clear that many homes are under-ventilated. The standard contains requirements that provide minimum ventilation rates and source control measures necessary for acceptable indoor air quality. Previously reported analytical techniques are used to compare the energy costs of various ventilation strategies for a wide variety of climates and housing types. Concludes that for new construction, mechanical ventilation is needed. In new houses with gas heating, the cheapest whole-house system is a central exhaust fan. The marginal energy costs to provide such ventilation are on the order of 50 cents per day. However, other systems can be more appropriate when depressurization, filtration, moisture, and more expensive heating fuels are considered. For most of the existing housing stock, concludes that infiltration provides adequate ventilation.

39. Zieman, M.L., and J. D. Waldman, 1984. “Moisture Problems in Mobile Homes.” RADCO, Inc., Gardena, CA.

59 existing manufactured homes with moisture problems were surveyed in 5 regions. Condensation problems are believed to be caused by low indoor ventilation rates. Authors recommend 0.5 ACH to maintain indoor relative humidity low enough to prevent mold and condensation. Other studies have shown air change rates due to natural infiltration of 0.09 to 0.3 ACH with a mean of 0.16 ACH (Moduline International tests of 9 homes) and 0.1 to 0.5 ACH with a mean of 0.27 ACH (1981 study by Jewell).