U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

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Minimizing moisture problems in manufactured homes located in hot, humid climates

Response of interior air pressures to various operating conditions

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Minimizing Moisture Problems in Manufactured Homes Located in Hot, Humid Climates

Response of interior air pressures to various operating conditions

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TABLE OF CONTENTS

LIST OF FIGURES

About the figures

The pressure graphs included in this report were all created at a uniform scale and size (with the exception of Figure 3-12) in order to allow the reader directly to compare data among different graphs. Presenting the data on a common scale facilitates making comparisons between the factors that impact air pressure. As a result, the data points in certain graphs are clustered closely together and may be difficult to distinguish from each other. However, in these cases, the salient fact is exactly that there is little pressure difference between those areas of the home. As an aid in distinguishing among the lines, the graphs can be viewed in color by downloading the electronic version of the report posted on the MHRA website at www.mhrahome.org.

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LIST OF TABLES

EXECUTIVE SUMMARY

Avoiding moisture-related problems—such as material degradation and staining—is a challenge in all types of structures, particularly those located in the hot, humid Gulf Coast region of the U.S. As part of a multiphase research program to better understand the underlying causes of moisture-related problems in manufactured homes and to develop effective abatement strategies, a series of tests were conducted on two manufactured homes to profile airflows under varying conditions. Air movement is a major mechanism for moisture transport. Therefore, understanding how a home's design, construction and operation impact airflow is an important step in developing moisture control strategies.

The goal of this phase of the research was to develop sets of conditions that would result in a home having a neutral to slightly positive pressure relative to the outside. Such conditions create a barrier to air, and therefore moisture, movement from outside into the living spaces and the building cavities.

Data was collected from a single and a double section home, of typical design and configuration. Air pressures were logged continuously in various spaces and cavities as a number of conditions in the homes were varied. Parametric analysis was used to study the impact of eight factors on the homes' pressure profiles. These eight factors, which together are largely responsible for airflow within the home and between the home and the outside, are:

1. Duct leakage
2. Shell leakage
3. Interior airflow
4. Exterior air barriers
5. Air supply balance
6. Return air handler grille opening size
7. Exhaust fan operation
8. Positive ventilation

As a result of the testing, the following conclusions and recommendations are made:

- Duct leakage and shell leakage have the most dramatic effects on a home's pressure profile.
- As duct leakage increases, most pressures decrease and pressure imbalances between spaces are exaggerated. Duct leakage should be limited to 5% to the outside to avoid severe negative pressures within the home relative to the outside.
- Tight envelopes exacerbate negative and imbalanced pressures, although it is possible to achieve near-neutral pressures with a shell as tight as 7.2 ACH_{50} (estimated as 0.29 $ach_{natural}$) if ducts are tight and adequate return air pathways are provided. Tight shells (a maximum of 8.8 ACH_{50}, estimated as 0.35 $ach_{natural}$) should be maintained to control airflow through the envelope.
- Of the factors that are controlled by the homeowner, those that have the biggest positive impact on pressure balance within the home are maintaining adequate return air pathways (such as keeping bedroom doors open if adequate return air grilles or jumper ducts are not provided) and limiting the use of exhaust ventilation fans to only when they are needed. In

the event that adequate return air pathways are not provided, closing of bedroom doors, in combination with a tight shell, is enough to create significant negative pressures within the home. The size of return air pathways from bedrooms should be maximized.

- Exhaust fan operation should be limited to only when it is necessary to exhaust interior moisture.
- An exterior wall sheathed with an effective air barrier can significantly affect the pressure gradient across the wall, as compared to a wall cavity that easily exchanges air with the exterior. Sheathing of exterior walls to create an air barrier should be pursued to minimize intrusion of humid outside air.
- While air distribution systems in manufactured homes are in some cases unbalanced, it does not appear that balancing them will appreciably reduce negative or unbalanced pressures within the home as a whole.
- Positive ventilation can play a major role in creating a balanced and positive pressure profile in the home. Future research is needed to identify the best strategies for accomplishing this goal.

The two homes tested, both of which are from a single manufacturer, are representative of homes produced in this industry, and thus the recommended operating parameters are expected to achieve the desired pressure profile for most HUD-Code homes.

Future testing will validate these recommendations, measure actual moisture levels in homes built to effectively manage air pressures and also provide a set of suggested practices for manufacturers, installers and homeowners.

1

INTRODUCTION

1.1 BACKGROUND

In 1999, the Manufactured Housing Research Alliance (MHRA) conducted a study to identify moisture problems for the manufactured home industry. The common problems were described in the publication ***Moisture Problems in Manufactured Homes – Understanding Their Causes and Finding Solutions*** (MHRA 2000). From those common problems a set of three checklists were developed for the various stakeholders: manufacturers, home installers, mechanical equipment designers, contractors and homeowners. That work prompted discussion of moisture-related problems currently plaguing the entire building industry. A consensus developed that moisture problems were most acute among homes in the hot and humid Gulf Coast region. In 2001, MHRA's moisture research was directed towards tackling problems common to homes built in this region.

While this report focuses on manufactured housing, moisture problems are in no way unique to this type of construction. Extensive problems have been reported in site-built housing, and other residential and commercial buildings. The physical forces that drive moisture dynamics and cause moisture to accumulate where it may cause damage are the same for all types of buildings[1].

Excess moisture infiltration and accumulation is a damaging agent affecting housing durability and potentially reducing its service life. Moisture is readily absorbed by many building materials, and when present at critical levels can cause these materials to fail to perform as designed, deteriorate, and develop odors or stains.

Moisture infiltration problems are particularly difficult to diagnose and address because of the complex mechanisms by which moisture migrates through building materials and assemblies. Many individual building components influence moisture dynamics through their thermal performance and through their capability to store moisture and/or to allow vapor diffusion. In some instances the design of the structure can contribute to the problem, while in others the material selection is the culprit. Furthermore, homes designed properly to control moisture flow may still have moisture problems as a result of homeowner activities and operation and maintenance of the home.

1.1.1 Why this work is timely

There is a lack of up-to-date and reliable information that addresses moisture problems in manufactured homes, and a lack of guidance available to manufacturers, installers, repair service personnel and homeowners. Although anecdotal stories of homes with moisture problems are numerous, there has been a general absence of thorough and comprehensive construction, installation and operation information or measured performance data. Prior to the current work, little data existed to describe whether the problems were predominant in single section or multisection homes or where

[1] Homes that exhibit moisture problems, even in the hot, humid Gulf Coast region (the focus of the current research) are a small fraction of all new homes. Many thousands of homes, both manufactured and site-built, as well as other structures, are built each year and serve their occupants well without signs of moisture problems.

in the home the problems most often occurred. Similarly, the suspected causes of moisture problem being cited were generally speculative, and often were based more on theory than on evidence. Manufacturers possess some information about their own homes, often as a result of post-installation servicing, but generally lack a sufficient sample size of data to broadly diagnose the underlying causes of and remedies for moisture-related building damage.

There is a renewed importance in addressing this very complex problem. Construction practices and home features in both site-built and manufactured housing are evolving in ways that impact the moisture balance in structures and may lead to an increase in the frequency and/or severity of moisture problems. Major reasons to be concerned that moisture problems may be on the increase include the following:

- The presence of central air conditioning has virtually saturated new housing markets – particularly in hot, humid climates - and has created many moisture challenges. Homeowners demand this feature and occupants typically operate cooling equipment for a large portion of the year. Air conditioning results in interior/exterior temperature differences that previously did not exist in warm-climate building environments, and, under some conditions, support condensation on building materials. Forced air delivery systems intentionally create small pressure differences in order to induce air circulation. However, excess pressure differences between the interior and outside, or between rooms, can draw humid air through the building shell, increasing the likelihood of condensation on cold surfaces. Air conditioning also generates condensate that, if not drained properly to the outside, can re-evaporate into the living space or drip into ducts. Occupants may fail to properly operate and maintain the equipment (for example, by neglecting the regular replacement of air filters). Oversized equipment can bring the interior temperature significantly below the outside temperature and often below the outside dew point without adequately dehumidifying the interior air. If the thermostat is set below the exterior dew point the chance that moisture will condense on building surfaces and within the building shell assemblies is increased.
- Building practices, materials and component designs have changed, often in ways that exacerbate moisture build-up. Increased insulation levels and tighter building envelopes have altered the thermal and moisture dynamics of the home, in many instances in ways that produce conditions more conducive to condensation.
- The use of exhaust ventilation equipment such as clothes driers, bathroom exhaust fans and high-volume cook top ventilators has increased in homes. These devices affect airflow, heat circulation and moisture movement, and induce pressure differentials and moisture flow between the outside and the interior of the home.
- Homeowners are increasingly installing high-end features such as whirlpool baths, adding to the moisture load inside the home.
- Ventilation designs commonly used in many homes to provide fresh air and moisture removal may not be appropriate for the climate in which they are situated. In some areas, ventilation systems linked to air handler operation may over-ventilate the home and increase the moisture load beyond the dehumidification capacity of the cooling equipment. Exhaust ventilation systems that contribute to negative home pressures may also contribute to bringing humid air into building cavities.

1.2 OBJECTIVES

Moisture problems can result from a variety of factors, often acting in combination, and no single action can completely protect a home from the detrimental effects of moisture accumulation and condensation. The primary objective of this research is the creation of a concrete set of recommendations that will significantly minimize the chances of moisture problems developing in manufactured homes, with a special emphasis on homes located in hot, humid regions.

Achieving this objective required a multifaceted research program consisting of the following parts:

1. Improving the understanding of the mechanisms that cause moisture problems in manufactured homes, through analysis of the design, construction and operational factors contributing to specific moisture problems;
2. Developing, testing and demonstrating cost-effective design, construction and operational practices through field investigations and laboratory analysis in order to minimize the chances of developing moisture problems; and
3. Disseminating results to industry and consumers through user-friendly information and tools that manufacturers, installers, repair service personnel and homeowners can use to minimize future moisture-related problems.

The research recommendations provided at the conclusion of the last phase of the research program will be presented as best practices for home manufacturers, installers and repair crews operating in the field, and for homeowners as well. Solutions will be in the form of actions that the manufacturer can take proactively in the plant, and installers can take when the home is set up, as well as routine maintenance procedures for homeowners that will reduce the occurrence of moisture problems.

Without this type of practical information, repair crews often tackle the symptoms rather than the causes of problems. With the information from this research, tools and techniques will be available that afford a better recognition of the underlying causes of moisture problems and provide solutions that will resolve these problems in field applications and prevent their reoccurrence.

1.3 RESEARCH PLAN

The research into moisture problems consists of four phases. Phase 1 provided general guidelines for avoiding moisture problems culled from current best practices. The subsequent phases (2 through 4) build on this work by creating guidelines for industry and homeowners in the most extreme and challenging of climates: the hot, humid Gulf Coast region. The scope of each phase is described in the sections that follow.

1.3.1 Phase 1 – Moisture problems in manufactured housing

Phase 1 (completed in 2000) provided an analysis of moisture problems and effective remedial measures in manufactured homes. The main product of this phase was a guide, ***Moisture Problems in Manufactured Housing – Understanding Their Causes and Finding Solutions*** (MHRA 2000). This guide provided basic information on moisture problems; checklists for manufacturers, installers, HVAC contractors and homeowners; and tips on moisture problem prevention and mitigation. Among the Phase 1 findings was that the moisture problems affecting manufactured homes were most acute in the hot, humid areas of the nation and that a robust research program to develop solutions in this region was warranted.

1.3.2 Phase 2 – Minimizing moisture problems in hot, humid climates

Phase 2 (completed January 2003) consisted of an extensive program of data gathering and analysis of moisture problems and their potential causes in hot, humid climates. In this phase, which culminated in the interim report ***Alternatives for Minimizing Moisture Problems in Homes Located in Hot, Humid Climates***, moisture problems were characterized and possible solutions were postulated.

The interim report suggested twelve areas for further investigation (a thirteenth area relating to homeowner operation of water generating devices was subsequently added). Ten out of the initial twelve contributors to moisture problems evaluated in the report related to the physical characteristics of the home and three contributors related to the activities of the homeowners. The report suggested that there are ample opportunities to make changes in design, production, installation and service procedures that will reduce the likelihood of moisture problems. Changing the habits of homeowners is a more difficult task and subsequent phases will suggest strategies for reaching the homeowner. Table 1-1 describes the major contributors to moisture problems in hot, humid climates.

Table 1-1 Possible contributors to moisture problems[2]

Contributors	
	AIRFLOW DYNAMICS
1.	Imbalances in the distribution of conditioned air. Imbalances in air pressures within the home and between the home and the outside were found to have a strong association with moisture problems, particularly when they were amplified by closed interior doors without adequate airflow returns.
2.	Duct leakage to the outside. Duct leakage contributes to pressure imbalances, which have a significant impact on moisture problems.
3.	High rate of shell leakage. Shell leakage will contribute to humidification of the home.
4.	Local cold spots. Cold spots such as those created by cold air registers directed on floor or wall surfaces can encourage localized condensation.
	MATERIALS AND METHODS OF CONSTRUCTION
5.	No ground vapor retarder under the home. Ground vapor retarders are effective in protecting homes from moisture damage, but only where a properly designed drainage system prevents the accumulation of water under the home.
6.	Damage to the bottom board. Homes experiencing floor moisture problems often have bottom board damage, indicating a need to develop guidelines, possibly including standard material specifications, for manufacturers, installers and owners in order to prevent damage to bottom boards and to facilitate repairs of those damaged during construction and set up.
7.	Location of vapor retarders. In hot, humid climates, the interior of building shell components should be vapor permeable, allowing cavities to dry in the direction of the home's interior.
8.	Lack of exterior air barrier. Air barriers should be located on the exterior wall surface in hot, humid climates in order to retard the introduction of outside air into building cavities.
9.	Ventilated attic space. From the limited data collected in the Phase 2 report and other studies of the effects of attic ventilation on moisture problems, it appears that ventilating attics may not impact significantly moisture problems in hot, humid climates.
10.	Oversized air conditioning equipment. Proper sizing of air conditioning equipment can be effective in addressing moisture problems, but only when combined with good air distribution design practices (i.e., a balanced system).
	HOME OPERATION
11.	Thermostat set point. Low interior temperatures contribute to moisture problems. Interim findings indicated that when the thermostat set point is below about 70°F, the chances of moisture problems developing increase significantly.
12.	Introduction of unconditioned outside air. The whole-home ventilation system and the opening and closing of windows and doors will impact the volume of outdoor, humid air introduced into the home.
13.	Raising the moisture level within the home. Homeowners introduce moisture into the home by domestic hot water use and operation of appliances, such as hot tubs, that generate large amounts of water vapor. Moisture from some of these devices and activities (such as bathing and cooking) can be exhausted to the outside by spot ventilation equipment. Moisture generated from other sources may be more difficult to eliminate.

[2] From a survey of 75 manufactured homes in the Gulf Coast region experiencing moisture-related problems. See *Alternatives for Minimizing Moisture Problems in Homes Located in Hot, Humid Climates: Interim Report*, Manufactured Housing Research Alliance, New York, NY (2003).

While all these factors, alone or in combination, can create an environment conducive to condensation and lead to moisture problems, a few items on the list, those related to pressure imbalances, have particular importance. By creating and maintaining a pressure profile across the building envelope that slows the introduction of moist outside air into the home and by effectively dehumidifying internal air, the conditions leading to condensation and related moisture problems can be minimized. Phase 3 of the research was designed to consider design options to achieve such a pressure profile.

1.3.3 Phase 3 – Response of air pressures to operating conditions in two manufactured homes

As noted above, results of Phase 2 of the research into moisture problems indicated that pressure imbalance is among the most significant factors contributing to condensation-related moisture problems. Without a driving force, moist air cannot enter building cavities. Imbalances are characterized by a pressure differential between interior spaces (including between building living spaces and wall, floor and ceiling cavities), and by having a negative interior pressure relative to outdoor air. The ideal condition is a uniform inside air pressure and, for hot, humid climates, one that is neutral to slightly positive relative to the exterior. For homes in northern climates, a slightly negative pressure is desirable to prevent condensation in the walls during the winter.

As part of Phase 3, the subject of this report, a strategy was developed for minimizing pressure imbalances within the home and across the thermal envelope. This included suggesting whole-home ventilation strategies, home design and construction techniques and operational parameters that result in homes that will reliably maintain internally balanced air pressures with a neutral to slightly positive pressure relative to the outside. The results of these investigations are described in subsequent sections of this report.

1.3.4 Phase 4 – Monitoring moisture performance in manufactured homes

While reducing pressure imbalances is theorized to be the best first line of defense against moisture problems, other strategies may also be important. Phase 4 will test the effects of the solutions developed in Phase 3 by monitoring homes in the field that incorporate these airflow design guidelines among other strategies in order to control moisture accumulation and condensation. Levels of humidity and surface moisture will be monitored in two homes, both within the interior of the home and in building cavities, including the attic space. The homes will be located in a hot, humid climate. Design guidelines and installation practices will be developed based on these findings.

The planned research will also provide more insight into the interrelationship between moisture problems and the following three important factors:

1. <u>Vapor retarder and air barrier placement in walls</u>. The impact of these elements on a home's moisture performance will be investigated by varying the locations of the vapor retarder and air barrier in the homes being monitored.

2. <u>Attic ventilation</u>. By monitoring the relative humidity, air pressures and temperatures within the attic cavity, ventilated attic moisture performance in hot, humid climates, and its response to interior home pressures, will be better understood.

3. <u>Whole-home ventilation</u>. The effect of whole-home ventilation on interior humidity will be evaluated by developing and implementing ventilation systems that improve the home's pressure profile and by examining the effects of cooling system dehumidification capacity on relative humidity of the home interior and building cavities.

1.4 SCOPE OF THE CURRENT RESEARCH

In Phase 3 of the moisture research, the impacts of various building characteristics and operational configurations on air pressure balance within the home were investigated. Pressure profiles were examined both in the home interior and in building cavities such as walls, floors and attics – concealed spaces where moisture problems often manifest themselves. Negative air pressures in these spaces relative to the outside can draw in large amounts of humidity from the outside, particularly if the building cavity communicates directly with outdoor air (i.e., no air barrier on the exterior of the wall).

Airborne moisture, often driven by pressure imbalances, is thought to be a major source of moisture migration within buildings, and a much greater driver than diffusion[3]. By investigating ways that these negative air pressures can be avoided, this research developed recommendations for home construction and operation that can minimize these types of moisture problems. The recommendations will be tested in subsequent research (Phase 4) by subjecting homes incorporating such techniques to continuous monitoring of moisture flow during peak cooling conditions.

The consistency of manufactured home design and construction enables tests of a limited number of homes to be generalized to the majority of manufactured homes produced nationwide. Most manufactured homes consist of either one or two factory-finished floors, referred to as single section and double section homes, respectively. One of each of these types of homes was tested in Phase 3. Although airflow characteristics vary between these two home types, manufactured homes in general possess many similarities that affect air movement and pressure differentials, including the following:

- All manufactured homes are built to the HUD standards. These preemptive Federal regulations are uniform across the nation (although some provisions differ by climate).
- Almost all homes have forced air heating and cooling delivery systems with an air handler located over (or under) a trunk duct.
- Trunk ducts are located under the floor or in the attic running the length of the home, possibly with branch ducts to perimeter locations (in double section homes, a crossover duct, usually a round flex-duct, connects the trunk duct of the two halves).
- Registers are located in the floor (or ceiling) depending on the trunk duct location.
- Manufactured homes seldom have return air duct systems.
- Single section and multisection homes have similar or nearly identical construction of envelope components, with the exception of a marriage line connecting the various sections of a multisection home.

Phase 3 testing was conducted over two separate one-week periods. The single section home was tested first, followed by the double section home. The testing consisted of placing multiple pressure probes in various locations within the home and connecting them to a data-gathering device.

A number of factors were identified as potentially having a significant impact on the pressure differential between the home and the outside. These include the following: duct leakage, envelope leakage area, return air pathways, volume of distributed air and ease of airflow between the spaces within the home envelope (i.e., wall cavity) and the exterior. The impact of each of these factors on air pressure relative to the outside was examined through sensitivity analysis where one factor was varied while the others are kept constant. The importance of each factor was gauged. As a result, combinations of conditions were suggested that are expected to lead to a desired pressure profile for the home.

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[3] Wilson, Alex, *Moisture Control in Buildings: Putting Building Science in Green Building*, Environmental Building News, Volume 12, Number 7, BuildingGreen, Inc., Brattleboro, VT (July 2003).

Structure of this report

Results of the air pressure testing are reported in next three sections. Chapter 2 describes the test protocol used in constructing the pressure profile for the single and double section homes. Also included is a description of the homes (size, duct location, ventilation system type) and the type and configuration of test equipment used for data collection.

Chapter 3 describes the test sequence followed and the results of measurements taken to profile each of the major factors affecting the homes' pressure profiles. A review of the findings, along with general observations and interpretation of the data, are also included.

Conclusions drawn from the data are contained in Chapter 4 together with recommendations for ways to construct homes to minimize potential moisture problems.

2

METHOD FOR CHARACTERIZING AIRFLOW DYNAMICS

For a period of one week each, two homes underwent testing with respect to internal air pressures. Over the course of the week, air pressures were monitored in critical locations in the home under various operating conditions. The purpose of the tests was to isolate those conditions or combination of conditions that result in the home or parts of the home becoming negatively pressurized relative to the outside, conditions that should be avoided through home design, construction and operation.

The homes were temporarily installed in an indoor test bay of a manufactured home plant located in the Southeast U.S. The indoor location minimized the potential impact on air pressures of wind acting on the home's exterior. Testing occurred during May and June 2003.

2.1 DESCRIPTION OF TEST HOMES

The two most popular manufactured home types were selected for the tests: a single section home (nominal floor dimensions of 16' x 68'—Figure 2-1) and a double section home (nominal floor dimensions of 28' x 64' including an 8' porch—Figure 2-2).

Figure 2-1 Single section test home

Figure 2-2 Double section test home

Both homes were standard production models and were selected to meet the criteria described below. Certain characteristics of the homes were specified to facilitate the testing, to accentuate pressure differentials and to enable the application of the test results of these homes to the general population of manufactured homes. The following home characteristics were specified:

- **Master bedroom location**: A location towards one end of the home was specified to maximize pressure effects of closing the master bedroom door.
- **Sheathing**: In order to examine the effects of a pressure barrier on the outside surface of the exterior wall, one sidewall of each home was constructed with no additional effort to create an exterior air barrier (wall construction type 1), and the other was built with an attempt to create an exterior air barrier (wall construction type 2). In the single section home, one sidewall had metal siding applied directly to the wall framing with no sheathing (type 1), and the other was sheathed with oriented strand board and the joints were taped (type 2). Both sides of the double section home were sheathed with blackboard. However, one side had the joints caulked and taped to further reduce airflow between the outside and the wall cavity (type 2). Because a primary aim was to investigate pressure differences between the interior and wall cavities, varying the sheathing type would permit the evaluation of these two constructions.
- **Bottom board**: Standard bottom board material was specified. No special steps were taken to seal the joints with the floor.
- **Interior vents areas**: A return air grille was installed on the master bedroom and secondary bedroom doors to study the effects of return airflow from these spaces.
- **Thermal design**: The homes were built as Energy Star compliant. Thus, the baseline shell and duct leakage were low. The double section home had a marriage line gasket, but the home was not trimmed out on the interior.
- **Whole-home ventilation**: A fresh air duct leading to the air handler was installed in the home. This is the most common ventilation system used in manufactured homes (Figure 2-3).

Figure 2-3 Fresh air intake duct sitting atop the cooling coil

- **Attic ventilation**: As is common practice with single section homes having a metal roof with no sheathing, and where air leakage paths from the living space to the attic are sealed, there was no provision for dedicated attic ventilation[4]. Nonetheless, tests indicated that the attic behaved as if it were ventilated, the result of having sufficient penetrations in the attic

[4] Manufactured Home Construction and Safety Standards, Subpart § 3280.504(c).

enclosure. The double section home was constructed with the typical passive attic ventilation system incorporating soffit and roof vents.

- **Duct location and size**: The ducts, located under the floor, were constructed of straight (non-graduated), uninsulated aluminum. The trunk duct measured 5" x 12", a size typical for homes in the Southeast. Under floor ducts are common in all areas of the nation, although overhead systems are commonly used in the Florida and other parts of the South.
- **Air handler location**: A location towards one end of the home was specified to maximize pressure drop along the length of the trunk duct.
- **Air handler fan speed**: A multispeed fan was selected to enable testing of airflows at various fan speeds.

2.2 EQUIPMENT SET-UP

Two, eight-channel automatic pressure monitors manufactured by the Energy Conservatory were placed in each home and connected to portable computers (Figure 2-4). Flexible tubing connected each monitor to eight pressure measurement locations. The equipment was arranged to measure pressure in the main living spaces of the home relative to the outside, as well as pressures in other spaces within the home (such as bedrooms) relative to the main living space. The data logging system was configured to record the pressure at prescribed fixed intervals.

Figure 2-4 Data logging equipment

Comparisons were made among candidate wall and floor cavity pressure probe locations to determine if they were representative of the cavity being measured and to assess the air barrier effectiveness of the sidewalls. Prior to installing the trunk duct pressure probes, a series of pressure measurements were taken in the single section home to isolate a site where pressure readings would not be influenced by branch supply duct airflow.

Pressure probes were installed at strategic locations in each home, including in the air supply ducts and within building cavities (Figure 2-5 and Figure 2-6). Pressure probe locations are shown in Figure 2-7 and Figure 2-8 and listed in Table 2-1.

Figure 2-5 Pressure probe at air handler fan

Figure 2-6 Pressure probe in wall

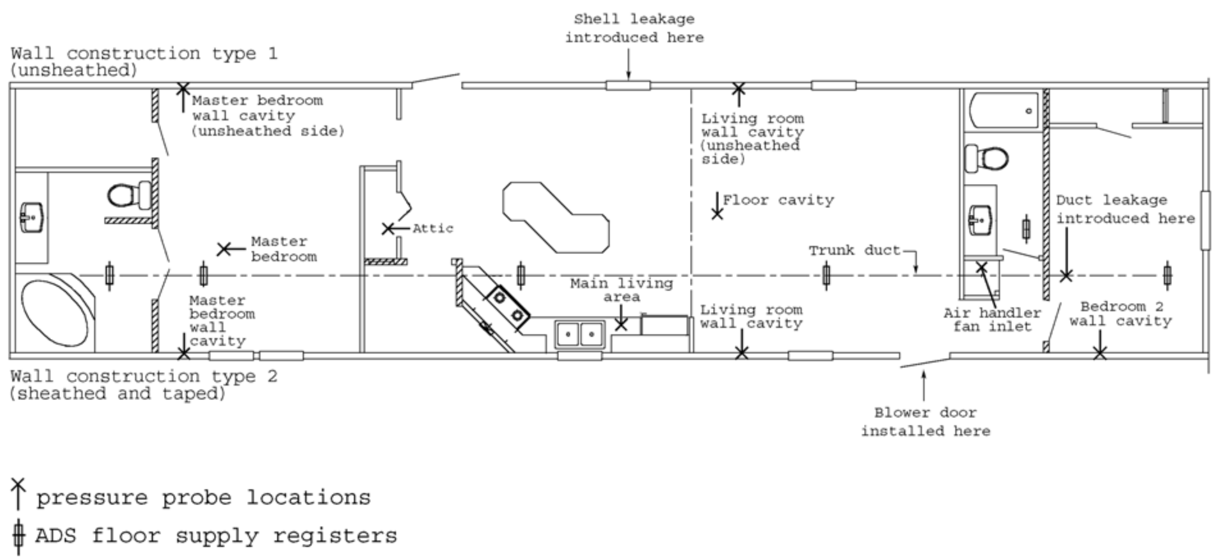


Figure 2-7 Floor plan of single section home showing pressure probe locations

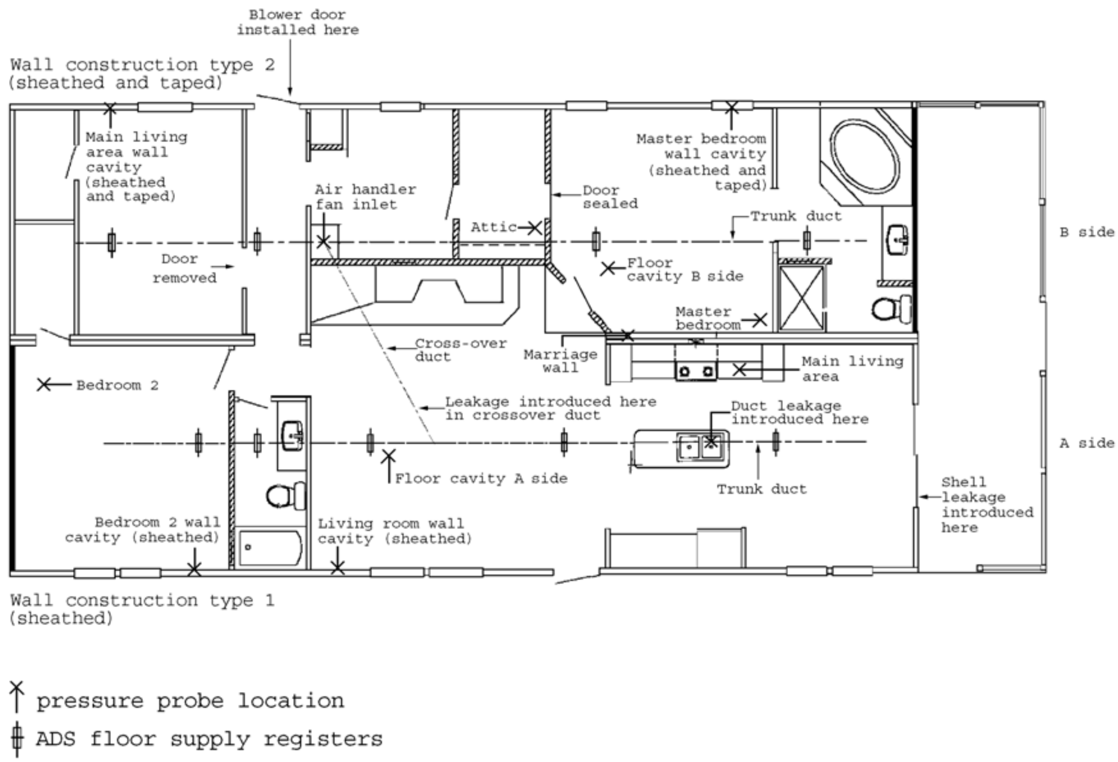


Figure 2-8 Floor plan of double section home showing pressure probe locations

Table 2-1 Pressure probe locations

Single section home	Double section home
1. Trunk duct at bedroom 2	1. Attic
2. Trunk duct at living room	2. Air handler fan inlet
3. Trunk duct at kitchen	3. Bedroom 2
4. Trunk duct at master bedroom	4. Marriage wall
5. Trunk duct at master bathroom	5. Trunk duct at master bedroom
6. Bedroom 2 exterior wall cavity in sheathed and taped wall	6. Trunk duct at hall
7. Master bedroom wall cavity in sheathed and taped wall	7. Trunk duct at living room
8. Main living area wall cavity in unsheathed wall / moved to fan inlet part way through the testing	8. Trunk duct at entry
9. Main living area*	9. Main living area*
10. Master bedroom exterior wall cavity in sheathed and taped wall	10. Master bedroom exterior wall cavity in sheathed and taped wall
11. Master bedroom exterior wall cavity in unsheathed wall	11. Bedroom 2 exterior wall cavity in sheathed wall
12. Main living area exterior wall cavity in sheathed and taped wall	12. Main living area exterior wall cavity in sheathed and taped wall
13. Master bedroom	13. Master bedroom
14. Main living area exterior wall cavity in unsheathed wall	14. Main living area exterior wall cavity in sheathed wall
15. Floor cavity	15. Floor cavity A side
16. Attic cavity	16. Floor cavity B side

* Note: All pressures were measured relative to the main living area, except for the main living area, which was measured relative to the outside.

2.3 ESTABLISHING BASELINE CONDITIONS

Prior to conducting the sensitivity tests described in Chapter 3, measurements were taken to establish performance measures for duct leakage, shell leakage and mechanical ventilation rates in each home prior to any modification. A summary of these measurements is found in Table 2-2.

Table 2-2 Measurements of shell leakage, duct leakage and exhaust fan airflow

Feature	Single section home	Double section home
Shell leakage	7.2 ACH_{50}	6.8 ACH_{50}
Total air distribution system (ADS) leakage	48 CFM_{25} or 4.8% of square feet (sf)	75 CFM_{25} or 4.8% of sf
ADS leakage to the outside	0	24 CFM_{25} or 1.5% of sf
Kitchen exhaust fan flow	Low speed: 37 cubic feet per minute (cfm) High speed: 66 cfm	Low speed: 34 cfm High speed: 55 cfm
Master bathroom exhaust fan flow	8 cfm	Tub area fan: 0 cfm Toilet area fan: 22 cfm
Small bathroom exhaust fan flow	22 cfm	19 cfm

Using the blower door to establish leakage rates[5] and applying the LBL method[6], natural air change rates were estimated at approximately 0.29 air changes per hour ($ach_{natural}$) for both homes (Figure 2-9), well below the low end of the targeted testing range (0.35 $ach_{natural}$).

The duct leakage rate, measured with a duct leakage testing fan, was very low for both homes (4.8% CFM_{25} total leakage). The single section home had no measurable leakage to the outside and the double section home recorded 1.5% CFM_{25} leakage to the outside[7].

Figure 2-9 Measuring shell leakage with a blower door

The airflow rates of the kitchen and bathroom exhaust fans were also measured. In both homes, the fans moved less air than expected, but further testing is needed to determine the underlying cause.

[5] The blower door tests were conducted by depressurizing the home to -50 Pa relative to the outside in all cases.
[6] Meier, Alan, *Infiltration: Just ACH_{50} Divided by 20?*, Home Energy Magazine Online (January/February 1994). Lawrence Berkeley Laboratory (LBL) correction factors used were: height of 1 (1 story), wind of 0.9 (exposed), leakiness of 1.4 (small cracks), climate of 20 (average); these factors equated to an overall divisor of 25.2.
[7] Unless otherwise specified, all references to duct leakage are measured in cfm leakage to the outside as a percent of home floor area.

2.3.1 Calibration of shell leakage

Four levels of shell leakage were established to assess the impact of this factor on home pressures. The shell "hole size" was adjusted by opening a window to fixed positions (Figure 2-10) with the home configured in the baseline condition (interior doors open, air handler and all other fans off) and with the duct leakage to the outside set at 5%. The resulting levels of shell leakage are shown in Table 2-3.

Figure 2-10 Adjusting shell opening in the single section home

Table 2-3 Shell leakage settings

Shell leakage	Single section home	Double section home
Position 0[8]	7.4 ACH_{50}	7.2 ACH_{50}
Position A	8.7 ACH_{50}	8.4 ACH_{50}
Position B	13 ACH_{50}	13 ACH_{50}
Position C	18 ACH_{50}	18 ACH_{50}

Position 0 was the baseline leakage of the home with all windows closed. Positions A, B and C were determined by opening a window in the main living area (a sliding door in the double section home). These positions were calibrated to correspond to shell leakage levels (under baseline conditions) of 0.35, 0.50 and 0.75 $ach_{natural}$, respectively[9]. These air change rates are theoretical estimates of approximate average natural air change rates under typical climactic conditions. The 0.35 $ach_{natural}$ was selected as minimum target cited by several standards and building codes; the 0.50 $ach_{natural}$ was selected as representative of a typical older home; and the 0.75 $ach_{natural}$ was selected as representative of a very leaky home.

[8] The shell leakage rates for position 0 reflect leakage after holes were introduced to the ducts and bottom board and therefore are higher than those in Table 2-2.
[9] Estimated with the LBL model described in footnote 6.

2.3.2 Calibration of duct leakage

In order to introduce additional duct leakage into the floor cavity, two adjustable dampers were installed in the metal trunk duct through an access hole cut into the floor (Figure 2-11). The dampers could be adjusted to achieve the targeted levels of duct leakage shown in Table 2-4. In the double section home, an additional damper was connected to the crossover duct.

Figure 2-11 Damper in trunk duct of the single section home

Table 2-4 Duct leakage settings

Damper position	Duct leakage to the outside (cfm @ 25 Pa, as a percentage of floor area)	
	Single section home	Double section home
Position 1	5.0%	5.2%
Position 2	10.1%	10.4%
Position 3	18.5%	18.4%

The positions of the dampers were calibrated to achieve approximately 5%, 10% and 18.5% duct leakage to the outside. The low value (5%) was selected to represent a well-sealed duct system, characteristic of what might be required of Energy Star homes. Ten percent was chosen to represent a typical home where no special steps were taken to seal the duct system. The maximum leakage level of 18.5% represented a home with a serious flaw in the design or installation of the air distribution system.

It should be noted that the actual shell and duct leakage rates vary throughout the testing. Each of the parameters that were tested also affected the actual shell and duct leakage. The various sizes of the openings made in the shell and duct are experimental variables; the measured duct and shell leakage are in reality valid only for the baseline homes under specific test conditions.

The as-built homes both had very well-sealed bottom boards and virtually no air leakage from the floor cavity to the outside. Therefore an opening was also introduced in the bottom board to allow approximately 50% of the duct leakage to escape to the outside (Figure 2-12). The openings in the bottom board and the crossover duct were sized to result in the desired leakage levels to the outside. The double section home was configured to produce 5% duct leakage in the A side. The B side was left as constructed and additional leakage was added to the crossover duct to bring the entire home up to 5%. In the double section home, the trunk duct leakage was added only to the A side, and so the floor cavity pressures differed substantially between the two halves of the home.

Figure 2-12 Bottom board hole in single section home

2.4 SENSITIVITY STUDIES

Once the equipment was configured, the baseline data recorded and the shell and duct leakage calibrated, the home was ready for a series of sensitivity studies. Air pressures were logged continuously by the data monitoring systems as a number of conditions were established in the home. Generally, the sensitivity tests required changing one factor at a time and holding the others constant; for example, the shell leakage was varied over a range while the clothes dryer fan (Figure 2-13), remained at a fixed setting. Table 2-5 describes the specific sets of conditions under which sensitivity study data was collected. The results of these studies are described in Chapter 3.

Figure 2-13 Fan simulating clothes dryer exhaust

Table 2-5 Testing conditions

Condition	Air handler on	Bedroom doors closed	Return air grilles sealed	Kitchen fan on high	Bathroom fans on	Simulated clothes dryer on 200 cfm	Various other return air grille sizes	Description
A	✓							**Baseline pressure ranges** Each series of tests consisted of measurements taken at each combination of four shell leakages and three duct leakages, for a total of twelve data points in each series. Pressures were recorded at fixed intervals. The data points within each test were then averaged.
B	✓	✓	✓	✓	✓	✓		
C	✓	✓	✓	✓	✓			
D	✓	✓	✓					
E	✓	✓		✓	✓	✓		**Establish pressure ranges incorporating corrective measures** Additional conditions were tested with the home set at the lowest shell leakage level, since pressure differences are significantly amplified in tighter homes.
F	✓	✓		✓	✓			
G	✓	✓						
H	✓	✓					✓	
I	✓	✓		✓	✓	✓		**Pressures with balanced ADS** The ADS flows were balanced by masking or removing supply registers such that the airflow into a room was nearly proportional to its square footage. This was done through trial and error. Tests were then conducted with the near-balanced ADS under a variety of conditions.
J	✓	✓		✓	✓			
K	✓	✓						
L	✓							
M	✓						✓	**Pressures with 100 cfm positive ventilation** Supplemental positive ventilation of 100 cfm was added to the home and tests were conducted with balanced and unbalanced ADS under a variety of conditions.
N	✓	✓	✓					
O	✓	✓						
P	✓						✓	

3

TESTING RESULTS

This chapter examines the impact of eight factors that together are largely responsible for airflow through the home and between the home and the exterior. Field testing of two homes was conducted to measure the impact of each of these factors on the homes' pressure profiles. Where there were strong interdependencies, two or more factors were examined in combination. This section explains how the tests were conducted, summarizes the results for the two homes and provides general observations and interpretation of the data.

The results are reported for eight factors followed by a section analyzing the data pertaining to each[10]. The factors impacting the homes' pressure profiles are as follows:

1. Duct leakage
2. Shell leakage
3. Interior airflow
4. Exterior air barriers
5. Air supply balance
6. Return air handler grille opening size
7. Exhaust fan operation
8. Positive ventilation

For most of the tests, pressure probes were placed at strategic locations within the homes (see Section 2.2). Readings taken at these locations suggest how air pressures will be influenced by changes in the key factors listed above. With the goal of creating a neutral to slightly positive interior pressure relative to the outside, particular attention was focused on conditions that might create negative pressures. When a negative pressure occurs, humid outside air is drawn into the home or building cavities, potentially creating the opportunity for condensation and moisture problems. The test results are instrumental in suggesting the conditions or combination of conditions that will result in the desired pressure profiles for the homes.

The first two factors examined are duct and shell leakage. These were investigated together because of the strong influence one has on the other and on the pressure profiles of the homes. The other sensitivity studies were conducted with low levels of duct and shell leakage, characteristics common to most manufactured homes. The Energy Star Labeled Homes program and recent related industry research[11] have standardized effective duct sealing practices. Further, careful quality control and the use of a combination of glues and fasteners have resulted in very tight envelope construction. Studies

[10] Unless otherwise specified, all references to pressures are relative to the outside air pressure at the time of reading.

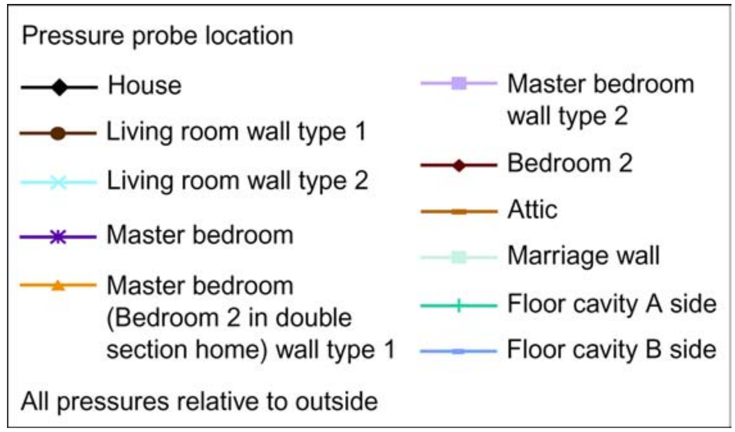
[11] ***Manufactured Home Duct Systems: Guide to Best Practices***, Manufactured Housing Research Alliance, New York, NY (2000) and ***Improving Air Distribution Performance in Manufactured Homes***, Manufactured Housing Research Alliance, New York, NY (2003).

of recently constructed manufactured homes suggest that the majority of homes are relatively tight, with leakage levels typically in the range of 0.15 to 0.35 $ach_{natural}$[12].

3.1 DUCT LEAKAGE

Not surprisingly, duct leakage can have a sizable impact on the pressure profile of a home. Figure 3-1 and Figure 3-2 show the change in pressure relative to the outside in the single and double section homes at eight probe locations at three levels of duct leakage (nominal 5%, 10% and 18% measured in cfm leakage to the outside as a percent of home floor area) and at a low shell leakage (position 0), in all cases with the air handler on, all other fans off and all interior doors open.

Key for all graphs, except Figure 3-12



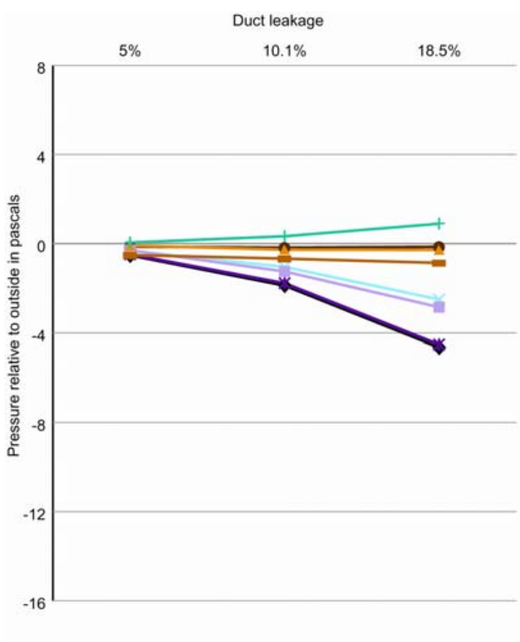


Figure 3-1 Pressures relative to the outside at low shell leakage, single section home

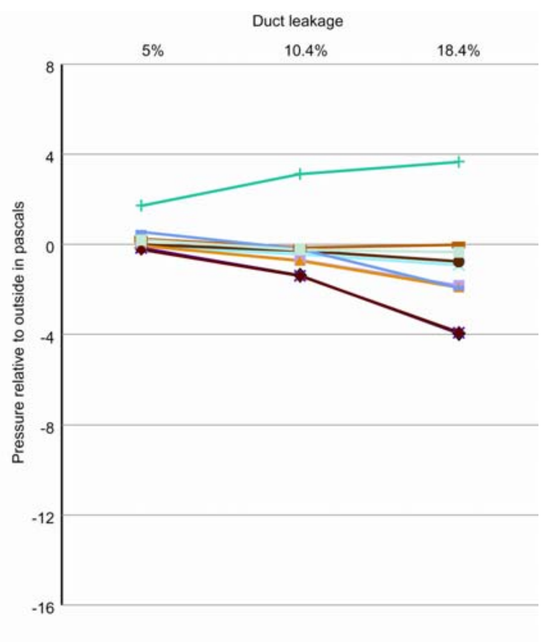


Figure 3-2 Pressures relative to the outside at low shell leakage, double section home

With a tight envelope and low duct leakage, pressures throughout the single section home relative to outside were tightly clustered between -0.52 and +0.05 Pascals (Pa) (Figure 3-1). As duct leakage increased to 10.1% and then to 18.5% the pressures diverged dramatically, ranging from a low of -4.5 Pa to a high of about 0.89 Pa.

[12] This data was collected by the Manufactured Housing Research Alliance as part of an effort to promote participation in the Energy Star Labeled Homes program.

Pressures in wall type 2 (sheathed and taped wall) fell off less dramatically to approximately -2.5 Pa due to the presence of a partial pressure barrier at the inside and outside wall surfaces. Pressures relative to the outside in the unsheathed walls were unaffected by the increase in duct leakage, as there is little resistance to airflow between these spaces and the outdoors.

The attic pressure dropped slightly to -0.86 Pa since the attic space is well-connected to the outside[13]. Predictably, the only probe location to experience positive pressure relative to the outside was the floor cavity, which increased in pressure to 0.89 Pa as air leakage from the ducts effectively pressurized the floor cavity.

In the double section home, the same trends were observed (Figure 3-2). The floor cavity pressure in the A side of the double section home is much greater than in the single section home because all trunk duct leakage was entering the A side, which was smaller and had a smaller bottom board opening than the single section home.

As the pathways of airflow through the shell increased, pressure differentials decreased. This is evident in the next series of measurements taken at a high level of shell leakage (18 ACH_{50}) (Figure 3-3 and Figure 3-4). In this instance, the pressures remained more tightly grouped between -0.64 and -0.08 Pa in the single section home for all levels of duct leakage, with the exception of the floor cavity pressure that increased from 0.19 Pa to 2.17 Pa at 18.5% duct leakage to the outside. Pressures in the double section home were grouped between -0.29 Pa and 0.76 Pa, except for the floor cavity in the A side, which was pressurized by the duct leakage.

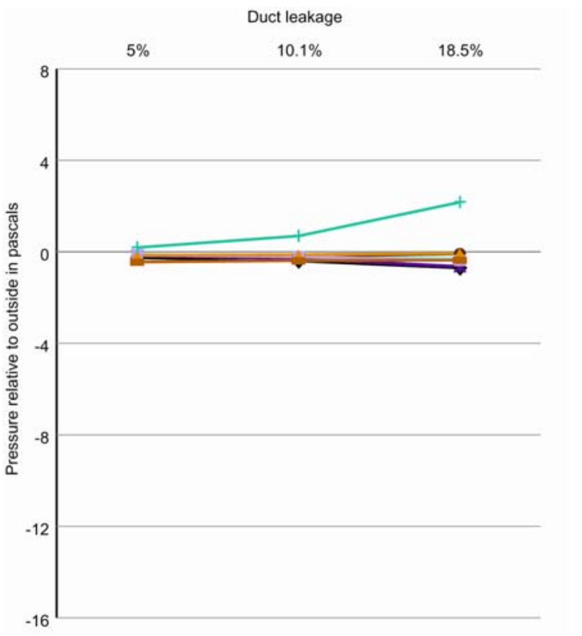


Figure 3-3 Pressures relative to the outside at high shell leakage, single section home

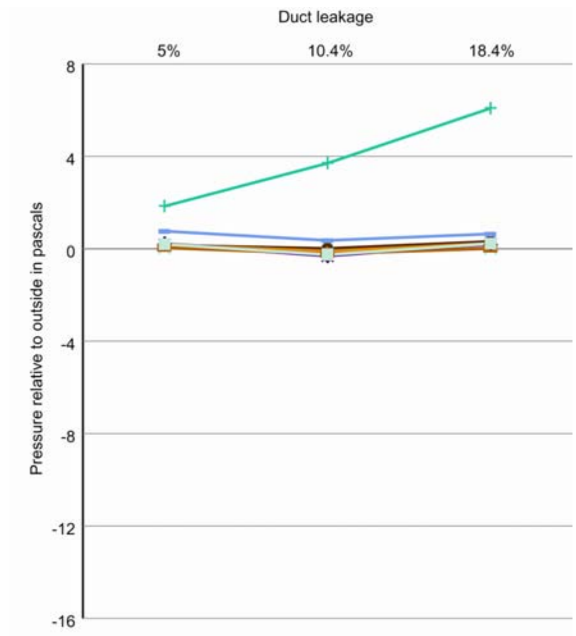


Figure 3-4 Pressures relative to the outside at high shell leakage, double section home

Clearly, duct leakage is a major cause of negative pressures within the home and every effort should be made to seal all leakage sites. However, it is important to note that even relatively low duct leakage levels (in this case 5% to the outside) result in negative pressures throughout the single section home, even with the fresh air intake ventilation system operating. As discussed below, other

[13] As described in Section 2.1, the attic of the single section home was effectively vented even though it was constructed without intentional ventilation.

factors often occurring coincident with duct loss depressurization, such as the operation of exhaust fans, will lead to even larger negative pressures relative to the outside.

3.2 SHELL LEAKAGE

Shell leakage has a dramatic effect on pressures and air movement within the home. In order to control movement of outside air into the home, any leaks through the building shell must be minimized. As the surface area of openings through the envelope (including window openings) is decreased, the ability of the shell to develop an interior/exterior pressure difference is increased.

Although it results in reduced pressure differentials between the interior of the home and the exterior, a leaky shell provides less resistance to the movement of outside air into the walls and living spaces, permitting unwanted humid outside air into the home. A leaky shell is a poor technique for managing moisture flow. It will reduce pressures, but potentially increase the amount of moisture brought into the home. Furthermore, just as it is difficult to maintain an undesirable negative pressure in a home with high shell leakage, it is also difficult to maintain a desirable positive pressure in the same home.

As shown in Figure 3-5 and Figure 3-6, pressures were recorded at eight locations in the single and double section homes at four levels of shell leakage. During these tests, the air handler was on, all interior doors were open, no other fans were operating and duct leakage was 5%. In both homes, increasing shell leakage with low duct leakage had little effect on the pressure profile of the home.

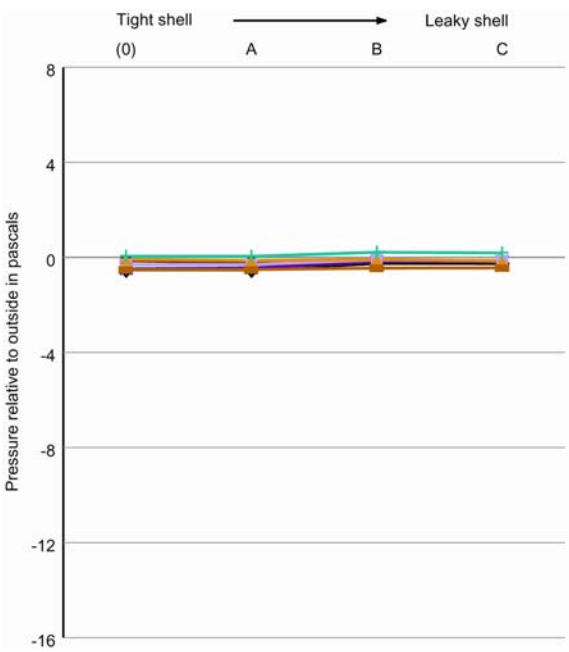


Figure 3-5 Pressures with 5% duct leakage to the outside, single section home

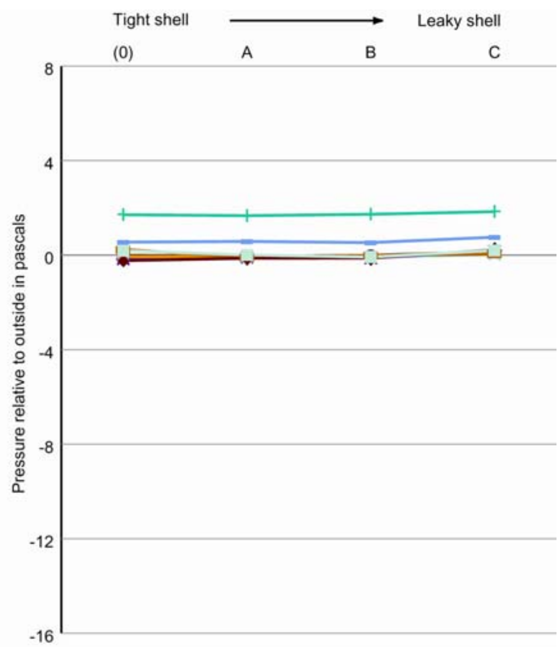


Figure 3-6 Pressures with 5% duct leakage to the outside, double section home

Figure 3-7 and Figure 3-8 show pressures in both homes with duct leakage to the outside of 18.5%. In all cases (with the exception of the floor cavity as discussed below) the pressures converged towards zero as the shell leakage area increased.

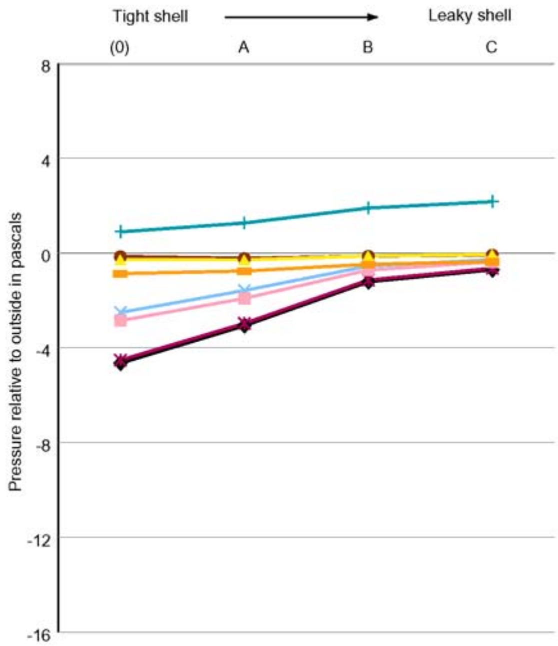


Figure 3-7 Pressures with 18.5% duct leakage to the outside, single section home

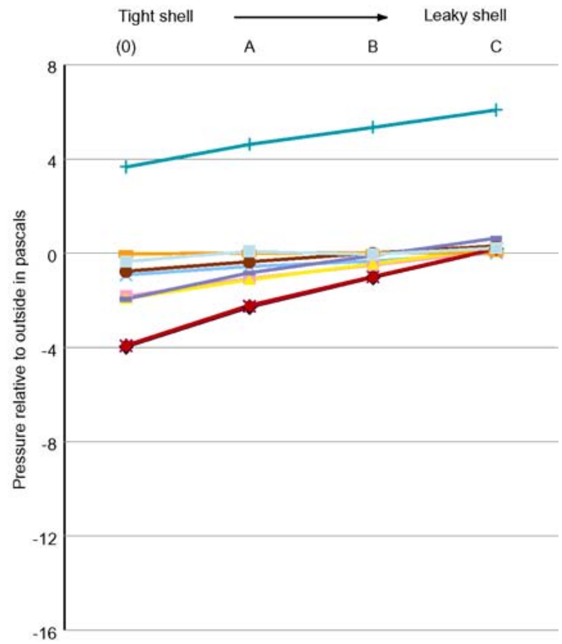


Figure 3-8 Pressures with 18.5% duct leakage to the outside, double section home

The data suggests that increasing shell leakage will be a promising strategy for achieving one of the project goals: defining conditions that result in a neutral to slightly positive pressure in the home relative to the outside. However, increasing shell leakage by increasing openings in the building shell, while diminishing the capability of the building shell to act as a pressure barrier, will increase air movement between the living spaces and the outside. The smaller pressure differentials seen in the leakier home indicate less resistance to air movement. If driving forces, such as those caused by duct leakage, are not reduced, air will move freely into the home, creating conditions more conducive to moisture problems.

The floor cavity pressure, positive at all levels of shell tightness, is the exception to this trend. This can be explained by the fact that the duct leakage introduced into the trunk duct flows directly into the floor cavity where it contributes to the pressure in this space. The floor cavity is well connected to the home interior by openings for plumbing and other services. Therefore, when the interior of the home is strongly negative (at the low shell leakage level), air is sucked into the home from the floor cavity, reducing its pressure. As pressure in the interior of the home converges towards neutral (as shell leakage increases), less air is drawn from the floor cavity, thereby allowing it to maintain a higher pressure for the same nominal level of duct leakage. Hence, the floor cavity pressure in the single section home is positive relative to the outside at low shell leakage levels and increases as shell leakage increases.

These same trends were observed in the double section home, with the pressure in the floor cavity of the A side (the half of the home containing the trunk duct leakage site) higher as duct leakage is introduced directly into this cavity from the trunk duct.

Minimizing shell leakage is a key strategy in controlling moisture flows between the interior and exterior. Although the data suggests that a leaky shell will minimize the interior/exterior pressure differentials, which is a primary goal of this phase of the research, negative pressures combined with high shell leakage can result in large volumes of humid outdoor air entering the home. The better practice, as described below, is to slightly pressurize the home, seal the envelope and condition (cool and dehumidify) fresh incoming air, thereby controlling the place where water condenses out of the air.

3.3 INTERIOR AIRFLOW

Conditioned air is distributed by the duct system to various rooms in the home. The loop is completed when the air is drawn back by the negative pressure created by the air handler fan, passed over the cooling coils, conditioned and redistributed through the ducts. The air handler is typically located in a closet in the main living area of the home. For most of the living spaces, such as the living/dining/kitchen area—where most of the air supply registers are located—there are no major obstacles (e.g., doors) encumbering the flow of air. Air moves easily between these rooms and the air handler.

Bedrooms and bathrooms, however, are separated from the main living area by doors. When those doors are closed, airflow back to the air handler from those rooms can become restricted and pressure can build up in these remote spaces. When air is trapped in a closed bedroom or bathroom, less air makes its way back to the air handler and therefore less air is available for distribution to the remainder of the home. As a result, the air pressure drops in spaces open to the main living area. To avoid these types of pressure imbalances, manufacturers undercut bedroom and bathroom doors and often put return air grilles in bedroom doors.

In both of the homes tested, the size of return air pathways was shown to have a dramatic effect on the pressure profile of the home. To demonstrate this effect, bedroom and bedroom wall cavity pressures were compared to pressures in the main living area with the air handler on and with return air pathways ranging from closed bedroom doors with no return air grilles (but with door undercuts) to fully open bedroom doors (Figure 3-9).

Figure 3-9 Adjusting the return air opening size through a bedroom door

Figure 3-10 shows the effects of the size of the return air pathway through the two bedroom doors for the single section home. Duct and shell leakage were set at their tightest levels and all other interior doors were open. The air handler was operating and all other fans were off. A total of six return air pathway sizes (Table 3-1) were explored in this series of tests. With the doors closed and grilles sealed, pressure in the master bedroom rose to more than 6 Pa, while pressure in the main living area fell to nearly -8 Pa. When the return air grille was opened, the master bedroom pressure dropped to about 3 Pa while the main living area rose to about -4 Pa. The pressures in these two rooms as well as the other probe locations continued to converge slightly as the grille area was increased, and then all converged to near neutral when the bedroom doors were opened.

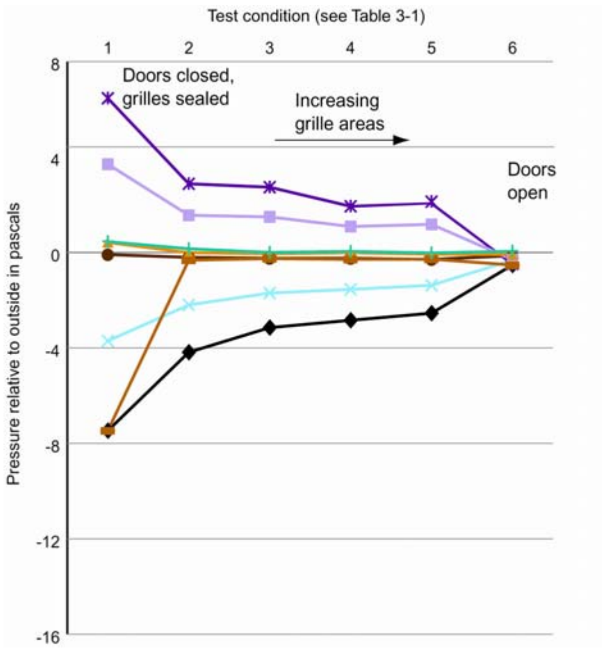


Figure 3-10 Pressures with variation in bedroom door openings, single section home

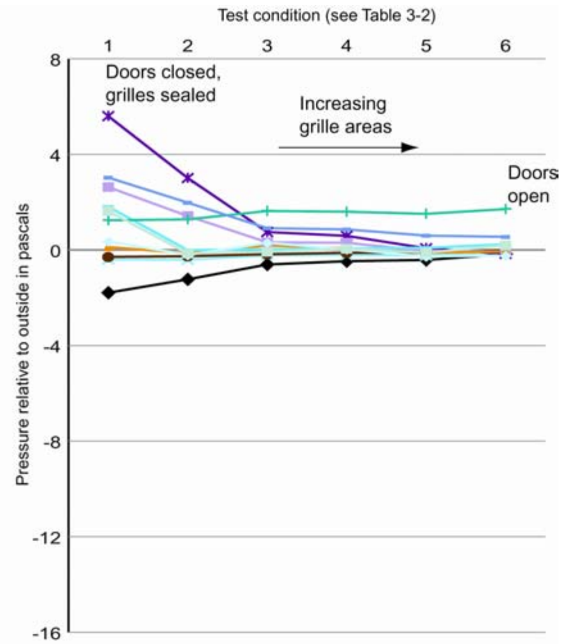


Figure 3-11 Pressures with variation in bedroom door openings, double section home

Table 3-1 Bedroom door return air opening sizes, single section home

Test condition	Total open area in square inches (master bedroom)	Total open area in square inches (bedroom 2)
1. Doors closed, grilles sealed	62	62
2. Grilles unsealed for both doors	117	117
3. Grilles removed from one side of each door	129	129
4. Grille removed from both sides of master bedroom door	140	129
5. Grilled completely removed from both doors	140	140
6. Doors open	2,200	2,200

Similar results were observed in tests of the double section home, where a somewhat wider range of return air pathway sizes were tested (Table 3-2 and Figure 3-11). Pressures in the master bedroom and main living area were approximately 6 Pa and -2 Pa, respectively, with doors closed and grilles sealed, and converged towards neutral as the openings were enlarged. The pressure differential was slightly less in the double section home as the proportion of supply air delivered to the closed rooms was only about 36% of the total supply air compared to 57% for the single section home.

Table 3-2 Bedroom door return air opening sizes, double section home

Test condition	Total open area in square inches (master bedroom)	Total open area in square inches (bedroom 2)
1. Doors closed, grilles sealed	68	68
2. Grilles unsealed for both doors	123	123
3. Florida recommended opening size[14]	229	108
4. Florida recommended opening size with grilles open	284	163
5. Maximum opening size	390	324
6. Doors open	2,200	2,200

The effects of the duct leakage on the floor cavity pressures are more evident in the double section home data, particularly in the A side where the duct leakage flowed directly into the floor cavity. The floor cavity pressure in the A side rose slightly as the return air pathway size increased. This is most likely due to the fact that as more air could freely make its way back to the air handler, the pressure in the duct system, and therefore leakage into the A side floor cavity, increased (Figure 3-11). This is confirmed by looking at the A side trunk duct pressure data, which increased about 25% when the opening area changed from doors closed (position 1) to fully open (position 6).

These results demonstrate that adequate return air pathways from bedrooms are critical to avoid imbalanced and negative pressures. Return air grilles with as little as 50 square inches of free open area can have a dramatic effect on the internal pressure balance; however, this arrangement may not be sufficient to achieve internal pressure balance in many cases.

From the ratio of the return air grille size to the pressure differential between the master bedroom and the main living area, it is possible to estimate a return air pathway size that will limit the pressure differential to a desired maximum for the home and conditions tested. Figure 3-12 displays the pressure differential between the master bedroom and the main living area as a function of the return air opening size in the double section home. The supply air delivered to the master bedroom suite was 327 cfm. The 70 square inches per 100 cfm of supply air guideline leads to a recommendation of 229 square inches of return air opening size. This opening size maintained a pressure differential of less than 2 Pa between the bedroom and the main living area in the double section home, and provides a reasonable rule of thumb.

[14] One of the return air opening sizes tested (70 square inches of free area per 100 cfm of supply air ducted into the room) is recommended by the Florida Solar Energy Center. This guideline is intended to meet a between-room pressure balancing requirement incorporated on March 1, 2002 as Section 601.4 of the Florida Building Code, which specifies that the pressure difference between the common central space and any room with a closed door (except bathrooms and laundry rooms) shall be no more than 2.5 Pa. (Source: Energy Design Update, Vol. 23, No. 1 (January 2003)).

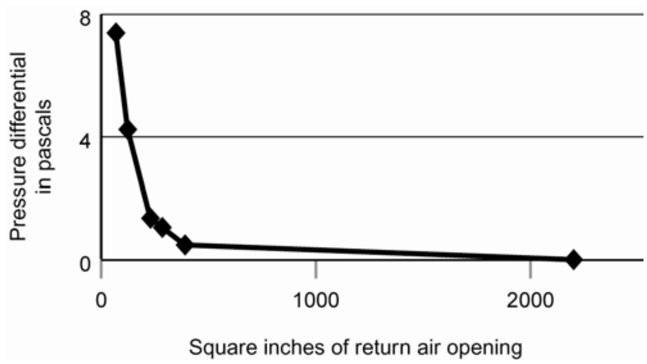


Figure 3-12 Master bedroom-living area pressure differential in the double section home

3.4 EXTERIOR WALL AIR BARRIERS

An air barrier, also known as a pressure barrier, inhibits air movement. Restricting airflow can result in air pressure building on one side of the barrier relative to the other. Air barrier integrity depends on creating a tight seal offering minimal pathways for the movement of air.

Sheathing materials on either side of exterior walls can serve as a barrier restricting air movement, depending on how well the walls are sealed. Insulation generally has a minimal impact on airflow. Exterior walls create three spaces that can all have different relative pressures: the interior of the home, the wall cavity comprised of spaces between studs and filled with insulation, and the exterior. Unless steps are taken to seal between these spaces (for example, by installing a well sealed material that is resistant to airflow), pressure differentials between them will generally be small. By observing the pressure in the wall cavity in relation to the pressure inside and outside the home, one can determine the relative porosity of the inside and outside surfaces of the wall and speculate about relative airflow across the wall.

In general, air drawn from the wall cavity into the home—the result of the interior having a negative pressure relative to the cavity and an airflow pathway—will be replaced by air moving into the wall from the outside. If the exterior air is hot and damp and the interior surface of the wall is cool, condensation may result. The testing, therefore, looked at the ability of exterior air barriers to reduce the infiltration of hot, humid outside air into the wall cavity and the home.

To evaluate the efficacy of air barriers in restricting air movement, two types of exterior wall construction (Table 3-3) were specified for each test home. One sidewall of the home was built to standard specifications and the other sidewall was constructed with the intent of creating a tightly sealed exterior air barrier. Pressures were monitored by probes placed in both walls in order to compare the effects of the different wall constructions.

Table 3-3 Exterior wall construction of test homes

Type	Single section home	Double section home
Wall construction type 1	Metal siding applied directly to wall framing (no sheathing). This wall is vented by design.	Vinyl siding over blackboard sheathing affixed to wall studs with adhesive.
Wall construction type 2	Metal siding over oriented strand board sheathing glued to wall studs. Joints in sheathing covered with duct tape.	Vinyl siding over blackboard sheathing glued to wall studs. Joints in sheathing caulked and covered with duct tape.

Table 3-4 shows the pressures the air handler induced in the main bodies of the homes and both types of wall cavities in the two homes relative to the outside and relative to the interior. In the single section home wall with wall construction type 1, the interior wallboard acted as the pressure barrier and the cavity had a low pressure difference with the outside, suggesting a relative ease of air exchange between the cavity and the outside. In the wall with construction type 2, both the exterior and interior materials served as air barriers. The pressure gradient suggests that the exterior sheathing had some of the desired effect of maintaining a pressure barrier at the outside wall surface.

Table 3-4 Pressure differences across the exterior wall

Test home	**Main living area**	**Wall construction type 1**		**Wall construction type 2**	
	Relative to the outside	Relative to the outside	Relative to the interior	Relative to the outside	Relative to the interior
Single section home	-0.5 Pa	-0.1 Pa	-0.4 Pa	-0.3 Pa	-0.2 Pa
Double section home	-0.2 Pa	0 Pa	-0.2 Pa	0 Pa	-0.2 Pa

In the single section home, the driving force (in the form of a pressure differential) to the inside from wall type 1 was double that of wall type 2 (-0.4 Pa versus -0.2 Pa). Assuming the holes in the inside wall surface are similar in all cases, and given that airflow is proportional to the square root of the pressure differential, wall type 1 allowed approximately 1.4 times the airflow into the building as did wall type 2. More air flowing through the wall means more air-transported moisture flow through the wall, resulting in more opportunities for condensation.

The total pressure differential between the main living area and the outside in the single section home was relatively small (-0.5 Pa), however, with only the air handler on and interior doors open. A 0.2 Pa reduction in pressure differential between the inside of the wall and the interior of the home is small and may not justify the expense of installing an air barrier around the entire home. At larger pressure differentials, however, the same ratio of pressures was observed, suggesting that as interior to outside pressure differentials rise, an effective air barrier may provide significant benefits by reducing the entry of humid outside air into the building (see Section 3.7).

In the double section home, there was virtually no pressure difference between the two wall construction types. Wall type 2 did not perform as intended, with cavity air freely communicating with the outside air. The taped and caulked blackboard was not an effective air barrier, and therefore more effective means of sealing the wall should be investigated.

3.5 AIR SUPPLY BALANCE

A balanced air distribution system (ADS) is defined for the purposes of this study as one in which the air supplied to a room is proportional to that room's share of the home's overall floor area (assuming ceiling heights are approximately consistent)[15]. For example, a 100 square foot room in a 1,000 square foot home should receive 10% of the overall supply air. Improperly balanced air distribution systems may result in pressure imbalances within the home. This was the case in the two homes tested; the air distribution systems were not balanced. Indeed, there was a wide variation in the volume of air supply (measured in cfm per square foot of floor area) in the as-built test homes. In both homes, the bathrooms were oversupplied, and living areas were undersupplied.

[15] More precisely, the air supply should be proportional to the heating and/or cooling load of a given space. This was assumed to be proportional to the area of the space for the purposes of this study.

In order to compare pressure profiles of a home with unbalanced ADS with that same home with a balanced ADS, sections of the supply grilles were covered in rooms that were oversupplied (Figure 3-13). Table 3-5 and Table 3-6 show the target balanced flow, the modified supply opening size and the resultant new near-balanced flow for both the single and double section homes, respectively.

Figure 3-13 Masked air supply register in small bathroom, single section home

Table 3-5 Supply balance, single section home

Room	Floor area of room (sf)	Percent of total home area (%)	Balanced flow (cfm)	As-built test home flow rate (cfm)	Modified supply opening size (sq. in.)	Modified flow rate (cfm)
Bedroom 2	131	13	144	245	10.5	140
Small bathroom	43	4.3	48	166	3.5	49
Main living area	520	52	569	304	33 each	423
Master bedroom	217	22	238	167	31	231
Master bathroom	82	8.2	90	206	8	92
Entire home*	994*	100	1,088	1,088	n/a	935**

* Entire home floor area is less than 1,010 sf (the gross floor area of the home) because wall thicknesses are not included.

** Post-balancing flow was less than pre-balancing flow; higher duct pressures were created by reducing the size of the supply outlet, thereby increasing duct leakage rates.

Table 3-6 Supply balance, double section home

Room	Floor area of room (sf)	Percent of total home area (%)	Balanced flow (cfm)	As-built test home flow rate (cfm)	Modified supply opening size (sq. in.)	Modified flow rate (cfm)
Main living area	880	64	847	714	(3) at 33 (2) at 40	846
Master bedroom	261	19	251	327	23 and 12	256
Bedroom 2	198	14	185	154	33	175
Small bathroom	45	3	40	128	7	50
Entire home	1,384	100	1,323	1,323	n/a	1,327

Figure 3-14 and Figure 3-15 are graphical representations of ADS airflows in the single and double section homes, respectively. The lines depict airflow in each space in the as-built, nearly balanced, and perfectly balanced (theoretical) configurations. The horizontal dimension (x-axis distance) is proportional to each room's square footage area. The vertical dimension (y-axis distance) is proportional to each room's airflow per square foot of floor area. The area of the chart (x-axis distance multiplied by y-axis distance) is proportional to each room's total supply flow. The flat horizontal line indicates a perfectly balanced system and deviations from this line for the as-built and rebalanced designs indicate oversupply or undersupply relative to ideal distribution.

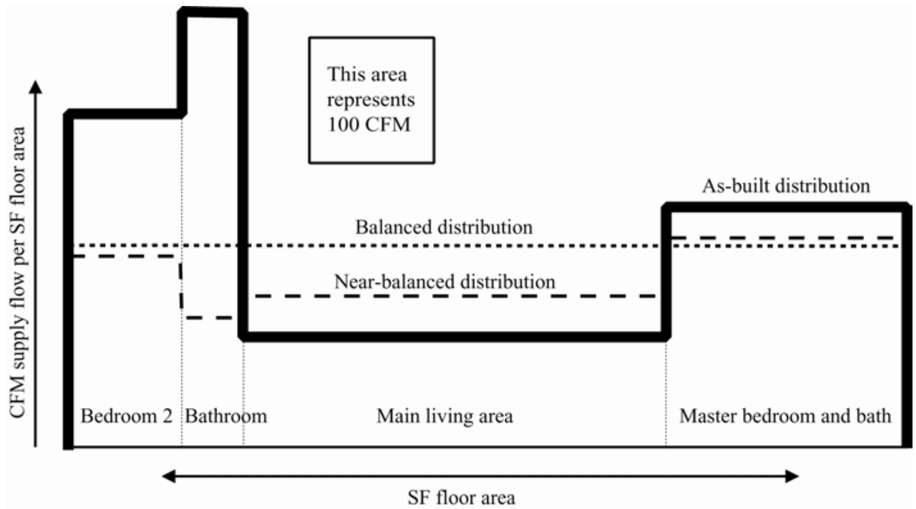


Figure 3-14 Graphical representation of ADS balancing, single section home

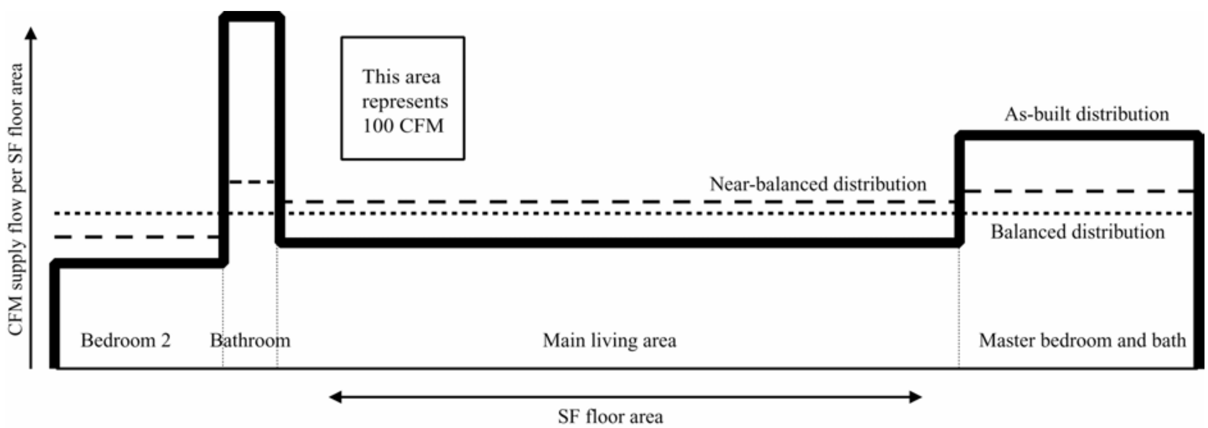


Figure 3-15 Graphical representation of ADS balancing, double section home

In order to test properly the effect of balancing the ADS, the balanced system must maintain the same total airflow (and therefore total duct leakage) as the original unbalanced flow (this proved difficult to achieve in the single section home). Artificially restricting the total flow through all supply registers results in greater duct leakage and, therefore, more negative (lower) pressures relative to the outside.

In the single section home, total supply register airflow was slightly restricted in the near-balanced configuration, and, therefore, it was not surprising that a slight decrease in interior home pressures relative to the outside was observed in tests with the near-balanced system as compared to the unbalanced system.

In the double section home, the near-balanced system was maintained at close to the original total system flow. The resulting pressure profile of the main living area was nearly identical to the unbalanced system through a range of test conditions, including with all fans on, and with only the air handler on with varying sizes of return air pathways (Figure 3-16).

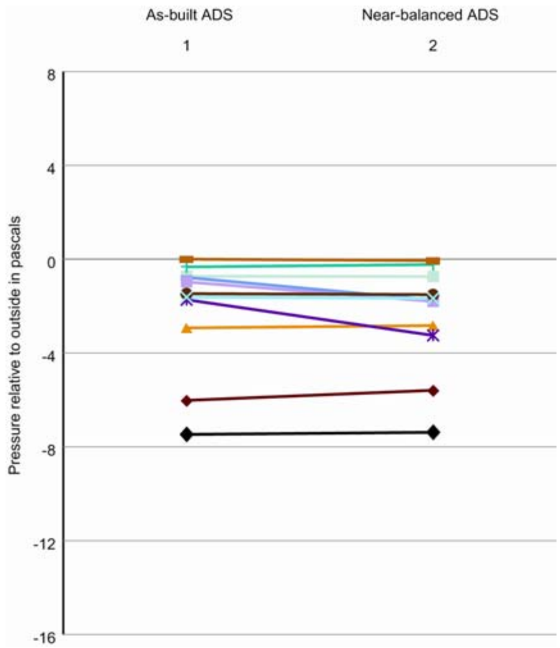


Figure 3-16 Pressure profile for balanced versus unbalanced supply, double section home

While air distribution systems in manufactured homes are in some cases unbalanced, it does not appear that balancing them will reduce appreciably negative or imbalanced pressures within the home. Redistributing air will, however, influence the pressure profile in individual spaces when doors are closed. Ironically, an unbalanced system with an oversupplied (unbalanced) master bedroom will help reduce the pressure difference of that space relative to the outside although the main spaces suffer as a result. Additionally, excess air provided to the bathrooms may serve to remove odors and moisture build-up when bath exhaust fans are not operated.

3.6 AIR HANDLER RETURN GRILLE OPENING

Pressures were recorded with and without the return air grille affixed to the air handler compartment in the single section home. Figure 3-17 shows the response of pressures to the removal of the return air grille with the air handler on, low duct leakage, no other fans operating, low shell leakage and all doors open.

When the return air grille was removed from the air handler compartment, pressures decreased slightly in all areas of the home and in the sheathed and taped wall cavities. Removing the return air grille permitted more air to enter the air handler by reducing friction between the grille and the air. Therefore, the pressure differential required to move air from the living area into the fan compartment was marginally lower. Unsheathed wall cavities, the attic cavity and the floor cavity were little affected by the grille placement due to their weak coupling with the interior spaces.

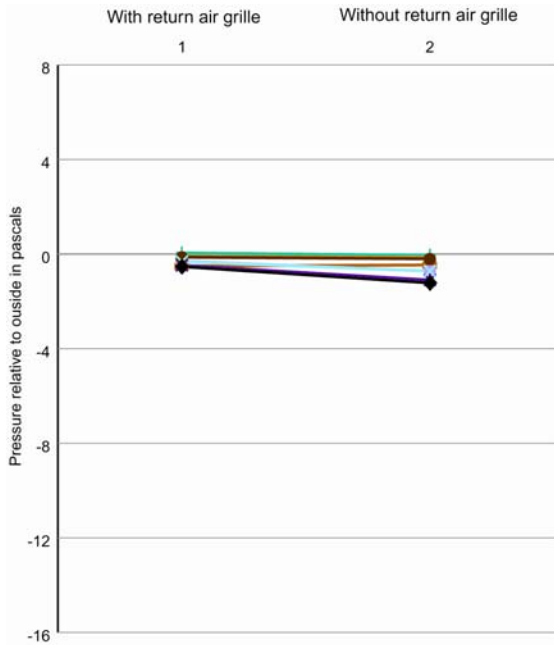


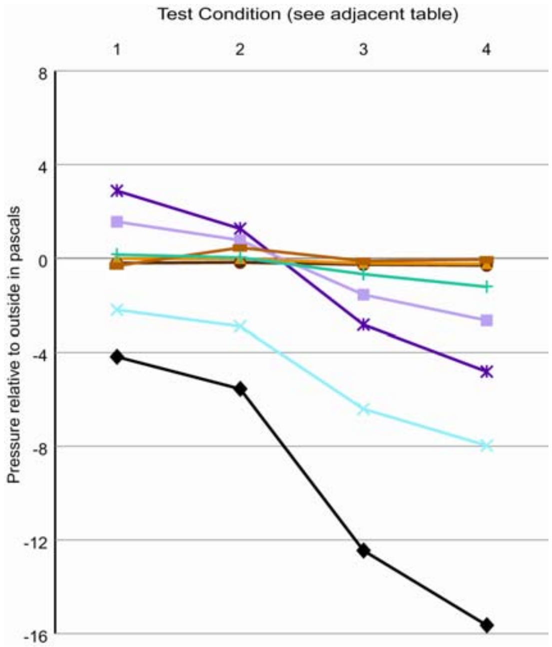
Figure 3-17 Impact of the return air grille on interior pressures

3.7 EXHAUST FAN OPERATION

Like most site-built homes, manufactured homes employ spot ventilation to remove moisture generated by cooking, bathing, laundry and other activities. As described in Chapter 2, the test homes had exhaust fans located in the bathrooms and kitchens as required by the Manufactured Home Construction and Safety Standards [16].

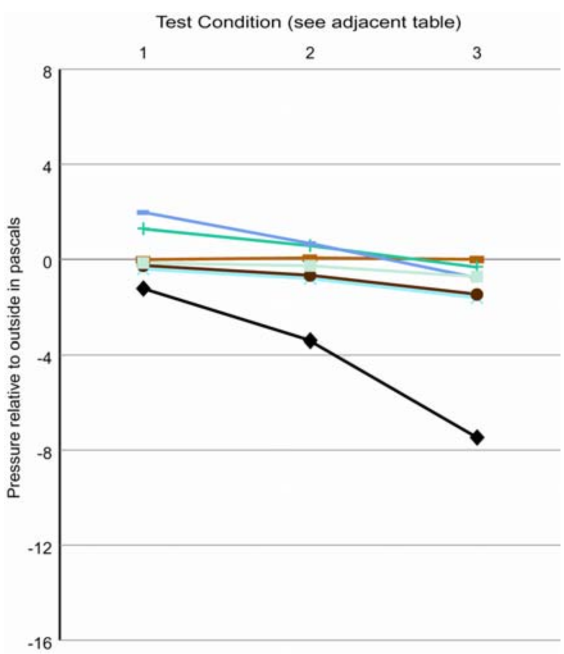
Pressure profiles were developed with these fans operating, as well as with an additional exhaust fan (a duct leakage testing fan set to 200 cfm) used to simulate a clothes dryer exhaust system (Figure 2-13). Figure 3-18 and Figure 3-19 show the impact of these fans on the pressure profiles of the single and double section homes, respectively. With these fans operating together, the quantity of air exhausted from the home created a negative pressure relative to the outside far in excess of the impacts of the other factors investigated in this series of tests.

[16] Manufactured Home Construction and Safety Standards, Subpart § 3280.103(c)(2) and (3).



Test condition	Air handler on	Bedroom doors closed, grilles open	Bathroom fans on	Kitchen fan on	Clothes dryer on
1	✓	✓			
2	✓	✓	✓		
3	✓	✓	✓		✓
4	✓	✓	✓	✓	✓

Figure 3-18 Impact of fan use on pressure profiles, single section home



Test condition	Air handler on	Bedroom doors closed, grilles open	Bathroom fans on	Kitchen fan on	Clothes dryer on
1	✓	✓			
2	✓	✓	✓	✓	
3	✓	✓	✓	✓	✓

Figure 3-19 Impact of fan use on pressure profiles, double section home

The main living area of the single section home reached -16 Pa relative to the outside with all fans operating (test condition 4 in Figure 3-18), compared to -5 Pa with only the air handler on (test condition 1). In the double section home, pressures reached nearly -8 Pa in the main living area with all fans operating (test condition 3 in Figure 3-19) as compared to approximately -1 Pa with only the air handler on (test condition 1).

In Section 3.4, it was suggested that an air barrier would have only marginal benefits due to the small pressure differences between the two wall construction types experienced at the baseline conditions (no fans operating). However, the difference grew to as much as 11 Pa between the two wall configurations with all exhaust fans on and interior doors closed. Under these conditions, the benefits of an exterior air barrier are significantly enhanced.

While the degree of negative pressure is of concern when all exhaust fans are on and all interior doors closed, it is unclear how often, and in what combination, these fans operate. It seems unlikely that all exhaust fans plus the clothes dryer would be operating simultaneously for an extended period of time. However, even one or two fans may exhaust enough air to cause high pressure differentials. The greater the capacity of the exhaust fans, the more the negative pressures would tend to be exacerbated The threshold pressure and duration of fan operation that may lead to moisture problems are factors that require further study.

If indeed homeowners operate these fans for durations long enough to draw significant amounts of moisture into the home, then one possible solution may be to increase proportionally the positive ventilation and to condition the fresh, incoming air (by passing the outside air over enough cooling coils) before distributing it to the living spaces. This would in essence create a balanced ventilation system and control the entry point for unconditioned outside air.

3.8 POSITIVE VENTILATION SYSTEM

Both test homes were constructed with positive ventilation systems (POS systems) that consisted of a fresh air duct from the outside terminating in the air handler above the cooling coils (Figure 2-3). This is a passive system without any additional controls or fans. When the air handler operates, air is drawn into the duct by the negative pressure generated in the air handler chamber. Air entering through this vent passes over the cooling coils and is conditioned (cooled and dehumidified). With the air handler operating at high speed, approximately 42 cfm of air was drawn through this duct in the single section home and 45 cfm in the double section home.

In order to evaluate the effects of the ventilation system on the homes' pressure profiles, a series of tests were conducted. In the single section home, these tests were run with the fresh air intake duct sealed. Additionally, in both homes, a series of tests were conducted with an additional 100 cfm of positive ventilation added into the main living area. This was done by connecting a duct leakage testing fan to bring in air through an open window in the same manner as the simulated dryer exhaust ventilation system.

Figure 3-20 shows the pressure profile of the single section home at three states: with the fresh air duct sealed; with the positive ventilation system operating (drawing in the 42 cfm); and with the positive ventilation system operating and an additional 100 cfm of ventilation provided by the supplementary fan. During this test, duct and shell leakage were low, bedroom doors were closed with return air grilles open and the air handler fan was operating. All pressures within the home increased as positive ventilation was added. The pressure in the main living area increased from approximately -5 Pa without mechanical ventilation, to -4 Pa with the 42 cfm fresh air ventilation system operating, to -1 Pa with the ventilation system and the additional 100 cfm fan operating. The lack of adequate return airflow from the bedrooms prevented the home from rising above 0 Pa.

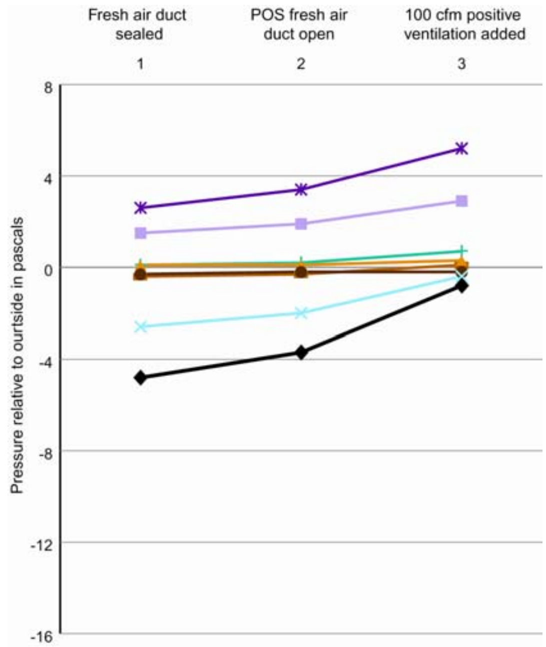


Figure 3-20 Effects of positive ventilation with bedroom doors closed, single section home

Figure 3-21 shows the pressures in the single section home under the same conditions, except that the bedroom doors were open. With the standard ventilation fan operating but without the added 100 cfm positive ventilation, pressures in all areas except the floor cavity were negative. With the 100 cfm positive ventilation supplementing the 42 cfm ventilation system, all pressures except the unsheathed living room wall cavity were positive.

Similarly, in the double section home, tested with low duct and shell leakage, all doors open and with the addition of 100 cfm positive ventilation, all pressures increased to neutral or positive relative to the outside, except for the attic, which was very well connected to the outside and not greatly affected by air pressure within the home (Figure 3-22).

In both homes, the additional 100 cfm positive ventilation came directly into the living area where it was most needed. With standard ventilation systems, the air is dehumidified and distributed throughout the house. The effect of the standard ventilation system will still be to increase the pressure, but not as much will be manifest in the main living area.

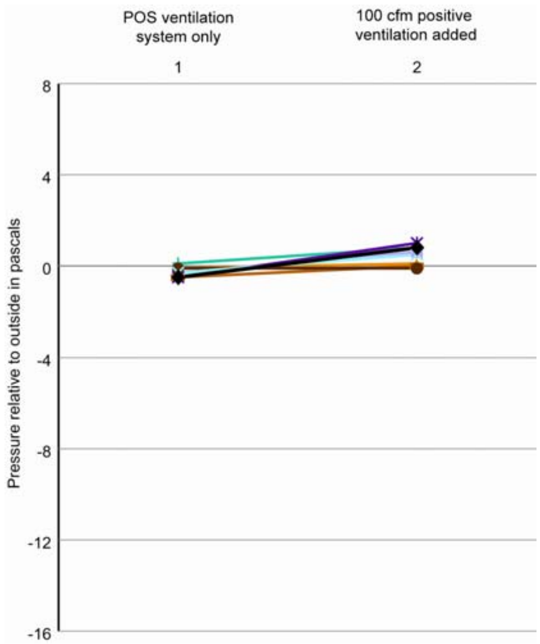


Figure 3-21 Effects of positive ventilation with bedroom doors open, single section home

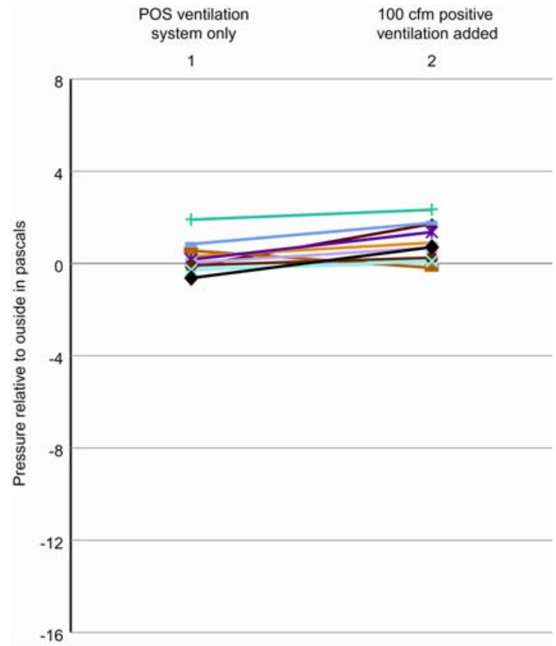


Figure 3-22 Effects of positive ventilation with bedroom doors open, double section home

Because the pressure changes in the homes resulting from the ventilation fans were small compared to the pressure differences across the fans, the flows may be added[17]. These results indicate that a total of 140 cfm of fan flow into the homes (100 cfm added to the approximately 42 cfm from the positive ventilation system) would be sufficient to maintain these homes at neutral to positive pressures relative to the outside under baseline conditions (i.e., no additional exhaust fans on, low duct and shell leakage and adequate return air pathways). This air would have to be dehumidified to have a beneficial effect. If additional exhaust fans were turned on, then a corresponding increase in positive ventilation might be required to maintain the positive internal pressures. In other words, based on this limited testing, a positive ventilation system with larger fan capacity than standard POS systems can play a major role in creating a balanced, neutral to slightly positive pressure profile in the home.

Further, drawing air into the home through a controlled ventilation system (as opposed to uncontrolled shell leakage) provides the opportunity to condition (dehumidify) the air before it reaches the living spaces. Introduction of unconditioned air contributes to the latent cooling load and potentially increases the chances of condensation. Future research is needed to identify the best strategies for providing additional positive ventilation with conditioned air.

[17] Because fan flows and their resulting pressures have an impact on infiltration, the change in net ventilation may not be exactly 100 cfm. For further discussion see Palmiter, Larry and Bond, Tami, *Impact of Mechanical Systems on Ventilation and Infiltration in Homes*, Ecotope, Inc., American Council for an Energy-Efficient Economy, Summer Study on Energy Efficiency in Buildings (1992).

4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The following is a summary of the findings drawn from the data collected through field testing of two manufactured homes: a single section and double section home of typical dimension, plan layout and material specification. While these conclusions are preliminary and based solely on the results derived from two homes built by one manufacturer and set up in a plant in the Gulf Coast area, the principal findings are likely to be broadly applicable to homes built under the HUD code.

Duct leakage
Duct leakage and shell leakage had the most dramatic effects on the homes' pressure profiles. Not surprisingly, as duct leakage increased, floor cavity pressure increased dramatically and other pressures decreased, and pressure imbalances between spaces were exaggerated. If the leakage is maintained at a maximum of about 5% to the outside, pressures will remain close to neutral if adequate return air pathways are provided (i.e., if interior doors are kept open). When duct leakage increases beyond 5% to the outside, the likely result will be severe negative pressures within the home relative to the outside. This was less evident at leakier shell levels than with a tighter home. As the building shell was made leakier all pressures approached equilibrium with the outdoors.

Shell leakage
Tightening the envelope is a good building practice, assuming other steps are taken in tandem to offset some of the potential drawbacks of sealing the shell. Tight envelopes exacerbate negative and imbalanced pressures, although it was possible to achieve near-neutral pressures with a shell as tight as 7.2 ACH_{50} (estimated as 0.29 $ach_{natural}$), if the ducts were tight and adequate return air pathways were provided.

Interior Airflow
Of the factors that are controlled by the homeowner, those that have the biggest positive impact on pressure balance within the home are keeping the master bedroom door open and limiting the use of exhaust ventilation fans to only when they are needed. A closed master bedroom door in combination with a tight shell was enough to create significant negative pressures within the home.

While it is impractical to keep interior doors open at all times, providing pathways for return air between bedrooms and the main living area of the home (where the furnace is located) is essential to maintaining near-neutral pressures in the main living area. The undercuts and return air grilles commonly used in bedroom doors have some beneficial effect, but in most cases are not sufficient air return paths.

Exterior Air Barriers
An exterior wall sheathed with an effective air barrier can affect significantly the pressure gradient across the wall as compared to a wall cavity that easily exchanges air with the exterior. In tests, a fairly well sealed air barrier, placed on the outer plane of the wall, reduced by about one-half the negative pressure differential between the wall cavity and the home interior.

The attempt to seal the wall using blackboard as sheathing failed. Further investigation is needed to determine the best strategies for sealing walls.

Air supply balance

While air distribution systems in manufactured homes are in some cases unbalanced, it does not appear that balancing them will appreciably reduce negative or unbalanced pressures within the home as a whole. Redistributing air will, however, influence the pressure profile in individual spaces when doors are closed and may improve comfort level in the spaces.

Attic ventilation

Even though the attic in the single section home was not constructed with intentional ventilation to the outside, the attic space freely exchanged air with the outside and acted as a ventilated cavity with a pressure profile similar to the unsheathed walls. Additional study is warranted prior to suggesting how attics can be part of a program for controlling moisture flows.

Air handler return air grille opening

Increasing airflow through the return air grille on the furnace resulted in negative pressures being exacerbated in the main living area.

Exhaust fan operation

Exhaust fans installed in manufactured homes have the capacity to create negative pressure relative to the outside far in excess of the impacts of the other factors investigated in this study. It is unclear how often, and in what combination, these fans operate. However, even one or two fans may exhaust enough air to cause high pressure differentials. The level of pressure and the duration of that pressure that are sufficient to lead to moisture problems are factors that require further study.

A possible solution may be to increase proportionally the positive ventilation and condition the fresh, incoming air (by passing the outside air over enough cooling coils) before distributing it to the living spaces. This would in essence create a balanced ventilation system and control the entry point for unconditioned outside air.

Positive ventilation system

Positive ventilation can play a major role in creating a balanced and positive pressure profile in the home. Further, drawing air into the home through a controlled ventilation system (as opposed to uncontrolled shell leakage) provides the opportunity to condition (dehumidify) the air before it reaches the living spaces. Introduction of unconditioned air contributes to the latent cooling load and potentially increases the chances of condensation. Future research is needed to identify the best strategies for accomplishing this goal.

Other observations

The manufacturer of the test homes employs building methods that are energy efficient, resulting in homes that have very low shell and duct leakage levels. Prior research has suggested that many manufacturers are routinely building homes with tight ducts and envelopes[18]. Not only are these homes more energy efficient than older homes, but their tight construction provides the opportunity to control and dehumidify incoming air.

[18] Energy Star plant certification measurements 2001-2003 compiled by the Manufactured Housing Research Alliance.

4.2 A STRATEGY FOR MAINTAINING THE DESIRED PRESSURE PROFILE

The principal objective of this phase of the research was to identify ways of building manufactured homes that minimize moisture flow through the building envelope where it might condense and cause moisture-related damage. The strategy for achieving this goal was to describe techniques for creating a neutral to slightly positive pressure within the home relative to the exterior. The testing showed that the houses came close to this objective under certain conditions, such as when the bedroom doors were open. When doors were closed, the objective was more difficult to achieve. When auxiliary equipment (exhaust fans and simulated clothes dryer) were activated, it made achieving the neutral to positive pressure much more difficult. The greater the capacity of the exhaust fans, the greater this problem likely will become.

The research examined individual and combinations of factors that together can achieve the desired pressure profile. The results, expressed as threshold or target levels for each of the factors, are summarized in Table 4-1.

Table 4-1 Summary of recommended construction and operating conditions

Design consideration	Importance for proper pressure balance	Recommendation
1. Duct leakage	Very important	Target: **≤5% to the outside**
2. Shell leakage	Very important	Target: **8.8 ACH_{50} maximum (estimated as 0.35 $ach_{natural}$)** Maintain a tight shell to control airflow through the envelope.
3. Interior airflow	Very important	Target: **≥70 square inches open area for each 100 cfm supply** Maximize return air openings for all major living spaces.
4. Exterior air barriers	Potentially important, if pressure differentials are great	Target: **Effectively seal the exterior side of exterior walls**
5. Air supply balance	Little importance	Target: **No target determined** Additional research is required to determine the effects of reducing air supply to bathrooms.
6. Air handler return air grille opening	Little importance	Target: **Do not remove or enlarge the air handler return air grille**
7. Exhaust fan operation	Potentially important, depending upon fan operating schedule	Target: **Run exhaust fans only when interior moisture must be exhausted. Consider balancing ventilation system by enlarging POS intake and/or adding control system**.
8. POS system	Very important	Target: **Increase controlled intake of outside air to approximately 140 cfm and effectively dehumidify**

This set of recommendations provides a starting point for further study and analysis, rather than constituting a group of proposed construction specifications or a set of suggested best practices. The implied precision of some of the recommendations should be interpreted cautiously, in light of the fact that testing was performed on only two homes from a single manufacturer.