Alternatives for Minimizing Moisture Problems in Homes Located in Hot, Humid Climates: Interim Report

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EXECUTIVE SUMMARY

An effort was undertaken to examine manufactured homes in the Gulf Coast area, gather information on condensation-related moisture problems in those homes, and determine the contributing factors to those problems. Building scientists gathered data from 70 homes with and without moisture problems. A thorough literature review, examination of the data, and neural network analysis of the data were used to evaluate and prioritize the significance of twelve potential contributors to moisture problems, in terms of their impact in causing such problems. This document reports on the findings of this research effort.

Significantly, the results of the neural network analysis indicated that 62% of the problems could be explained by a number of the identified contributors. These results, in combination with other data analysis and the literature review helped to prioritize the full list of contributors in terms of their impact on moisture problems and to and classify them into three groups. In order of decreasing significance, these were found to be:

1. Pressure imbalances, including those caused by imbalances in the distribution of conditioned air, duct leakage, and shell leakage.

2. Vapor retarders and air barriers as a complete system, including the walls (wall air barriers and vapor retarders), floor (bottom board and ground cover) and ceiling (ceiling air barrier and vapor retarder).

3. Occupant comfort, which is affected by a combination of indoor temperature and humidity levels.

It was also concluded that statistical analysis and modeling can play a supporting role in identifying major causes of condensation-related moisture problems but cannot fully explain the nature and source of moisture problems.

As a result of this prioritization, further work is recommended that will focus on the three moisture problem contributor areas identified above, with an emphasis on the first two: pressure imbalances and vapor retarders/air barriers. This work will require testing and evaluation of unoccupied homes and building subsystems under controlled conditions. It will produce specific guidelines for the minimization and remediation of moisture problems for manufacturers, installers, service personnel, and homeowners of manufactured homes in the hot, humid climate of the Gulf Coast region.

2

INTRODUCTION

2.1 BACKGROUND

In 1999, the Manufactured Housing Research Alliance (MHRA) conducted an initial phase study to identify non-geographic specific 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, HVAC Contractors, and Homeowners. Although the focus of this work is manufactured housing, the moisture migration problems noted are found in all types of structures in the gulf coast region (site-built homes and commercial buildings as well as manufactured housing).

A second phase of the study was initiated because of reports of moisture problems in manufactured homes located in the Gulf Coast area of the United States. The objective of this second phase was to examine manufactured homes in the Gulf Coast area, gather information on the moisture problems, and determine the contributing factors to those problems.

Excess moisture infiltration and accumulation is a damaging agent affecting housing durability and potentially reducing its service life. Structures negatively affected by moisture intrusion and migration problems include single-family, multi-family and commercial buildings. Moisture is readily absorbed by many building materials, and when present in critical levels can cause these materials to not perform as designed, cause metal to rust, and result in odors or stains.

Moisture intrusion problems are particularly difficult to diagnose and address because of the complex mechanisms available for the migration of moisture through building materials and connections. Many individual building components influence moisture dynamics through their thermal performance and/or their capability to store moisture or to allow vapor diffusion. In some instances the design of the structure can contribute to the problem, while in others the material selection can create the problem.

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, the lodging industry and other buildings. The physical forces that drive moisture dynamics and cause it to accumulate where it may cause damage are the same for all types of buildings.

Both the construction and operation of housing have changed over the past 10 years in ways that can affect moisture performance. Whereas no one action can completely protect a home from moisture; for the most part, no one building practice can be solely blamed for moisture problems either.

It should be emphasized that homes with moisture problems, even in the hot, humid Gulf Coast region (the focus of this interim report) are the overwhelming minority of 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. This research effort is geared towards minimizing moisture problems in a small number of manufactured homes, with a special emphasis on homes in hot, humid regions.

2.1.1 Moisture migration mechanisms

Complicating the efforts at diagnosing and mitigating moisture problems is the fact that moisture can move by a number of migration paths, aided by a number of mechanisms. These can be divided into three basic categories:

1. Bulk water intrusion moisture problems, such as those caused by rain and plumbing leaks. This class of problems typically has a single identifiable cause such as damaged flashing, missing caulking or a pipe leak. In the vast majority of cases, these types of moisture problems can be corrected with relatively straightforward measures. This research focuses on the far more complex issue of condensation and humidity-related moisture problems and therefore bulk water intrusion problems are out of the scope of this report[1].

2. Condensation-related moisture problems due to the interaction of humidity and temperature. This project addresses this type of moisture problem. Condensation-related moisture problems are far more complex and can have a number of migration paths, including:

   - Air movement. Hot, humid air contains water vapor that condenses when the air temperature drops below the dew point. Humid air movement can transport moisture in the absence of adequate barriers to air flow.

   - Vapor diffusion. Water vapor pressure continuously seeks equilibrium with its environment and thus will move from areas of high concentration to areas of low concentration in the absence of a sufficient barrier.

3. Capillary action. The movement of water within the spaces of a porous material due to the forces of adhesion, cohesion, and surface tension. Water must have previously entered the structure via bulk water intrusion or condensation (and be in liquid form) for capillary action to come into play.

Condensation is a difficult moisture problem to isolate. It can occur when high humidity air comes into contact with any surface or substance that is at a temperature below the dew point of the air. The high moisture content of the ambient air in hot humid climates provides an abundant source of moisture to feed moisture problems in homes that provide a sufficiently low temperature. Thus the key to minimizing condensation-related moisture problems in homes is to minimize the interactions between hot, humid air and cooler temperatures in and around the living area of the home and the building shell.

These migration mechanisms affect the moisture balance in homes. The objective in building design is to maintain a balance of moisture and temperature conditions throughout the structure such that building materials and assemblies are not subjected to extended periods where their moisture content is in excess of their capacity to perform adequately. Often, measures that address one problem result in a less than optimal moisture balance, and can shift the problem to another area. Fortunately, building systems tend to be forgiving of occasional moisture build up and will dry out if given the opportunity. Because some migration paths allow both inflow and outflow of moisture, eliminating such migration paths completely can cause an imbalance that allows moisture to accumulate over

[1] For a discussion on bulk water intrusion issues, see "Durability by Design - A Guide for Residential Builders and Designers" published by the U.S. Dept. of HUD.

time to levels that damage the home. Thus, small changes in design, construction, operation, or the local climate can push conditions over the threshold to the point of moisture problems.

2.2 PROJECT OBJECTIVES AND IMPORTANCE

The overall objective of this project is to minimize the extent and frequency of moisture problems in manufactured homes by:

1. Improving the understanding of the mechanisms that cause moisture problems in manufactured homes, through characterization of the design, construction and operational factors contributing to specific moisture problems.

2. Developing, testing, and demonstrating cost-effective design, construction and operational practices that minimize the chances of developing moisture problems through field investigations, and laboratory analysis.

3. Dissemination of project results to industry and consumers by developing user-friendly information and tools that manufacturers, installers, service personnel, and occupants can use to apply this knowledge.

2.2.1 Why this work is timely

There is a lack of up-to-date and reliable information available that addresses moisture problems in manufactured homes, and a lack of guidance available to manufacturers, installers, service personnel, and homeowners. Although anecdotal stories of homes with moisture problems, often with photographic detail, are generally available, there has been a general lack of detailed construction, installation and operation information or measured performance data. No data existed to describe whether the problems were predominant in single- or multi-section homes or where the problems most often occurred. Similarly, moisture problem causes being cited were generally speculative, and often were based more on theory than on evidence. Manufacturers were beginning to amass some data on their own homes, but generally lacked a sufficient sample size to come to a definitive conclusion.

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 the structure and may lead to an increase in the frequency and/or severity of moisture problems.

- 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 this equipment for a large portion of the year. Air conditioning sets up temperature differences that previously did not exist in warm-climate building environments; and under some conditions can support condensation on building materials. Forced air systems intentionally create small pressure differences in order to induce air circulation. However, excess pressure differences between the house and outside, or between rooms, can drive potentially humid air through building components. Air conditioning also generates condensate and the critical need to remove it from the building interior. Often, occupants fail to properly operate and maintain the equipment, for example, neglecting the regular replacement of air filters. Oversized equipment typically installed by homeowners can bring the indoor temperature significantly lower than the outside temperature and often below the outside dew point, without adequately dehumidifying the home interior. Anytime occupants set the thermostat below the exterior dew point temperature, conditions may be created that will support moisture condensation within the building shell assemblies, regardless of the building design.

- Building cavity designs have changed, largely due to increases in insulation but also due to the use of new materials and to increased structural requirements in areas subjected to high winds. Design changes – such as in walls - have changed the way these structures respond to both heat and moisture transfer.
- The use of exhaust ventilation equipment such as clothes driers, bathroom exhaust fans and high-volume cook top ventilators has increased in homes and can effect heat and moisture movement, as well as induce pressure differentials between the house and outside.
- Homeowners are increasingly installing high-end features such as whirlpool baths, steam showers and dual bathroom sinks, adding to the moisture load inside their homes.
- Ventilation designs commonly used in homes to provide adequate fresh air and moisture removal may be counterproductive in some climates. Ventilation systems tied to air handler operation may over ventilate the home and can add more moisture load than the dehumidification capacity of the cooling equipment – particularly if operation times are high. Ventilation systems that contribute to negative house pressures may also contribute to bringing humid air into building cavities.

2.2.2 Who will benefit from this project?

While the present interim report is intended for the engineering community, the intended audiences for the overall project results are both manufacturers in the plant environment, installers and repair crews operating in the field, and homeowners. Solutions will be in the form of steps that the manufacturer can apply proactively in the plant that will reduce the occurrence of moisture problems. When a problem does arise in an installed home, a retrofitter is charged to resolve the problems. Often, however, the retrofitter repairs only the symptoms, for example: replacing damaged wallboard. With the information from this research, they will have tools and techniques available that will enable them to better identify the underlying causes and provide solutions that will resolve moisture problems in field applications and prevent their reoccurrence.

2.3 PROJECT DESCRIPTION

This project is divided into three phases.

2.3.1 Phase 1 – Moisture problems in manufactured housing

Phase 1, completed in 2001, identified moisture migration patterns in various US climates. As a result of this phase, the Manufactured Housing Research Alliance (MHRA) published the guide, *Moisture Problems in Manufactured Housing – Understanding Their Causes and Finding Solutions*. The guide provided moisture problem basics, checklists for manufacturers, installers, HVAC contractors, and homeowners, and tips on moisture problem prevention and mitigation.

2.3.2 Phase 2 – Alternatives for minimizing moisture problems in hot, humid climates

Phase 2 was initiated to address the moisture problems observed in Gulf Coast manufactured homes. This document reports on the findings of this phase of the project.

The Gulf Coast has become an important region for moisture problems. Shifting demographics continue to see population growth along the Gulf Coast. The hot, humid climate of the region provides challenges for manufacturers, installers and homeowners that are significantly different from colder climate practices developed to meet the challenges of freezing temperatures and snow loads.

In this phase, moisture problem dynamics were investigated and explained from the unique Gulf Coast perspective. Phase 2 included the following steps:

1. Characterization of manufactured homes with moisture problems in the hot, humid climate region based on a literature review and interviews with manufacturers and building scientists.

2. Conducting a field survey and collecting data from a sample of homes experiencing moisture problems in the Gulf Coast.

3. Identifying, with statistical analysis, the characteristics most strongly associated with moisture problems.

4. Preparing additional recommendations for manufacturers, installers, service personnel, and homeowners, based on data analysis and literature review.

5. Determining objectives and work elements for Phase 3 to measure effectiveness of specific recommendations.

2.3.3 Phase 3 – Developing and testing solutions to moisture problems

Phase 3 of the project will explore solutions to address the key contributors to moisture problems identified and characterized in Phase 2:

1. Pressure imbalances

2. Non-continuous vapor retarders and air barriers

3. Occupant comfort

Solutions will be developed and tested in the laboratory and/or the field and user-friendly information will be published to enable designers, manufacturers, installers and homeowners to minimize their risk of moisture problems by incorporating these solutions into their practices. A detailed plan for this phase is included in Section 7 of this document.

2.4 RESEARCH METHODOLOGY

This phase of the project employs the following methodology to characterize construction, installation, maintenance, and operational factors in homes and to associate them with the degree of moisture problems in order to suggest targeted solutions.

MHRA visited a sample of manufactured homes with moisture problems in hot, humid climates and identified a set of key construction, installation, maintenance, and operational characteristics and moisture damage patterns. Analysis of this data was undertaken to identify which of these characteristics were more strongly associated with the moisture related damage and that, consequently, could be used to control such occurrences. This was accomplished through four steps:

1. A literature search and review was conducted (Appendix E). Twelve potential contributors to moisture problems were identified from the literature and through interviews with building scientists and home manufacturers.

2. A protocol was developed for surveying a large sample of moisture problem-homes in the field. These homes were located in the Gulf Coast region of the American South. The data

collection process and data collection protocol are explained in Appendix A and B respectively.

3. Sixty-seven homes were identified through contacts with manufacturers, retailers and service people (58 homes had recognizable moisture problems, 9 homes had no signs of moisture problems). These homes were each visited on at least one occasion by a building scientist for the collection of the data and the assessment of the various moisture problems (Appendix C). The data was collected between the months of April and October, the period during which moisture intrusion problems characteristic of the Gulf Coast region are typically at their peak.

4. Due to the complexity of the moisture dynamics, statistical methods were needed to correlate the many factors that jointly contribute to moisture problems. The data was analyzed through the use of a neural network model (Appendix D), as well as by looking at simple data relationships among the homes. The hypothesized moisture problem contributors were rated as to their degree of importance in causing moisture problems (Table 4-2). Initial conclusions and recommendations were made based on the analysis (Section 6).

2.4.1 Limitations of the research

Moisture dynamics is highly complex. Field investigations of homes with moisture-related damage offer a real world laboratory for exploring the major moisture problems and the likely sources of those problems. Field study affords the opportunity to document the entire building dynamic and to infer how moisture problems originate within their actual operating environments. Identifying which factors contribute most to moisture problems is complex, as each home is unique in many ways and even side-by-side matched homes may have unrecognized differences in installation and occupant lifestyle habits. It is thought that factors as subtle as the duration for which interior doors are closed may have a significant effect on the level of moisture problems. A number of other variables and challenges may have affected the data gathered:

- ***Bulk water intrusion*** There are two basic classes of moisture problems – bulk water intrusion and condensation/humidity-related problems. This project focuses on the later. The former is not specific to the hot, humid climate and typically has a single identifiable cause such as damaged flashing, missing caulking or a pipe leak. In the vast majority of cases, this type of moisture problem can be identified and corrected with relatively straightforward measures. Efforts were made to eliminate homes with bulk water intrusion-related problems in the identification of homes surveyed for this study, but it is not possible to completely rule out the possibility of bulk water intrusion as a factor in the moisture problems identified in this study.

- ***Lifestyle and occupancy variables.*** In order to gather data from a large number of sample homes with moisture problems in the Gulf Coast region, MHRA chose to survey occupied dwellings. This strategy necessitated the use of a non-invasive investigation and testing protocol. For example, it was not always possible to open up walls to determine the extent or type of wall sheathing present or whether the exterior walls were intentionally ventilated to the outside. Because the homes were occupied, additional variables that could not be reliably quantified were also introduced. For example, family composition and lifestyle characteristics such as how often laundry was done may affect the moisture balance within a home, but could not be measured in a one-time visit by a building scientist.

- ***Data collection challenges.*** Some of the data was difficult to accurately and consistently collect. Items such as bottom board holes and ground vapor barrier coverage could not be accurately measured by the surveyor, and had to be estimated.
- ***Weather variation.*** Moisture problem severity is highly dependent on the weather over the course of the preceding days and weeks. Day-to-day, seasonal, and year-to-year variations also have significant influence over the degree of moisture problems. All homes were visited over the course of a single summer season, however it was not practical to visit each home during identical or similar climactic conditions and so it is possible that this variation had some affect on the data collected.

2.5 HOW THE REPORT IS STRUCTURED

The report is structured to focus on the specific symptoms and contributors of moisture problems in manufactured homes. After a discussion of the fundamental dynamics of moisture migration in section 4.1, the symptoms observed in the data collection effort are described and contributors to those symptoms are detailed in sections 4.2 and 4.3. These contributors were the primary factors analyzed in the course of the field work and data analysis. In section 5, each contributor is described in detail based on the analysis of the data, with specific characterizations from the literature review, data description and analysis. Finally, specific recommendations to address each contributor are provided, also in section 5. Interim results that lead to specific recommendations are included as an independent Section 6. Section 7 includes next steps for a pilot program to implement design recommendations and monitor their effectiveness. The detailed analytical work and reference material are included as appendices.

3

THE NATURE OF MOISTURE PROBLEMS IN HOT, HUMID CLIMATES

3.1 THE DYNAMICS OF MOISTURE PROBLEMS IN HOT, HUMID CLIMATES

Moisture problems can be defined as degradation of the performance or the appearance of building materials resulting from an accumulation of moisture to levels that exceed a material's storage capacity or design operating conditions. The intention of this report is to focus on the most difficult moisture problems in hot, humid climates. Characteristics of difficult moisture problems include homes with suspected condensation concealed within building assemblies and homes that have been repeatedly repaired for identical recurring problems.

The movement of moisture in homes is a dynamic, complex phenomenon such that individual measures are often insufficient to cause or to prevent moisture problems. When moisture accumulates on surfaces or within materials and building components, several factors contribute to the moisture imbalance making it difficult to pinpoint single definitive strategies for prevention.

The complex mass transfer mechanisms within the housing envelope are further complicated by climactic conditions. Sources of moisture within the home include heating, cooking, cleaning, bathing and other sources. In colder climates, the moisture mass transfer is generally from these sources inside the living space to the colder, drier air outside. Precipitation also plays a role in transfer of moisture from outside to inside the home. Therefore, solutions to mitigating moisture damage in housing have been largely directed at preventing moisture from entering the building materials that comprise the inside walls of the living space.

In hot, humid climates the mass transfer mechanisms are complicated by the fact that there are many of the same moisture sources inside the living space in addition to a tremendous reservoir of moisture in the ambient air. Because of high ambient dew points in hot, humid climates, moisture migration paths are tied to the movement of moist outside air and the conditions which contribute to the condensation of moisture from the air. Moisture migration paths occur primarily by air movement through gaps in the building shell, and secondarily, by diffusion through building materials. The driving forces behind this migration are the difference in total pressure and water vapor pressure between the air-conditioned interior and the humid ambient air.

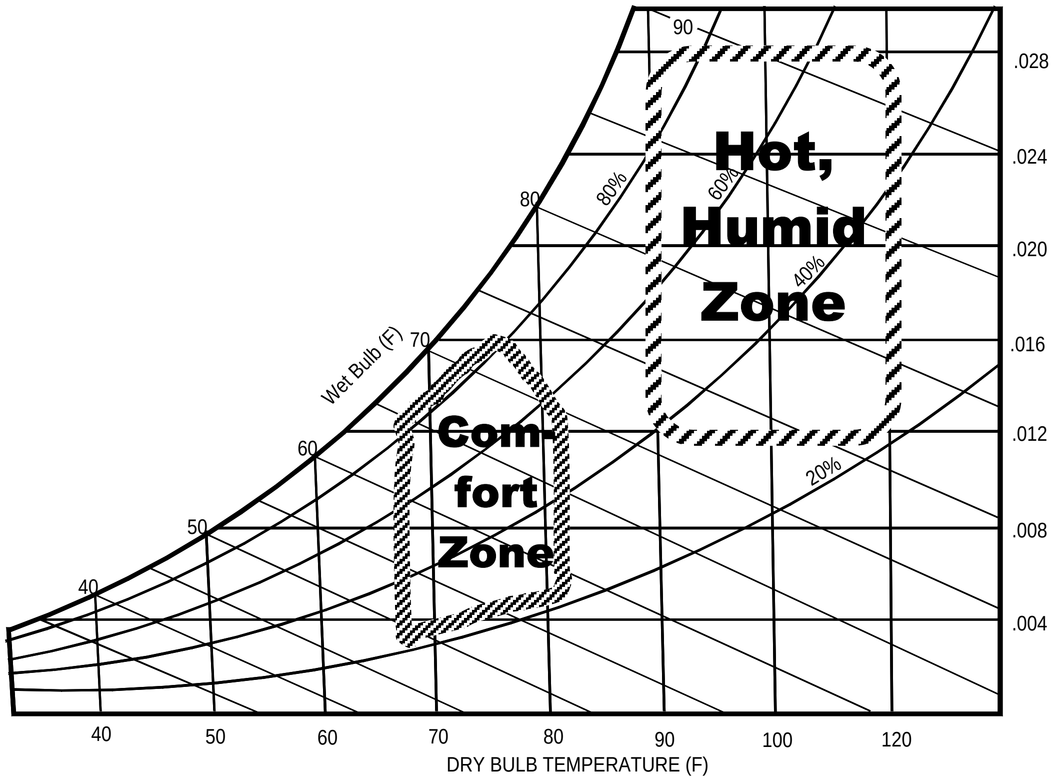

Figure 3-1. Psychrometric Chart Showing Humid Climates and Human Comfort Zone[2]

Relative humidity is a measure of the moisture content of air as a function of its maximum moisture capacity. As air temperature increases, so does its moisture capacity. Inversely, as hot, humid air is cooled, its relative humidity increases. When relative humidity levels reach 100%, condensation occurs on surfaces whose temperatures are lower than the dew point of the air. Such is the dynamic of hot humid air as it migrates through the building envelope. Though most building materials have the capacity to absorb and store some moisture, over time building materials subject to such conditions may exceed this capacity and sustain moisture damage. Building materials naturally seek moisture content equilibrium with the surrounding environment: for example, 100% relative humidity air achieves equilibrium with wood with 30% moisture content. However, through continuously changing ambient conditions caused by daily and seasonal cycles, equilibrium conditions are rarely maintained over long periods and moisture is constantly moving from one material to the other.

[2] Comfort zone from Energy Conservation Through Building Design, Donald Watson, Editor, Architectural Record Books/McGraw-Hill Book Company, 1979. Hot, humid zone from The Engineering Toolbox, www.engineeringtoolbox.com, Sam C.M. Hui.

This added complication of moisture mass transfer in hot, humid climates suggests that solutions to moisture problems in colder climates may not be appropriate in hot, humid climates. Although there is a well-established body of building moisture problem theory, the interplay of the many design and operational factors involved and their relative importance is not as well understood. One of the primary goals of this study is to categorize moisture problem symptoms and dissect the contributing factors to these problems through qualitative analysis and quantitative field data.

The psychrometric chart in Figure 4-1 illustrates typical conditions in the hot, humid climate region in summer as compared to the human comfort zone. The psychrometric chart is a graphical representation of the thermodynamic properties of moist air. It describes all the possible combinations of temperature, moisture content, density and energy relating to air at one time.

3.2 CATEGORIZING MOISTURE PROBLEMS

Moisture problems are varied; some cause visible damage to building materials, while others cause uncomfortable conditions inside the space and are indicative of damage that is not readily visible. Categorization of these problems was critical to the data collection and analyses of the study. In all, eight categories of moisture problem symptoms were identified (Table 4-1).

Table 3-1. Moisture problems

Moisture problem	Quantifiable visible damage	Can determine presence, but not quantifiable	May be caused by moisture imbalance
Bowing and buckling	✓		✓
Softening of interior surfacing materials	✓		✓
Condensation		✓	✓
Standing water in ducts		✓	✓
Elevated humidity	✓		✓
Odors		✓	✓
Stains	✓		✓
Rust		✓	✓

3.2.1 Bowing and buckling

One of the most common symptoms of moisture problems is bowing and buckling of wall, floor or ceiling elements. Bowing and buckling is typified by a series of wave-like distortions along building element. Reports indicate that distortion is greatest in the summer when the conditions for condensation are greatest, i.e. cold wallboard and humid outside air. It was also reported that the distortions become less severe in the winter season when the air is drier and the living spaces are heated. These bowing and buckling problems are often associated with softening of the sheet material. In fact, the data collected indicate that more than sixty percent of walls that were reported to suffer from bowing and buckling also were reported to suffer from structural softening. Both bowing and softening are found in floors and ceilings as well.

Several walls near the front door showed swelling near the light switch (Figure 4-2). It could be significant that within these stud cavities was a penetration to the outside from the outside lamp fixture (Figure 4-3).

Figure 3-2. Bowing wall near the front door light switch

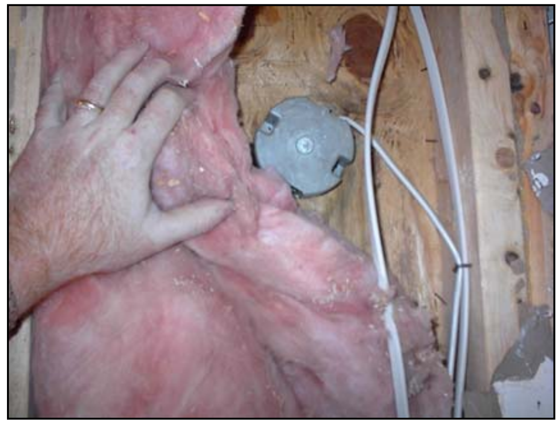

Figure 3-3. Penetration to the outside in wall cavity with outside light

3.2.2 Softening of interior surfacing materials

Another common symptom is softening of wall, floor or ceiling material. Softening of interior surfacing materials is often characterized by the lack of strength to support nails for hanging items such as picture frames on the wall or noticeable pliability of wallboard or floor decking material. Sixty-two percent of walls with structural softening problems also reported bowing and buckling.

Figure 3-4. Bowed wall seen along floor.

This mildly bowed wall (Figure 4-4) had softened wallboard and stains at the wall-floor interface. Problems were reported to be worse during summer. The wallboard in this home was reported to bulge by as much as two inches.

3.2.3 Condensation

Condensation is visible accumulation of water drops on non-absorbent surfaces. Thus, condensation is most often found in light fixtures, dripping out of electrical outlets, on metal ducts, and on other glass, metal, or plastic surfaces.

3.2.4 Standing water in ducts

Water in ducts is often caused by undiagnosed plumbing spills, but can also be caused by failure of the air conditioning condensate removal drainage system due to poor maintenance and/or installation.

3.2.5 Elevated humidity

Relative humidity is a critical element of human comfort in a conditioned space. High interior relative humidity is generally defined as greater than 65% RH. Values of relative humidity above this threshold lead to discomfort and can thus greatly impact the temperature set point behavior of the occupant. High relative humidity also increases the risk of condensation, as humid air comes into contact with surfaces at temperatures below the dew point. Relative humidity values are subject to significant variation during the day, thus this data was not used in the quantitative analysis.

3.2.6 Odors

While somewhat subjective, odors can be indicative of long-term moisture problems that exist behind visible building material surfaces. Such odors can provide indications of physical damage, in addition to being an annoyance to occupants. Documentation of odors is challenging in that they are subject to the data gatherer's and occupants' perceptions.

3.2.7 Stains

Staining is the discoloration of materials. It can be found along intersections of building assemblies; on wall, floor or ceiling surfaces; or between building materials such as carpet and floor decking. Stains can range in color from light to dark and can vary greatly in size. They may be caused by water penetration of materials or through organic growth. No testing was conducted to determine the specific causes of staining in the sample homes.

Figure 4-5 shows stains on the ceiling wallboard at the intersection of a cathedral and flat ceiling. Air barriers are difficult to maintain at such locations and humid attic air is often at the right conditions to condense onto the cold interior wallboard.

Figure 3-5. Ceiling staining.

3.2.8 Rust

Indicative of long-term condensation, rust occurs on metal surfaces such as nail and screw heads,air distribution grilles, and electrical components.

Figure 3-6. Rust on light fixture.

The light fixture in figure 4-6 shows rust stains on metal components and water stains in the glass globe, possibly indicating condensation of humid air from the attic into the light fixtures. Most likely condensation occurred when the light was off and cooled to room temperature.

Figure 3-7. Rusty nail heads.

Figure 4-7 shows rust spots on nails. Most likely, the nails have been exposed to high humidity. Molding previously covered these nails.

3.3 MAJOR CONTRIBUTORS TO MOISTURE PROBLEMS

There are several factors widely believed to contribute to moisture problems in hot, humid climates. The literature review identified a common list of factors that are recognized by building scientists as contributing to moisture imbalances within the home. What is not known and what this study sought to better understand is how and to what degree these factors individually and in combination correlate with moisture problems. Following is a list of contributors categorized by related phenomena.

- ***Pressure imbalances***: Imbalances in distribution of conditioned air and duct leakage to the outside are hypothesized contributors to moisture problems and are related to the overall pressure balance of the housing envelope. The literature review, data analysis and observations of researchers all indicate that pressure differentials between indoors and outdoors, as well as between rooms have a significant impact on moisture problems in homes. Internal pressures are primarily affected by air distribution issues such as duct supply balance, return air system design, ventilation system design and duct leakage. The findings of the work completed to date suggest that a house experiencing pressure imbalances is vulnerable to moisture damage.
- ***Non-continuous vapor retarders and air barriers***: Ground vapor retarder integrity, damage to the bottom board, interior vapor retarder location, exterior air barrier and type of attic ventilation all contribute to the overall moisture migration pathways in the home. The homes in the sample population had vapor retarders on the walls in the form of vinyl covered wallboard, often on the ceiling in the form of vapor retarding paint, and under the home in the form of a bottom board and ground vapor retarder (in most cases). These elements are intended to work together to inhibit the diffusion of moisture into building cavities. It was not possible to assess wall and ceiling vapor retarder effectiveness in preventing moisture problems because either all homes in the population had these elements or it was not possible to determine if these elements existed. The literature, however, predicts that these elements will best prevent moisture problems if located on the exterior side of the wall insulation where they can prevent the intrusion of humid air in hot, humid climates, and where they will not prevent moisture from drying from the walls and ceiling towards the de-humidified interior of the home. The data did indicate that the ground vapor retarder and bottom board were influential in protecting the home against moisture problems. The data suggests that homes with poor ground cover and penetration through the bottom board are more likely to have moisture problems.

- ***Occupant comfort***: Low indoor temperature settings and cold spots have long been thought to be contributors to moisture problems. The literature review and experience of researchers indicates that temperature is an important contributor to moisture problems. The neural network analysis also indicated that low interior temperature is correlated with moisture problems. Local cold spots were also associated with moisture problems, particularly on the floor where cold air registers were directed. This phenomenon was noticed in a limited number of homes where data could be collected. Without extensive monitoring equipment, the research team was unable to measure surface or air temperatures throughout the house over an extended period of time and therefore, this data is less useful. The introduction of unconditioned air into a house can be a potent transfer mechanism for moisture. Whole house ventilation systems that deliver air into the living space without consideration of humidity conditions allow unconditioned air to enter the house. Another cause of inadequate humidity control is infrequently running air conditioners, often as a result of their being oversized for the home's cooling needs.

The relationship of each contributor to moisture problems was analyzed in three different ways; through a review of the topical literature, an examination of the data combined with observation by building scientists, and through a neural network analysis of a number of the contributors. Table 4-2 contains a brief definition of each contributor and a rating from 1 to 4 of the significance of each contributor to moisture problems as a result of each of these types of analyses.

Table 3-2. Relative importance of moisture problem contributors

Contributor	Definition	Importance to moisture balance / problem		
		Literature	Data Obervation	Neural Network Analysis
Pressure imbalances				
Imbalances in distribution of conditioned air	Pressure differentials between the inside and outside or within the home caused by operation of the air handler	1	3	1
Duct leakage to the outside	Air leaking from the ducts that makes its way to the exterior	1	4	3
High rate of shell leakage	Leakage of air into or out of the home through gaps in the home's envelope	1	4	4
Non-continuous Vapor Retarders and Air Barriers				
Poor ground vapor retarder integrity	Lack of, or holes in ground cover placed under the home	1	4	3
Damage to the bottom board	Holes or tears in the flexible membrane fastened to the underside of the home	N/A	1	4
Interior wall vapor retarder ineffectiveness	Presence of a vapor retarder on the interior of exterior walls, including vinyl-covered wallboard	1	N/A	N/A
Lack of exterior air barrier	Lack of barrier to prevent exterior air from entering building cavities	1	N/A	N/A
Ventilated attic	Attic airspace open to the exterior through ventilation openings or mechanical systems	3	4	N/A
Occupant Comfort				
Low thermostat setting	Lowest of measured temperature, observed thermostat set point, occupant reported set point	1	4	1
Local cold spots	Surface temperatures within the home considerably cooler than the homes air temperature	N/A	1	N/A
Oversized A/C equipment	A/C capacity larger then recommended for size of the given home	1	3	1
Introduction of unconditioned outside air	Uncontrolled and unconditioned air entering the home through openings in the envelope or home ventilation systems	N/A	N/A	N/A

1 = Large quantity of supporting data and strong correlation
2 = Significant quantity of supporting data or significant correlation
3 = Some supporting data or some correlation
4 = Low quantity of supporting data or low correlation
N/A = No data / Not possible to evaluate with data collected

Nine of these hypothesized contributors are physical characteristics of the home of which measurements of varying precision can be made:

- Oversized A/C equipment
- No ground vapor retarder under the home
- Damage to the bottom board
- Duct leakage to the outside – actually a measurement of gaps in the air distribution system
- High rate of shell leakage – actually a measurement of gaps in the building envelope
- Interior vapor retarder on walls
- Lack of exterior air barrier
- Ventilated attic
- Local cold spots

Three of these hypothesized contributors are highly dependent on the activities and habits of the occupant and therefore measurements relating to them can at best be approximations and in some cases are not possible at all.

- Imbalances to the distribution of conditioned air, via the opening and closing of interior doors and operation of whole house and spot ventilation systems
- Low thermostat setting
- Introduction of unconditioned outside air, via night flushing or the operation of occupant-controlled whole-house or spot ventilation systems

Three of these hypothesized contributors are also, or exclusively, conditions resulting from the characteristics and operation of the home, that by nature vary over time with varying operational and climactic conditions:

- Imbalances to the distribution of conditioned air due to imbalanced design of the air distribution system
- Local cold spots, due to location and orientation of registers
- Introduction of unconditioned outside air, as a result of pressure differentials created by imbalanced air distribution systems

4

QUALITATIVE AND QUANTITATIVE REVIEW OF POTENTIAL MOISTURE PROBLEM CONTRIBUTORS

Homes with moisture problems were identified for this investigation from an eight-state coastal region reaching from Texas to North Carolina. Data was collected primarily during the summer of 2001 in Louisiana and Florida, from homes that had a history of reported moisture problems. The data collected included both homeowner perceptions and building science diagnostic measurements of the house. Details of the protocol, data collection process and data analysis methodologies are included in Appendices A through D.

Data was gathered to identify both the type and extent of the various moisture problems encountered. Moisture problems were first categorized based on the building components where they occurred; either walls, floors or ceilings. Many homes had multiple problems and problem sites; in 22% of the sample homes more than one building component had visible problems and half of the homes reported three or more types of moisture problems. Figure 5-1 shows the number of homes reporting zero to eight problem types.

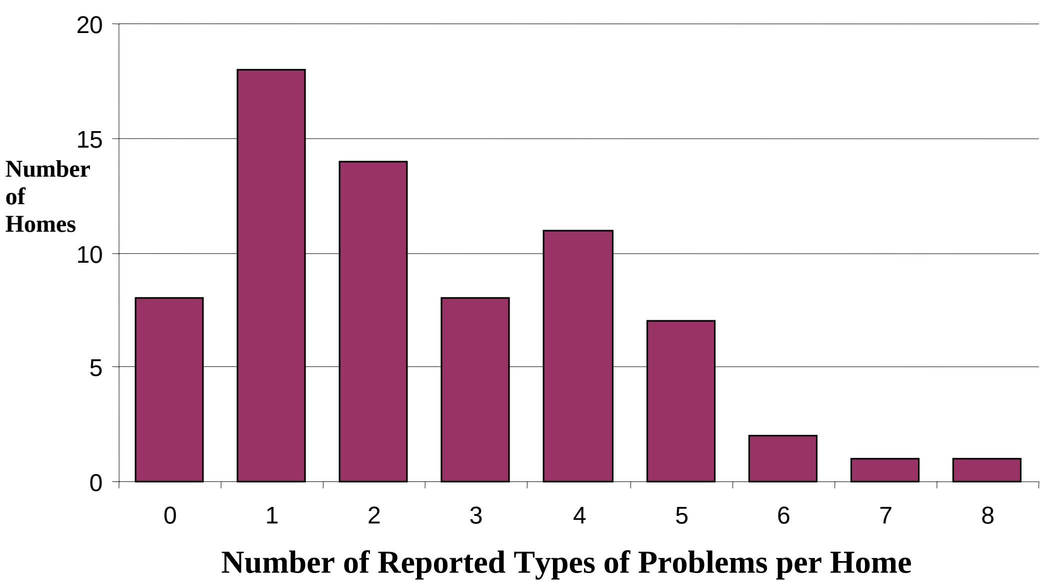

Figure 4-1. Sample homes and reported moisture problems

Moisture problems were scored to provide an index of problem intensity. Moisture problems with a single element such as “odors” received a lower score than a home with “odors and structural softening”. The data analysis included characterizations of the data, regression analysis and ultimately a neural network analysis that helped rank the contributors to moisture problems. A discussion on the neural network analysis appears in Appendix D.

The objective of neural network analysis was to find an equation that provides a “best fit” representation of data. The data spreadsheet was analyzed in an iterative manner similar to multiple regression by progressively deleting lower significance factors. However, unlike in regression analysis, in a neural network analysis the form of the equation does not need to be known ahead of time. This is a tremendous advantage over multiple regression analysis. Neural network analysis uses trial and error to shape a form of the equation according to the data. The amount of variation in the data that is explained by the equation is often significantly higher in neural network modeling than it is for multiple regression analysis.

Section 5-1 discusses for each potential contributor , an interpretation of the topic literature, a description of the data collected, a discussion of the data analysis and recommendations based on the data analysis. In Section 4 a classification was developed for the moisture problem contributors grouping them into areas for further study, as shown in Table 5-1.

Table 4-1. Classification of Potential Moisture Problem Contributors

Pressure Imbalances	Non-continuous Vapor Retarders and Air Barriers	Occupant Comfort
Imbalances in the distribution of conditioned air (section 5.1)	Poor ground vapor retarder integrity (section 5.4)	Low thermostat setting (section 5.9)
Duct leakage to the outside (section 5.2)	Damage to the bottom board (section 5.5)	Local cold spots (section 5.10)
High rate of shell leakage (section 5.3)	Interior wall vapor retarder ineffectiveness (section 5.6)	Oversized A/C equipment (section 5.11)
	Lack of exterior air barrier (section 5.7)	Introduction of unconditioned outside air (section 5.12)
	Ventilated attic (section 5.8)	

Note: For a description of each potential contributor, see Table 4-2.

4.1 IMBALANCES IN THE DISTRIBUTION OF CONDITIONED AIR

4.1.1 Background and interpretation of the topic literature

While pressure differentials are used to distribute conditioned air throughout a home and to return indoor air to the cooling equipment, they can also cause undesirable air movement from outside the house to the inside. Imbalances in air distribution lead to pressure differences which induce air movement within the home and across the home's envelope. This air movement plays a critical role in the migration of moisture into and within the home.

Pressure differentials may be caused by imbalanced air distribution systems and/or leaking ducts, and may be induced whenever the air handler is engaged. Negative pressures caused by air handler operation are relatively common in homes with air distribution systems dominated by supply ducts. Leaks in these ducts leave the air handler starved for return air. This air is then replaced by inducing a negative pressure in the home, which brings in air through any available leakage pathway (figure 5-2).

Imbalances in the distribution of conditioned air within a house can create air pressure differentials between rooms or between the inside and outside of a house. Measurements of supply air in some homes show that it is possible to have 50% of the conditioned air supplied to the master bedroom as shown in the example in Figure 5-3. Typically, the end of the home closest to the air handler is well supplied and the main section of the home receives less supply air per square foot of floor area. This phenomenon is observed to be less severe in multi-section homes (Figure 5-4) than in single section homes. Designers have a number of options to choose from in order to avoid imbalanced air supply.

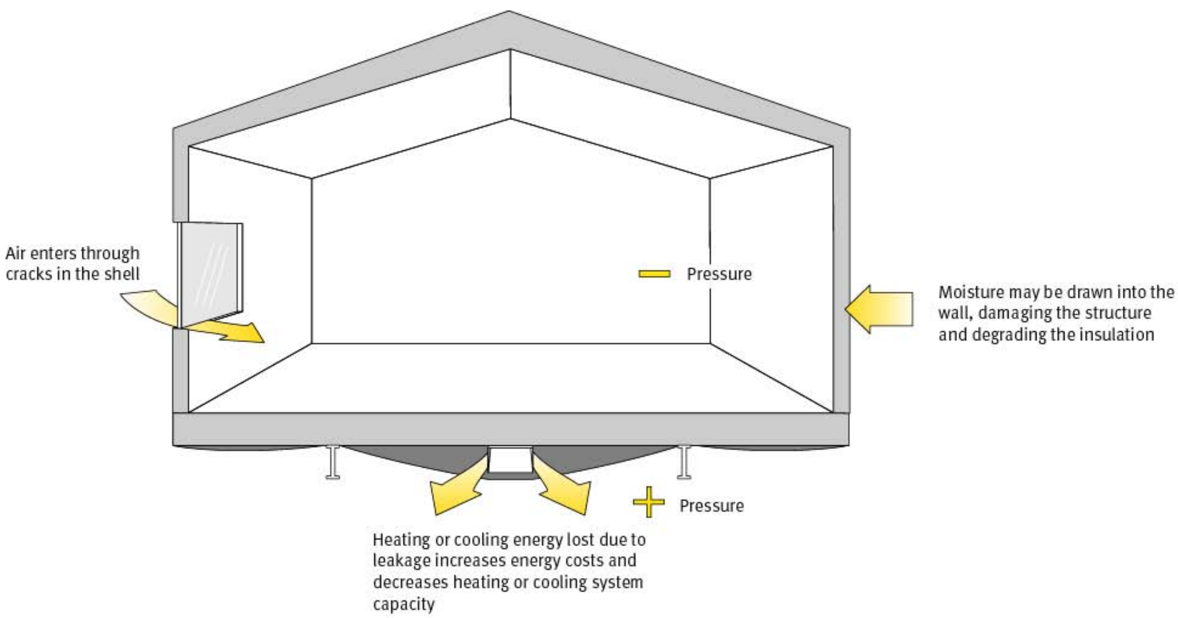

Figure 4-2. Factors affecting pressure balance

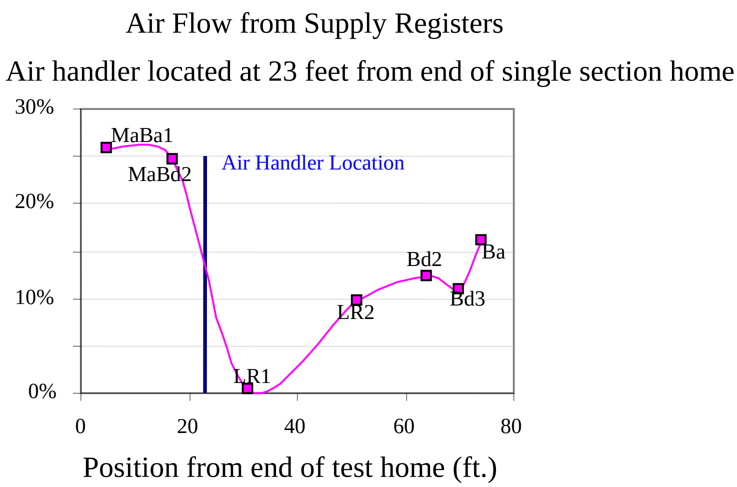

Figure 4-3. Distribution of airflow in a sample single section home

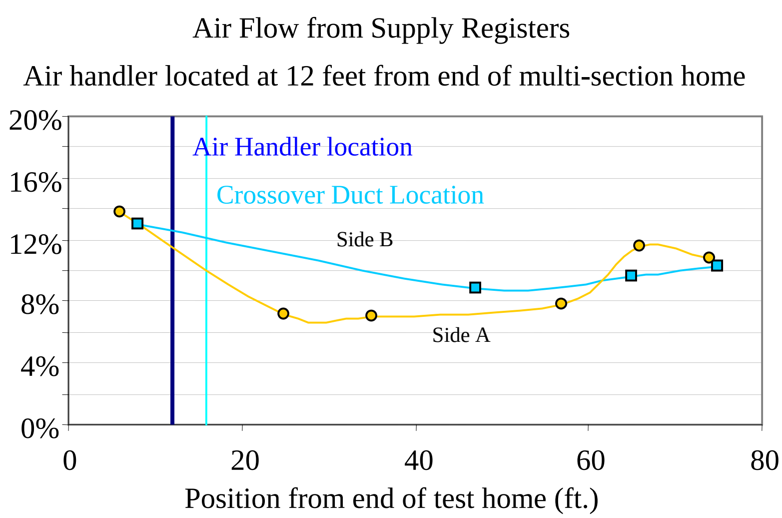

Figure 4-4. Distribution of air flow in a sample double section home

The opening and closing of interior doors can also affect interior pressure imbalances, by isolating rooms with air supplies from areas of the home with fewer air supplies per unit volume of interior space. It is not uncommon to have positive pressure in one area of a living space even as other parts experience negative pressure. In order to mitigate this effect, designers often employ door undercuts, transom grilles, and jumper ducts to provide a return air pathway from one room to another. However, if the air being supplied to the room is more than these devices can accommodate, then air pressure will build up behind a closed door. Opening the door eliminates this condition.

Such pressure differentials may be the cause of, or exacerbate the problem of shell leakage and are therefore of great concern. They may drive moisture-laden air through small openings in building assemblies as described in section 5.3 on shell leakage. Even very small negative pressures can drive moisture into the building through imperfect air barriers in assemblies and other parts of the building shell. Moist air infiltrated into the building will condense when it comes against sufficiently cooled material.

Pressure differences rise until air being added through infiltration matches that being removed by other means. This process may continue for many hours each day as the air handler unit is operating. Tighter houses (those with fewer openings in the envelope) are less prone to infiltration and therefore can sustain higher pressure differentials with an equivalent driving force. The pertinent question is whether these sustained pressure differences provide a driving force for moisture migration.

The literature recommends operating a house at a slightly positive pressure in hot, humid climates, as this will tend to drive dehumidified and conditioned interior air from the interior into building cavities and prevent moist outside air from infiltrating in the reverse direction and potentially causing moisture problems[3].

4.1.2 Data

Three pressure measurements were made in each home while the air handler unit was operating: baseline house pressure (all interior doors open), master bedroom pressure with door closed, and house pressure with the master bedroom door closed.

Baseline house pressure, measured with all interior doors opened and the air handler operating, ranged from +1.0 Pa to –8.6 Pa and averaged -1.46 Pa, compared to the outside at a baseline of 0 Pa. Nine homes had positive pressures, four of which did not exhibit any moisture problems. Six homes measured at 0 Pa, or in balance with the outside. The majority of the homes (51) had negative pressure readings. Only 16 of the 66 homes for which this data was collected had pressure readings lower than -2.0 Pa (Figure 5-5).

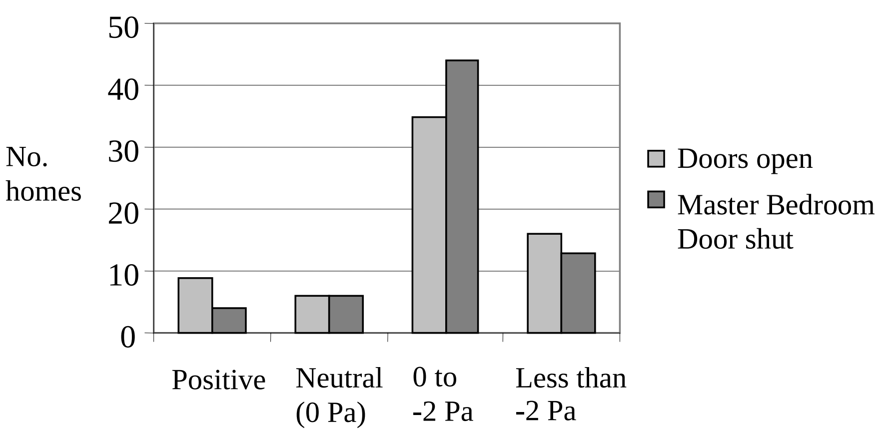

Figure 4-5. House pressure ranges with doors open and closed

[3] "Because exhaust ventilation systems that depressurize houses can cause hidden moisture problems in hot humid climates, a system that pressurizes a house (supply ventilation) or operates at a neutral pressure (balanced ventilation) is a better choice in air conditioning climates." Bower, John Understanding Ventilation, pp. 109-111, Published by The Healthy House Institute, Bloomington IN, 1995.

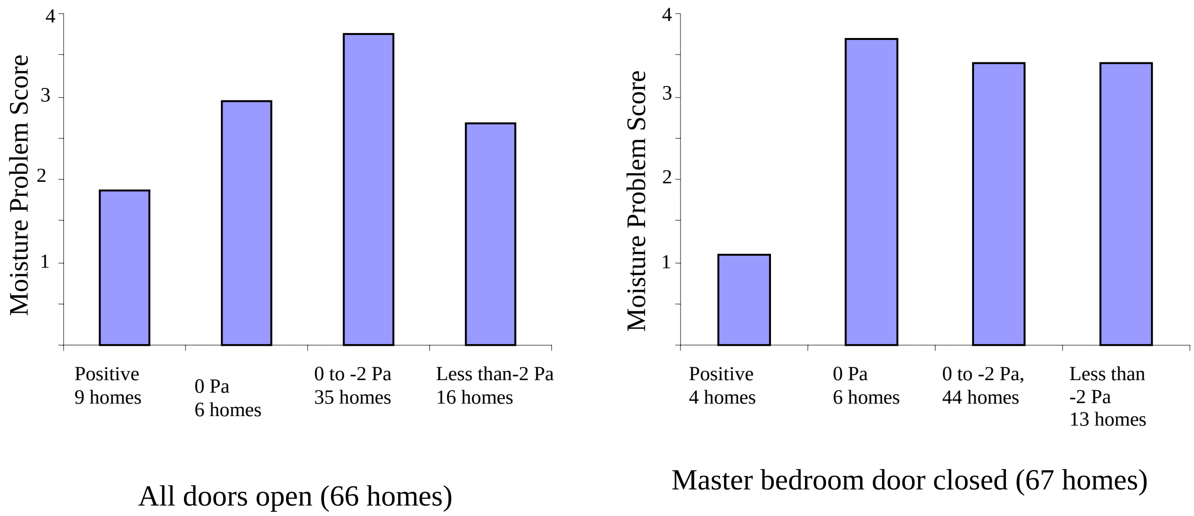

Figure 4-6. Average moisture damage score as a function of house pressure grouping

Master bedroom pressure with master bedroom door closed and air handler operating is an important factor to consider when investigating moisture problems. The pressure differential is measured between the master bedroom and the main portion of the house. The value is an indication of how well the air is distributed between those two spaces. Rooms with supply air volumes that exceed the return capacity will build up pressure when the door is closed. This will often cause the remainder of the house to experience negative pressures which can induce outside air into the building through shell leakage. The pressure build-up between the master bedroom and the rest of the house averaged 5.0 Pa and went as high as 26 Pa compared to the outside at a baseline of 0 Pa.

House pressure with master bedroom door closed is closely related to the master bedroom pressure with door closed as discussed above. It averaged -2.3 Pa, over 50% higher than the pressure differential prior to closing the door. Isolating the master bedroom with its air supply, tended to starve the remainder of the home of a large portion of the overall air supply, resulting in increased negative pressure relative to the outside. Conversely, for many homes the pressure within the closed bedroom increased as the air supplied to that room was trapped within it, indicating that the capacity of the jumper ducts and/or return air system was inadequate for these homes. In fact, this divergence of pressures is demonstrated by the data – in 43 of the 53 homes with complete data, the pressure decreased in the main living area and simultaneously increased in the master bedroom upon closing the master bedroom door.

In the neural network analysis, house pressure with master bedroom door closed, and master bedroom pressure with the door closed strongly correlated with moisture damage elsewhere in the house. Baseline house pressure did not correlate strongly and was omitted from the final analysis.

4.1.3 Discussion

There is no single measurement that quantifies a well balanced air distribution system. However, measurement of several pressure differentials can quantify individual effects caused by imbalances. The three pressure measurements selected for scrutiny were taken with the air handler operating and are common operating scenarios that can easily be measured.

House pressure with respect to the outside (with all interior doors open) is a baseline pressure created by the air handler.

The change in house pressure from closing a bedroom door provides insight as to whether provisions for supplies and return air distribution into individual rooms are balanced. Pressure between the closed bedroom and the remainder of the house is a different way of measuring the same effect but is exaggerated because the room pressure increases as the house pressure decreases (or vice versa).

The strong correlation between moisture problems and pressures measured with the master bedroom door closed (see Figure 5-6) suggests that this measurement may be used as an indicator of potential moisture problems. Designs that lower these pressure differentials may provide some protection from moisture problems.

4.1.4 Interim Conclusions

The literature recommends operating homes at a slightly positive pressure in hot, humid climates. The data indicated that unbalanced pressures correlate with moisture problems, suggesting that addressing this contributor to moisture problems will require particular attention to the air distribution system, air return system, ventilation system and other related items.

4.2 DUCT LEAKAGE TO THE OUTSIDE

4.2.1 Background and interpretation of the topic literature

Duct leakage to the outside is air that leaks from a pressurized duct system and finds its way to the outdoors, either directly, as when ducts are located in unconditioned spaces, or indirectly, as when leaky ducts pressurize building components resulting in air exchange with the outside.

Air that leaks from ducts to the outside can result in negative indoor pressure relative to the outside, as the lost air must be replaced through infiltration. Infiltrated humid outside air that comes into contact with cooled building materials can result in condensation within the building cavities and on interior surfaces. Humid infiltrated air also decreases comfort levels and may lead the homeowner to lower thermostat settings. Duct leakage is generally considered by the literature to be detrimental to moisture control[4].

Duct leakage can also result in positive pressures in homes that are return-duct dominant; however manufactured homes are typically supply-duct dominant and will tend to see negative pressures.

ASTM E1554-94 Standard Test Methods for Determining External Air leakage of Air Distribution Systems by Fan Pressurization, describes the protocol by which duct leakage is quantified. Duct leakage measurement, commonly known as a duct blaster test (see Figure 5-7), provides a quick method to quantify the level of duct leakage, but does not specifically indicate where the breach is located. It is normally quantified in terms of the cubic feet per minute of air leaking to the outside while the duct is pressurized to 25 Pa, divided by the square footage of interior floor area and expressed as a percentage.

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[4] Manual D Residential Duct Systems – New Edition, Hank Rutkowski, P.E. Air Conditioning Contractors of America Educational Institute, Washington DC, 1995.

Figure 4-7. Duct leakage apparatus connected to air handler

4.2.2 Data

Average duct leakage to the outside was approximately 10% (or 1 cfm per 10 sf floor area). Two homes with extreme duct leakage measurements (64% and 72%) were not included in the average, as they fall well outside the typical range of 1% to 30% of this and other studies[5]. Duct leakage to the outside of less than 5% is generally considered good. Approximately 23% of the homes in the sample achieved this level, while 18% had leakage in excess of 15%, a relatively poor performance. The duct leakage range for homes with moisture problems was similar to those without.

One might expect a correlation between high levels of duct leakage and low thermostat set point, as duct leakage causes negative pressures in the home (see Figure 5-2), leading to increased levels of unconditioned air infiltrating into the home, increasing the home's temperature and humidity and prompting the occupants to lower the thermostat. While there was a slight correlation between duct leakage and house pressure (see Figure 5-8), this correlation to thermostat set point was not observed in the data.

[5] Air of Importance – A Study of Air Distribution Systems in Manufactured Homes, NC Alternative Energy Corporation, May 1996.

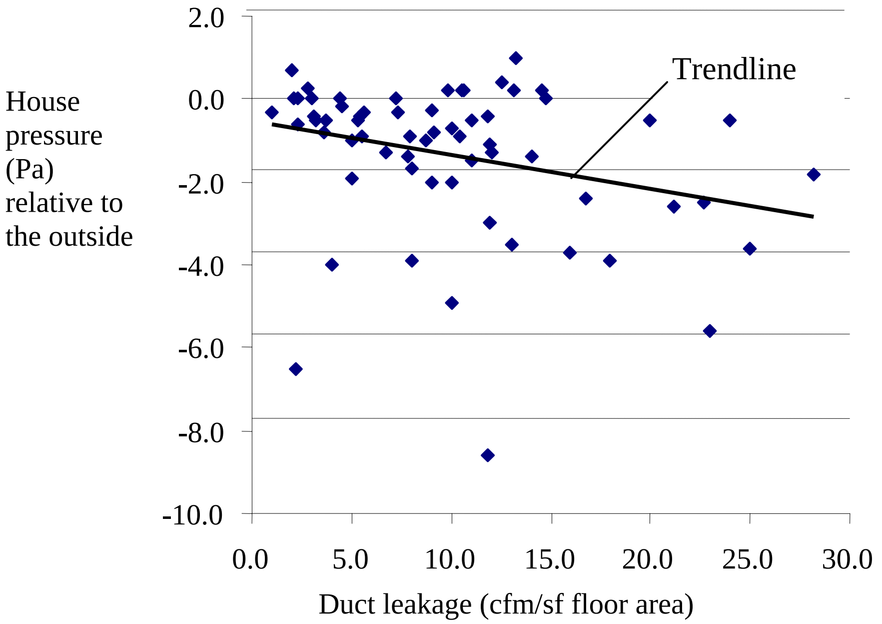

Figure 4-8. House pressure as a function of duct leakage

In the neural network analysis duct leakage to the outside was found to moderately correlate with moisture problems in walls and ceilings.

4.2.3 Discussion

Duct leakage is known to contribute to negative pressures in manufactured homes and was expected to show a strong correlation with moisture problems. The data showed a weaker correlation than expected, possibly because other factors that effect air pressures may have overridden the effects of duct leakage.

4.2.4 Interim Conclusions

The lack of a strong correlation between duct leakage and moisture problems in this study further highlights the complexity of moisture problems and their causes. The strength of the literature tying these two phenomenon together cannot be discounted. Duct leakage is typically minimized as an energy conservation and comfort maximization strategy, as well as a method to decrease the risk of moisture problems. Research shows that duct leakage can easily be improved in manufactured homes[6],and creating tight ducts should be part of a comprehensive effort to protect against moisture problems.

4.3 HIGH RATE OF SHELL LEAKAGE

4.3.1 Background and interpretation of the topic literature

Shell leakage is the passage of air through unintentional openings in the building envelope such as small cracks between building components and assemblies. For energy conservation purposes, homes

[6] Duct Improvement in the Northwest; Part II: Mobile Homes," B. Manclark and B. Davis, Home Energy, (13:1) pp. 27-32, January/February 1996.

are typically built with the goal of minimizing shell leakage. An exterior air barrier (see Section 5.7), is one tool to minimize shell leakage by preventing it from passing through wall assemblies. Other locations where shell leakage is common are around doors and windows, intersections between walls and between walls and floor or roof, at floor openings, and along the marriage line.

Imperfections in the building shell air barrier can be measured by a blower door test (see Figure 5-9). The test does not indicate the actual leakage rate, however; it is merely a measure of the "composite hole size", i.e. the sum of the area of all the openings in the building envelope. In order for these holes to result in leakage, they must be coupled with a driving force, i.e. a differential in air pressure between the outside and inside of a house. This pressure differential can be caused by exhaust fan or air handler operation, wind, or stack effects in the building. Once a pressure differential is established, air may be forced through cracks and holes in the building envelope, resulting in leakage.

Moist air brought into the living space may decrease occupant comfort and may support condensation on cooled surfaces that lie in the path of infiltrating air[7]. Shell leakage has been cited in the literature as increasing moisture load in the home, as well as within wall and floor cavities[8].

Shell leakage is expressed in terms of cubic feet per minute per square foot of interior home area at a given pressure differential, and is often converted to an estimated air changes per hour using a variety of conversion methods, the simplest of which is to divide the cfm per sf figure by 20[9].

Building envelope leakage measurements quantify not just the integrity of air barriers in building assemblies, but also include the integrity of marriage line gaskets and seals around plumbing, electrical and other penetrations in the building shell, as well as intentional ventilation of wall cavities (see Section 5.8.1). High shell leakage rates can bring moisture into the building cavities and into the living area, and can result in uncomfortably high humidity in the living area, and other moisture problems. Openings in the envelope may include recessed lighting, through-the-wall fans and electrical conduits.

HUD does not specify an air infiltration performance criterion; although it states that "The opaque envelope shall be designed and constructed to limit air infiltration to the living area of the home"[10]. In the section of the HUD-code on whole house ventilation, the overall air change rate via unintended natural ventilation is assumed to average 0.25 air changes per hour[11].

4.3.2 Data

Shell leakage less than 1.0 CFM per square foot of floor area at 50 Pa depressurization of the home generally translates between 0.35 and 0.5 air changes per hour, and is a quick indicator of shell leakage performance used by the building science community. The average shell leakage rate of homes in the sample was 1.26 CFM per sf of floor area at 50 Pa, 26% higher than the benchmark rate.

When converted to air changes per hour (ach) using a modified version of the Lawrence Berkeley Laboratory conversion method[12], shell leakage for the sample ranged from 0.25 ach to 0.93 ach and averaged 0.43 ach. This is significantly higher than the approximate average rate of 0.25 air changes

[7] 1997 ASHRAE Handbook of Fundamentals, chapter 25.14, Residential Infiltration. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta GA
[8] ibid
[9] Meier, Alan, "Infiltration: Just ACH50 Divided by 20?", Home Energy Magazine Online, January/February 1994
[10] HUD MHCSS § 3280.505
[11] HUD MHCSS § 3280.103
[12] Meier, Alan, "Infiltration: Just ACH50 Divided by 20?", Home Energy Magazine Online, January/February 1994

per hour under natural conditions found by a number of field studies conducted from the late seventies through early nineties[13].

ASHRAE[14] and HUD have established a minimum whole-house ventilation requirement of 0.35 ach for the purpose of maintaining acceptable indoor air quality. HUD assumes that the natural air change rate provided via shell leakage for manufactured homes is 0.25 ach, with the balance to be provided by a designed ventilation system. Sixty percent of the sample homes reported shell leakage alone above 0.35 ach. Ninety percent of the sample homes had a shell leakage rate above 0.25 ach. In fact, the average shell leakage rate was 70% higher than the 0.25 ach assumed by HUD in determining whole house ventilation requirements.

Tests of new manufactured homes often yield results in the 0.25 ach range[15], however it may be that the homes in this study have increased air leakage because they were built prior to the increase in attention to shell leakage, or because less attention has been paid to shell leakage in the south than in the north, where energy and comfort penalties are more obvious.

Figure 4-9. Blower door test.

High shell leakage might be expected to lead to higher levels of indoor humidity in hot, humid climates. High indoor humidity was reported in 35% of the homes studied. Because high indoor humidity often prompts occupants to lower their thermostat set-points, a correlation might be expected between shell leakage and set-point temperature, however the data showed no such simple relationship.

In a number of homes, staining was noted at sites on the interior of the building shell, such as the marriage line, that are thought to typically be locations of high shell leakage. The relative humidity of these sites will generally be high if humid outside air leaks into the interior and comes into contact with cooled interior surfaces. Condensation may even occur in extreme cases. High surface relative humidity and condensation can cause staining.. Therefore it is not unreasonable to conclude that shell leakage may be a significant contributor to these specific cases of staining.

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[13] Burch, D.M. May 1993, Indoor Ventilation Requirements for Manufactured Homes, Building and Fire Research Laboratory, NISTIR 4574; Hadley, D.L. and S.A. Bailey, Aug. 1990, Infiltration/Ventilation Measurements in Manufactured Homes, Pacific Northwest Laboratory, Richland, WA.
[14] 1989 ASHRAE Handbook of Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta GA.
[15] MHRA Energy Star plant certification measurements 2001-2002

Shell leakage was not strongly correlated to the degree of moisture damage in the neural network analysis, whether analyzed for only wall damage; only ceiling damage, or both. The factor was thus eliminated from the final analysis.

4.3.3 Discussion

Shell leakage is a quickly measured, oft-cited building science performance indicator. Yet, for this data set, it does not seem to be an important contributor to moisture problems. It showed no correlation with severity of moisture damage in the neural network analysis or when comparing shell leakage data to moisture damage score directly.

Interestingly, this sample of homes exhibited significantly greater leakage than has been published in the literature as typical for manufactured homes of similar vintage. The average leakage rate for homes with a moisture damage score of zero was higher (1.4 CFM per sf of floor area @ 50 Pa) than those with moisture damage score greater than zero (1.2 CFM per sf of floor area @ 50 Pa). The fact that the leakage rates for houses with no moisture problems was very similar to houses with moisture problems indicates that shell leakage tests may not be an effective way to gauge susceptibility to moisture problems.

As discussed above in Section 5.3.1, the blower door measurement for shell leakage does not indicate that air is actually passing through the building shell, only the potential to do so in the presence of a driving force. It may be that the driving force is the more important contributor to moisture problems, not composite hole size measured by blower door tests.

In isolated cases, staining was noted in specific locations that may be related to shell leakage. In these cases, shell leakage may have been providing a direct supply of moist air to a concentrated location causing a moisture problem.

4.3.4 Interim Conclusions

There appears to be no correlation between full building shell leakage and moisture problem severity. Therefore, correcting shell leakage should not be a high priority in minimizing moisture problems. However, shell leaks may be the cause of isolated moisture problems when at suspected leakage locations such as the marriage line and envelope penetrations.

With the results concerning pressure imbalances, it appears that prolonged exposure to pressure imbalances is a greater driver of moisture migration into houses than is shell leakage as measured under test conditions.

4.4 POOR GROUND VAPOR RETARDER INTEGRITY

4.4.1 Background and interpretation of the topic literature

A vapor retarder is often placed on the ground under the home to prevent moisture from evaporating out of the ground and being carried by the air up into the home (Figure 5-10). Moisture emanating from the ground is a source of moisture that can potentially enter the home through diffusion and air movement. Possible leakage paths include gaps in the marriage line gasket, penetrations in the envelope for plumbing and other services, seams around crossover ducts and tears in the bottom board. Studies of crawl spaces[16] suggest that a vapor retarder covering the ground is an important part of a crawl space moisture control strategy.

[16] ASHRAE Transactions 1994. "A Review of the Regulatory and Technical Literature Related to Crawlspace Moisture Control", Bill Rose, Small Homes Council, Building Research Council. (An in-depth literature review on the history of crawlspace moisture control)

According to the literature, proper installation of the ground vapor retarder requires positive drainage of the ground under the home[17]. A lack of positive drainage may result in the vapor retarder being counterproductive for moisture control, by holding water from rain, condensation, or other sources under the home that would otherwise drain into the soil.

The HUD-code does not address the ground vapor retarder because it is outside the home. Installation issues are regulated by the states and vary greatly. The model manufactured home installation standards currently under revision require a minimum 6 mil polyethylene sheet or its equivalent as a ground vapor retarder[18].

Figure 4-10. View of crawlspace showing ground cover

4.4.2 Data

Field investigators visually estimated the percentage of the ground underneath each home that was covered by a vapor retarder. The home's crawlspace is typically dark, cramped, and cluttered with piers and other components of the support system, making this measurement a rough approximation at best.

Of the 67 homes for which ground vapor retarder data was collected, 43 of them had no ground vapor retarder. The remaining homes had vapor retarder coverage ranging from 20% to 100%, with an average of 79%.

Only one of the 24 homes that had any ground vapor retarder coverage (home #64) reported a floor moisture problem (4% of this subset), while 17 of the 43 homes without ground vapor retarders did (40% of the subset) (Figure 5-11).

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[17] *Builder's Foundation Handbook*, J. Carmody, J. Christian, and K. Labs, Oak Ridge National Laboratory, ORNL/CON-295, 1991. National Technical Information Service.
[18] NCSBCS/ANSI A225.1 1994

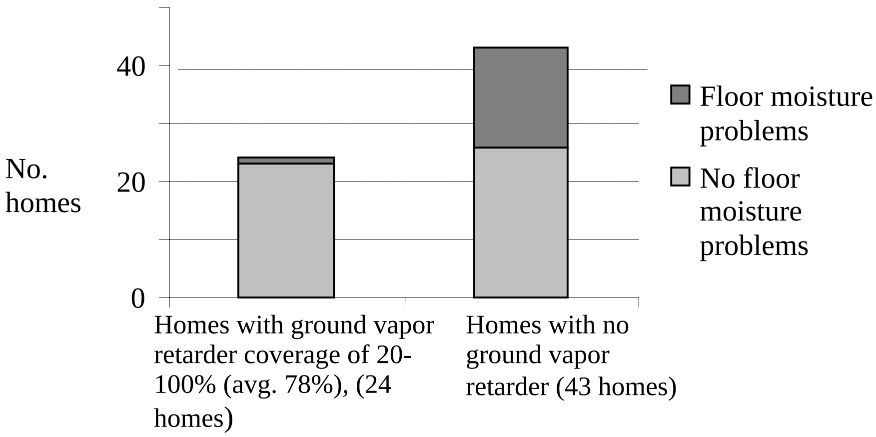

Figure 4-11. Moisture problems in homes with and without ground vapor retarders

Residents of some of the homes without ground vapor retarders reported that portions had been washed away by bulk water flow due to flooding or rain.

In the neural network analysis, ground vapor retarder coverage ranked in the middle among factors correlated with moisture problems in walls and ceilings. A higher percentage of ground covered correlated with a lesser degree of moisture problems. This correlation may actually under-represent the effect of the ground vapor retarder on moisture problems, because floor moisture problems, where one would expect moisture emanating from the ground to have the largest impact, were not included in the neural network analysis.

4.4.3 Discussion

The ground vapor retarder, positive ground drainage, crawlspace ventilation, and bottom board integrity are closely related in terms of their impact on moisture control and must be considered together as a system in any discussion. The first three of these methods are intended to foster a dry environment under the home. Positive drainage contributes by preventing liquid water from encroaching into the crawlspace and shedding it if it does; the ground vapor retarder prevents moisture within the earth from evaporating into the crawlspace air; and crawlspace ventilation is intended to flush humid air from under the home. The negative effects of improper installation of these elements may compound each other. An improperly graded site can turn the ground vapor retarder into a collection pool (this was observed in a number of homes) from which water vapor can rise into the home through a breached bottom board before it has been flushed from the crawlspace by ventilation.

4.4.4 Interim Conclusions

The data analysis supports the hypothesis that ground vapor retarders help prevent moisture problems in houses.

4.5 DAMAGE TO THE BOTTOM BOARD

4.5.1 Background and interpretation of the topic literature

The bottom board is a membrane fastened to the underside of the home. Its primary function according to the HUD-code is to resist infestation of the home by rodents and vermin[19]. The code specifies the puncture resistance of the bottom board, but no other properties. While it does require that the opaque envelope of the home be designed and constructed to limit air infiltration into the living area[20], it does not specifically address the floor system in this respect.

Damage to the bottom board may allow outside air – particularly that from the potentially moisture-laden crawlspace - access to the floor cavity. Low density fiberglass insulations used in most floors offer little resistance to air movement; and the moist air can easily come in contact with cooled surfaces, such as uninsulated metal ducts and floor sheathing, resulting in condensation, pooling and material degradation. Moisture damage in floor cavities may be somewhat mitigated by duct leakage. Air leaking from ducts in floor cavities can displace the outside air entering through holes in the bottom board.

Bottom board holes typically originate from failed factory and field repairs, transportation damage, set up damage, or failed or absent repairs after the installation of services such as telephone and cable television (Figure 5-12). Holes of three to five square feet are not uncommon, often with floor insulation over the hole missing. Most bottom board materials will hold liquid. Condensed water can drip onto an intact bottom board and drain to a low spot far removed from the source of the condensation. Floor cavities are not intentionally vented and so are very slow to dry.

Little research has been published specifically on bottom board performance and effectiveness as an air or vapor retarder. The bottom board may act as the primary air barrier and as a vapor retarder (polyethylene, a common bottom board material, has a permeance of less than 1.0 Perms), but it is typically not sealed at the edges and bottom boards of other materials may have little or no vapor retarding properties[21].

4.5.2 Data

The overall area of bottom board holes was visually estimated by the building scientist. Data collection for the bottom board evaluation was particularly challenging because the building scientist often had to estimate the total cumulative area of many small openings. Therefore, the estimated areas of the holes are imprecise for many homes, but give a general idea of the level of integrity of the bottom board.

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[21] MHCSS § 3280.305
[20] MHCSS § 3280.505
[21] Moisture Control Handbook: New Low-Rise Residential Construction, Joseph Lstiburek and John Carmody, U.S. Department of Energy DE92002388, National Technical Information Service, October 1991

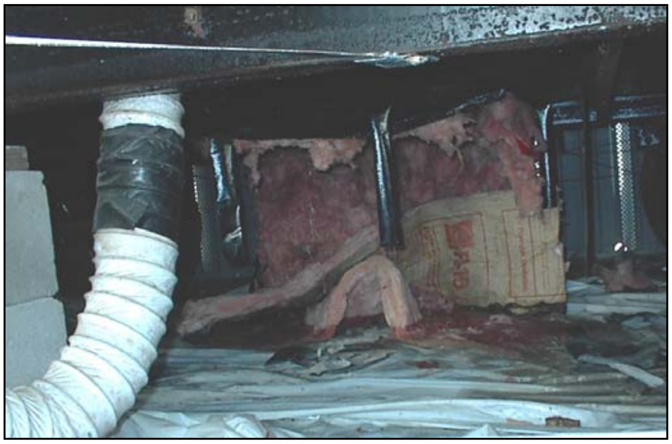

Figure 4-12. View of crawlspace showing damaged bottom board

Thirty-one homes, or 46% of the sample, had no visible bottom board holes. The remaining homes had cumulative hole areas ranging from one to 200 square feet. Eliminating two homes that had approximately 200ft^2 of holes, the average cumulative area of damage was approximately 10ft^2 (Figure 5-13).

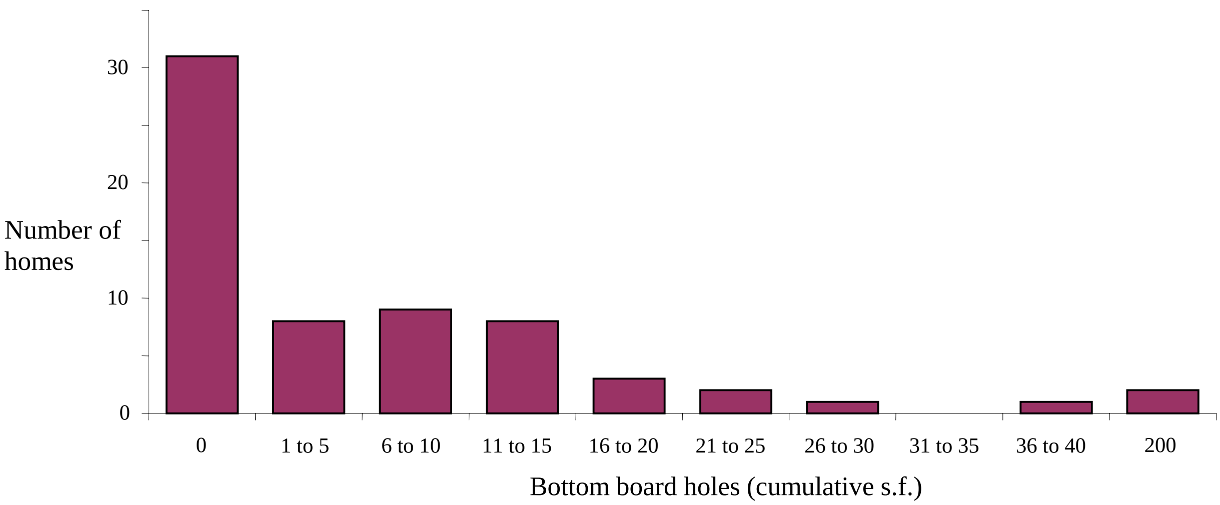

Figure 4-13. Distribution of bottom board holes

Homes with bottom board holes reported a higher incidence of floor moisture problems than those that had no holes, by a ratio of more than 3 to 1, suggesting a fairly strong link between bottom board holes and floor moisture problems (Figure 5-14). Of the ten homes for which bottom boards were assessed that had no moisture problems, only two had any bottom board holes and both holes were 5ft^2 or less.

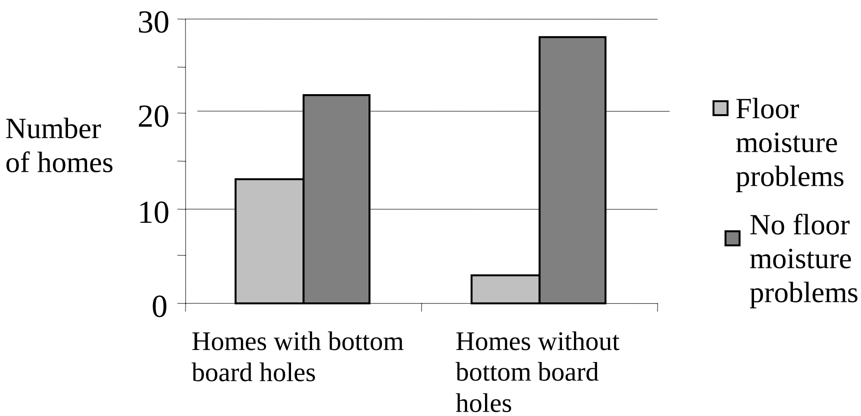

Figure 4-14. Homes with and without bottom board holes

Part of the data collection protocol involved depressurization of the test homes to -50 Pa relative to the outside. Pressure measurements were taken in the floor cavity above the bottom board for 38 homes, 16 of which had holes greater than 3 square feet in the bottom board. The air pressure differentials between the home and the floor cavity averaged -38 Pa for homes with holes (Figure 5-15) and -37 Pa for those without holes, indicating that even a bottom board without holes has little effectiveness as an air or pressure barrier, contradicting the supposition that this property of the bottom board defends the home from moisture problems. In cases where field repairs had been made to damaged bottom boards, the repairs were reported to have failed in many instances.

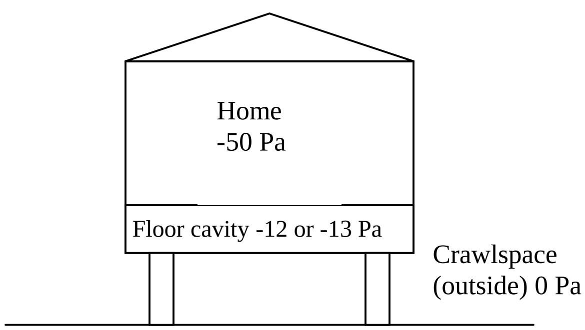

Figure 4-15. Average pressure map of homes with no bottom board holes

The neural network analysis ranked bottom board holes low in correlation with moisture problems. This lack of correlation may be partially attributable to the fact that floor moisture problems are generally more difficult to diagnose than wall or ceiling problems. If moisture problems caused by bottom board holes are more likely to manifest in the floor, as is suspected, then this contributor may have been underrepresented in the analysis.

4.5.3 Discussion

Logic dictates that an intact air and vapor retarder under the floor system of the home is preferable. The data does provide some evidence of its importance in minimizing moisture damage; however, the mechanism is not easily explainable because the bottom board appears to lack the integrity required of an air barrier.

The interactions between floor system elements complicate the analysis of moisture problems in floor systems. For example, while crawlspace air can easily migrate into floor cavities through holes in the bottom board, duct leakage tends to positively pressurize and ventilate the cavity with cool, dehumidified air. Warm, infiltrating air may condense on cool duct surfaces, drip onto the top of the draped bottom board, and accumulate far from the site of condensation, making its source difficult to trace.

Individual homes with floor moisture problems often had cool air supplies oriented directly on the floor surface, potentially triggering condensation of the moisture that migrates through the bottom board holes into the floor system. This is discussed in more detail in section 5.10, local cold spots.

4.5.4 Interim Conclusions

The data analysis supports that idea that the integrity of the bottom board is relevant to the prevention of moisture problems in floors. Additional research is warranted to develop improvements to bottom board performance as an air or vapor barrier. Methodologies to identify and execute effective, durable repairs for bottom board materials are also warranted.

4.6 INTERIOR WALL VAPOR RETARDER INEFFECTIVENESS

4.6.1 Background and interpretation of the topic literature

A vapor retarder inhibits the movement of moisture vapor. Generally, vapor retarders are located to keep a building cavity and its insulation dry. When a vapor retarder is located on only the interior side of a wall assembly, the vapor pressure in the wall cavity is more similar to the outside weather conditions. This strategy is generally effective in predominantly cool or cold climates, where the interior vapor retarder exposes the wall cavity to the relatively dry exterior conditions.

In climates characterized by extended hot and humid conditions, however, the cavity is more likely to dry if moisture is allowed to migrate from the cavity into the less humid air-conditioned interior of the home. Locating the vapor retarder on the interior of the wall assembly slows the cavity drying rate and allows moisture to accumulate inside the wall cavity.

Under the current HUD standards (up until the recent HUD waiver), a wall vapor retarder is required on the interior side of the wall insulation, regardless of climate. The standards make no reference as to whether the vapor retarder should be continuous or non-continuous. To conform to this rule, homes are generally manufactured with a low perm-rated vinyl laminated wall board on the interior qualifying as a vapor retarder. The recently published waiver permits the vapor retarder to be on the outside of the wall insulation in the “humid and fringe” climate, providing the interior wall surface has a combined perm rating of not less than 5.0.[22]

Most building scientists agree that a vapor retarder is preferred on the warm side of the wall assembly (the outside in predominately hot, humid climates)[23][24]. Vapor retarders located on the interior side of a wall (the cool side in hot, humid climates) diminishes the ability of the wall cavity to dry towards the climate-controlled interior, and can allow moisture invading from the outside to accumulate within the wall cavity, potentially leading to condensation.

During periods when the outside air vapor pressure is higher than that within building assemblies, the only opportunity to dry the cavity is toward the inside of the home, where the conditioned air has a lower vapor pressure. HUD 3280.504 (b) 1 and 3 both assume outside ventilation of the wall cavity

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[22] *Condensation Control for Exterior Walls of Manufactured Homes Sited in Humid and Fringe Climates,* Federal Register, Vol. 67, No. 79, April 24, 2002

[23] 2001 ASHRAE Fundamentals 24.8 Moisture Control Options for Warm, Humid Climates. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta GA.

[24] Lstiburek, Joseph, 2002, Moisture Control For Buildings, ASRRAE Journal, February 2002, p. 36-41

specifically to dissipate moisture. Such ventilation will not serve the intended purpose of keeping the cavity dry if the vapor pressure of the outside air is greater than that in the cavity.

Computer modeling studies of typical manufactured housing wall designs with interior vapor retarders have suggested that vapor diffusion alone can lead to high levels of humidity within wall cavities during summer months in hot, humid climates[25]. Burch, et al. go further to investigate alternatives to typical wall designs that are projected to perform well in all climates; even designs utilizing interior vapor barriers.

4.6.2 Data

Virtually all of the 67 sample homes, including those reporting no moisture problems, had vinyl-covered wallboard, which functions as a vapor retarder..

Vapor retarding paint may sometimes be used on interior ceiling gypsum board[26]. This could not be verified on-site by visual inspection. No other types of vapor retarder were reported or observed.

Because all of the sampled homes had vinyl-covered walls, and it was not possible to determine whether homes had vapor retarder ceiling paint, it was not possible to compare the field performance of this wall or ceiling type with alternatives. Therefore, interior wall vapor retarder effectiveness was not included as a factor in the neural network analysis.

4.6.3 Discussion

Additional drying potential may be provided by using a vapor permeable interior wall surface; however, it is not clear what level of wall permeance is sufficient to dry wall cavities dampened by uncontrolled air movement from outside. The recent moisture control waiver issued by HUD permits exterior walls with a minimum of 5 perms on the inside and a maximum of 1 perm on the outside.

The HUD waiver also specifies that, in this case, the "exterior wall cavities shall not be ventilated to the outdoors[27]", presumably implying that exterior sheathing is not to be purposefully ventilated. Those walls that have openings to the outside through electrical and other penetrations may still be accidentally ventilated to the outside and communicate between adjacent wall cavities via electrical raceways. Unless an active approach is taken to sealing these penetrations on the outside vapor retarder surface, there may be considerable vapor infiltration into wall cavities.

The engineering community believes that vapor retarders should be installed on the exterior in hot, humid climates. The dominant current practice, however, is to install a vapor retarder on the interior in the form of vinyl-covered wallboard. In fact, this was the case with all homes in the sample; therefore no conclusions can be drawn on the effects of interior vapor retarders from the data. The prevailing theory states that interior vapor retarders in hot, humid climates will reduce the drying potential of the wall system and increase the likelihood of experiencing moisture problems. HUD has recognized this consensus with the new waiver.

4.6.4 Interim Conclusions

The data confirms the fact that a large number of homes have interior vapor retarders. Therefore, it was not possible to determine a relationship between the presence of vapor retarders and moisture problems. However, through the literature review and data analysis of other contributors, it appears

[25] Douglas M. Burch et. al., "Manufactured Housing Walls That Provide Satisfactory Moisture Performance in all Climates" National Institute of Standards and Technology NISTIR 5558, January 1995 Prepared for HUD Policy Development and Research.
[26] Conversation with engineering department of major HUD-code manufacturer, Spring 2002
[27] Federal Register, Vol. 67, No. 79, April 24, 2002

that vapor retarders and their placement have an important impact on the moisture-related performance of houses in general. They may contribute to the degradation of wallboard in hot, humid climates in particular when placed on the interior wall surface, such as the case when vinyl wallcovering is used. Therefore, it is recommended that further study, perhaps in a laboratory setting, examine vapor retarders in this and other configurations.

4.7 LACK OF EXTERIOR AIR BARRIER

4.7.1 Background and interpretation of the topic literature

Air within the building interior is separated from outside air by materials that serve as an air barrier. Moist air passing into cavities without an exterior air barrier can flow through the adjacent insulation where it will encounter cooler conditions that may support condensation.

Locating the air barrier on the exterior, particularly in walls, is intended to keep the outside air out of the building cavities. The exterior shell often is an insufficient air barrier – either through design intent or due to lack of integrity of the exterior surfaces. Good construction practice calls for an air barrier that is located adjacent to the thermal insulation and leak-free. Air barriers generally consist of materials such as house-wrap products and of interior or exterior sheathings. Commonly, the interior and exterior wall surfaces act as partial air barriers; and the dominant air barrier is the surface with the fewest leaks. Thus, the air barrier location may inadvertently change by adding materials such as exterior sheathing for high wind load designs. To reduce the opportunities for moisture problems, building assemblies should be designed with the location of the air barrier in mind and assembled in such a way as to keep that barrier leak free.

Many manufactured home designs often include ventilated wall cavities achieved by intentionally boring holes into the outer sheathing or by accidental ventilation resulting from not sealing the outside sheathing. Ventilating wall cavities places the duty for the air barrier on the interior surfaces and in hot, humid climates, has been shown to allow moisture entry to the cavity during certain times of the year.

Controlling moisture entry is recognized as the most effective moisture control strategy for wood frame home construction[28]. In hot, humid climates, an exterior air barrier is such a source control approach. According to the Moisture Control Handbook, air barriers are acceptable in hot, humid climates when located either on the interior or exterior of building cavities, but only if the vapor retarder is on the exterior (for wood frame walls)[29].

In hot, humid climates, moisture can enter a wall cavity from the outside via vapor diffusion and/or movement of moisture-laden air. A vapor retarder is intended to prevent vapor diffusion. An air barrier is intended to prevent air movement. In practice, these two elements are often the same material and are located in the same plane, as they should be to perform most effectively (vapor retarders often also act as air barriers, but air barriers do not necessarily act as vapor retarders). In hot, humid climates, this plane should be the exterior surface of the wall.

Contrary to the recommendations of the literature, HUD permits either vented or sealed wall cavities in all climates. If the cavity is sealed to the outside, the exterior of the wall must act as an air (or pressure) barrier and have a minimum permeance of 5.0 perms[30]. This is in opposition to the HUD Waiver: *Condensation Control for Exterior Walls of Manufactured Homes Sited in Humid and Fringe*

[28] Lstiburek, Joe, and John Carmody "Moisture Control Handbook: New, Low-Rise, Residential Construction", University of Minnesota, October 1991
[29] ibid.
[30] MHCSS § 3280.504 (3) (b)

Climates (April 2002), which specifies a vapor retarder (less than 1 perm) on the exterior of walls which are also specified as not to be ventilated to the outside. Figure 5-16 shows a typical ventilated wall cavity, including notch for connection between cavities.

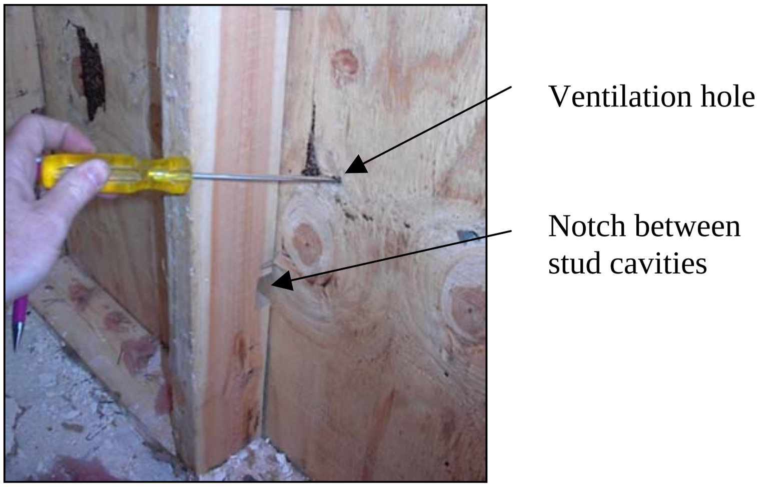

Figure 4-16. Typical ventilated wall cavity

4.7.2 Data

The location and integrity of the primary air barrier can be estimated for a given wall cavity (section of wall between two framing members) by measuring the air pressure within the cavity when the house is depressurized. Because both wall surfaces will often act as partial air barriers, there will usually be partial pressure drops across each surface, with one surface acting as a primary and the other as a secondary air barrier. Wall cavities are often interconnected via electrical chases and other penetrations, resulting in partial pressure barriers between adjacent cavities. These facts complicate efforts to determine air barrier location and integrity. Nevertheless, if the pressure measured within the cavity is similar to that in the house, then the primary air barrier is located on the exterior surface of the wall for that cavity. If there is a large pressure drop from the interior to the wall cavity, then the primary air barrier is on the interior.

Pressures were measured inside 55 wall cavities from 34 homes in the sample. Twenty-four of these wall cavities had moisture damage within the cavity. As shown in figure 5-17, in the moisture-damaged walls, the average pressure drop across the interior surface of the wall was measured at approximately 60%, indicating that the interior sheathing was often acting as an air barrier. In the undamaged walls, the average pressure drop across the interior surface of the wall was approximately 35%, indicating that the exterior sheathing was often acting as the primary air barrier. Despite the small size of the sample, it appears that wall cavities with moisture damage were more likely to have their primary air barrier located on the interior, rather than the exterior of the wall. This finding is consistent with generally accepted building science.

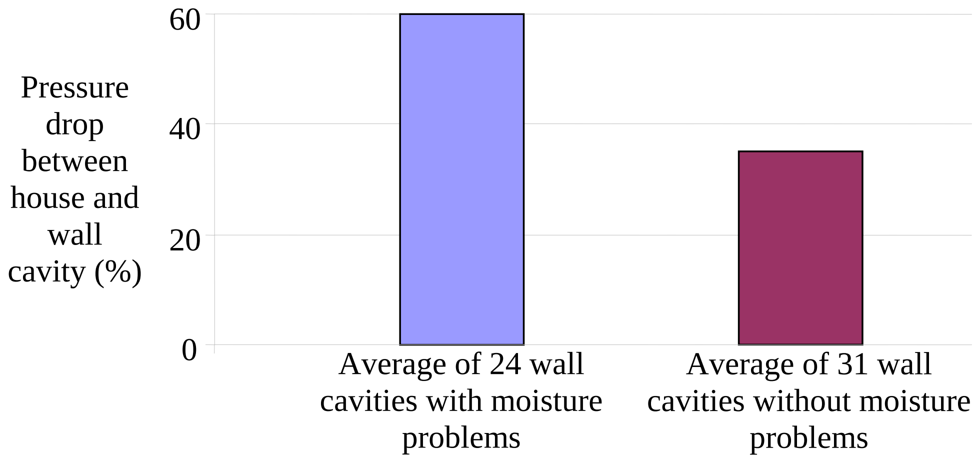

Figure 4-17. Statistics for Wall Cavity Pressure Measurements

Wall cavity pressure data was not suitable for neural network modeling. Cavity pressures were not collected on every home, and only a limited number of cavities were measured in those homes where this data was collected.

4.7.3 Discussion

Both interior and exterior wall assemblies act as air barriers. The primary air barrier is the one with fewer leaks. The location and effectiveness of an air barrier may change by adding materials such as exterior sheathing for high wind load designs. As demonstrated by wall cavity pressure measurements, location and effectiveness of the primary air barrier varies from house to house and within a given house. Remediation efforts to seal air barrier leaks must consider the location of the air barrier and the fact that adjacent wall cavities may have openings between them.

4.7.4 Interim Conclusions

The data shows that wall cavities with moisture damage more often have their primary air barriers located on the interior surface of the wall, inhibiting drying to the home's interior via air movement. Conversely, the data indicates that wall cavities without moisture damage more often have their primary air barrier on the exterior surface, inhibiting outside air from entering the wall.

4.8 VENTILATED ATTIC SPACE

4.8.1 Background and interpretation of the topic literature

Attic ventilation is intended to reduce cooling loads by reducing heat buildup in the attic and reduce moisture problems by allowing humid air to exit the attic.

Although intended to allow accumulated moisture to escape to the outside, ventilated attic designs have more obvious benefits in cold climates where the source of moisture is predominantly from inside the home. In hot, humid climates in homes with intentionally ventilated attic assemblies, moisture-laden outside air is easily brought into the cavity by wind, attic stack effects or negative house pressures where it can condense on the insulation, on the gypsum board or find its way into the interior through openings in the ceiling such as light fixtures and at transitions between flat and cathedral ceilings.

Most of the scientific literature states that ventilating the attic should not be the primary means of controlling moisture in a hot, humid climate[31]. Some researchers suggest that the attic should be sealed for optimum moisture control in hot humid climates[32], and if the attic is not sealed, more moisture may be brought into the attic cavity by introduction of humid outside air than will be expelled through ventilation[33].

The consensus of the literature is that creating a well-sealed ceiling air barrier is essential in minimizing attic-related moisture problems[34]. This is not required by the HUD-code, except for certain single section homes as noted below.

The HUD-code permits either passive attic ventilation, by providing openings to the outside, or active attic ventilation through the use of mechanical equipment. The passive option requires a minimum ventilation area of 1/300th of the attic floor area, with at least 50% being in the upper portion of the attic space and at least 40% being provided by eave, soffit, or low gable vents. The active option requires a mechanical system providing a minimum air change rate of 0.02 cfm per sf attic floor area, with intake and exhaust vents located to provide air movement throughout the space.[35]

Single section homes with metal roofs and no sheathing or underlayment may be constructed without attic ventilation, providing air leakage paths between the roof cavity and living space are sealed. [36]

4.8.2 Data

Nearly all of the homes in the sample for which data was collected (a total of 25), had ventilated attics based on pressure measurements of the attic cavity[37].

In the three homes (home ID #'s 14, 16, 30) where attic ventilation was compromised (attic pressure measurements showed poor exchange with the outside) two homes (home ID #'s 14 and 16) had severe staining and structural damage involving 100 square feet of ceiling or more. This may be explained by the reduced level of ventilation, i.e. moisture-laden air was free to enter the attic via diffusion through the restricted ventilation openings but ventilation was not able to remove it sufficiently. Given the small data set (2 homes) there may have been some other cause of these moisture problems unrelated to attic ventilation.

Aside from these three homes, most damage to ceilings in these 25 homes was relatively minor and generally in the vicinity of the marriage line, where its root causes may have had little to do with attic ventilation.

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[31] TenWolde, A., W.B. Rose. "Issues Related to Venting of Attics and Cathedral Ceilings." ASHRAE Transactions 1999, V. 105, Pt. 1.

[32] A.F. Rudd, J.W. Lstiburek, 1997. "Vented and Sealed Attics In Hot Climates. " Presented at the ASHRAE Symposium on Attics and Cathedral Ceilings, Toronto, June 1997. ASHRAE *Transactions* TO-98-20-3

[33] Burch, D.M., 1992. "Controlling Moisture in the Roof Cavities of Manufactured Housing " Building and Fire Research Laboratory, Building Environment Division, NIST. NISTIR 4916 (An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing)

[34] TenWolde, A., W.B. Rose. "Issues Related to Venting of Attics and Cathedral Ceilings." ASHRAE Transactions 1999, V. 105, Pt. 1.

[35] HUD MHCSS § 3280.504

[36] HUD MHCSS § 3280.504

Because all but a few of the homes in this reduced sample had ventilated attics (whether or not they were designed as such), this characteristic could not be modeled with neural network analysis.

4.8.3 Discussion

The two most effective methods of dealing with attic moisture problems are source control (via a sealed attic and an air barrier) and removal of moisture (via ventilation). The two homes with poor attic ventilation referred to above had neither source control (the reduced ventilation area was sufficient to allow moisture to enter via diffusion) nor removal capacity (due to reduced ventilation area as demonstrated by the pressure readings). This mechanism is likely to have contributed to the severe ceiling moisture problems in these homes.

Attics with mechanical ventilation, even when the fans are disabled, can demonstrate good ventilation to the outside through the open vents. Indications are that some attic ventilation systems were inadvertently disabled when the home's whole-house ventilation system was intentionally disabled.

4.8.4 Interim Conclusions

Additional research is required to determine whether the best strategy to minimize moisture problems in hot, humid climates is to maximize source control by sealing the attic or a combination of a well-sealed ceiling air barrier and ventilating the attic.

Based upon the literature and the field observations, it appears that the air barrier located at the ceiling controls moisture migration from the living space to the attic. Pressure measurements in the attic cavity may help diagnose inadequately vented attics.

4.9 LOW THERMOSTAT SETTING

4.9.1 Background and interpretation of the topic literature

The building science community agrees that low interior temperatures are associated with higher condensation potential in hot, humid climates. Condensation is dependent on two factors: surface temperature and dew point of the surrounding air. If the temperature of a surface falls below the dew point of the air, moisture will condense out on that surface. Therefore, moisture will condense first on the lowest temperature surface. Keeping surface temperatures sufficiently high will control condensation.

For the purposes of this study, humid climate regions are considered to be those that regularly experience a dew point of 73°F or higher for 40% of the time in summer season, the ASHRAE definition[38]. Regions that experience these conditions risk moisture condensation within building cavities whenever the thermostat is set below 71°F. (gypsum wallboard provides a 1-2°F temperature drop during summer design conditions). Human comfort in air conditioned environments depends on both temperature and humidity. Human occupants often compensate for high humidity conditions by lowering the temperature settings. Conditions such as breaches in the air barrier that allow excessive infiltration of outside humid air can overtax the air conditioning system's dehumidification ability. In such cases, temperature control is the only avenue available to the occupant to attain comfort.

4.9.2 Data

Accurate and representative interior temperature is difficult to determine, as it varies over time and from location to location within the home. The temperature at time and place of measurement may

[38] ASHRAE 1989, Fundamentals Handbook, Chapter 21.12 Air-Conditioned buildings in Humid Climates

not be representative of the home's typical temperature or the temperature at the site of moisture problems. The interior temperature of a given sample home was taken to be the lowest of three readings: the as-found temperature, the thermostat temperature setting, and the thermostat temperature setting reported by the resident. The lowest temperature of the three was used because of the time sensitivity of this data and the fact it could be expected that the lowest temperature of these three methods was the temperature most likely to occur over extended periods of time during the most humid conditions.

As shown in figure 5-18, the temperatures in the sample homes ranged from 65°F to 80°F with an average of 71.8°F. Forty-five percent of the homes reported temperatures at or below 71°F, the threshold beyond which homes experiencing the ASHRAE-defined humid climate conditions would be expected to suffer moisture problems.

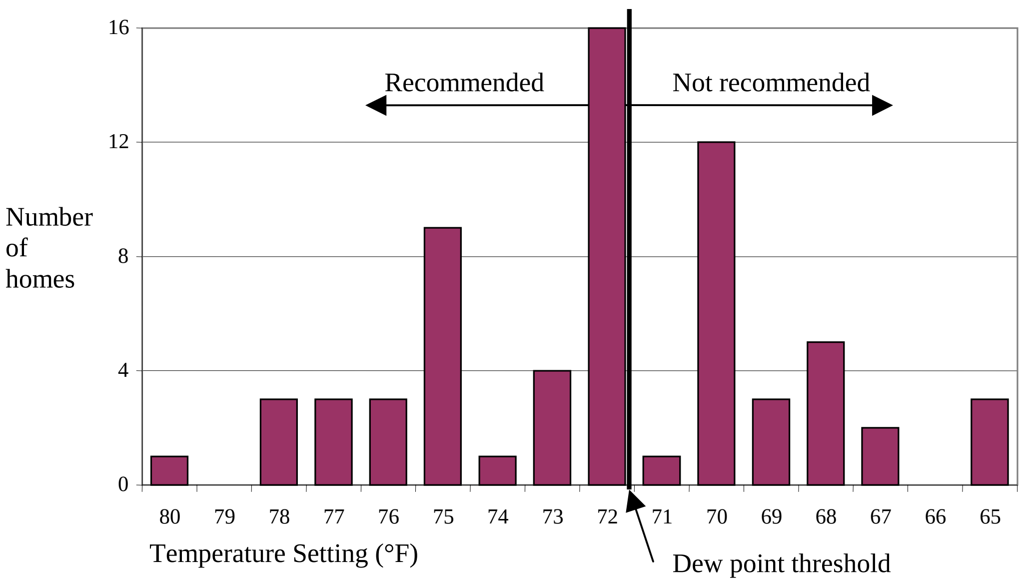

Figure 4-18. Temperature settings

Homes that reported wall moisture problems had a slightly lower average temperature of 70.8°F, and there was a correlation between lower temperature settings and higher moisture problem scores (Figure 4-19). However, there were homes with a temperature of 80°F with significant moisture problems, indicating that high interior temperatures alone are not sufficient to prevent moisture problems (assuming we have confidence in the temperature measuring methodology).

In the neural network analysis, low interior temperature correlated strongly with moisture problems.

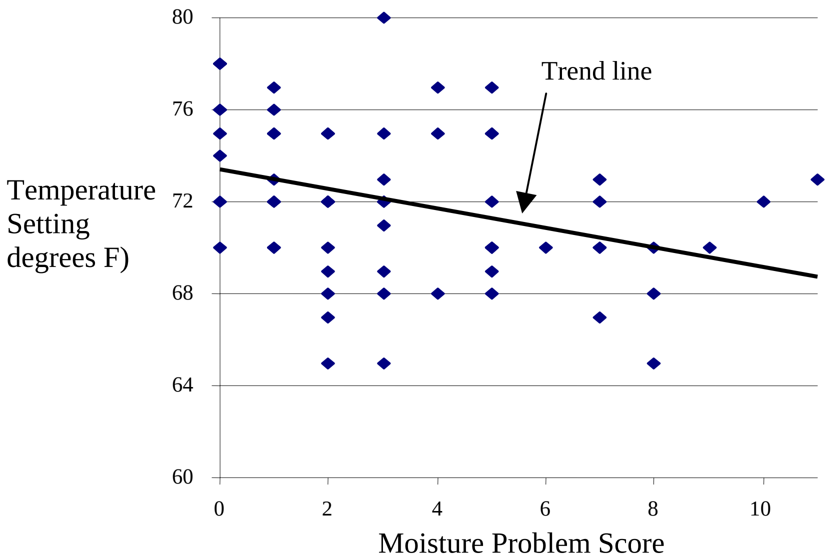

Figure 4-19. Moisture score as a function of temperature setting

4.9.3 Discussion

The literature strongly suggests that lower temperature set points are associated with moisture problems. In combination with sufficiently moist air, low temperatures will result in condensation.

Human comfort in indoor environments is dependent on both air temperature and humidity. In the absence of control over either humidity or temperature, human occupants will generally overcompensate with the controllable variable. For example, when breaches in the air barrier allow excessive infiltration of humid outside air, humidity is uncontrollable and temperature is the only control variable available to provide comfort. In this situation, residents may resort to lowering the interior temperature in an effort to remain comfortable, thereby increasing the likelihood of condensation. There was a fairly strong correlation between temperature set point and degree of moisture problems, as expected. However, even though a fairly strong correlation between shell leakage and temperature set point was expected at the outset of the study, the data indicates only a slight correlation between these two variables.

4.9.4 Interim Conclusions

The strong correlation between low indoor temperatures and moisture problems suggests that avoiding low temperatures will reduce the chances of a home developing moisture problems.

It is not clear whether it is more efficient to design building assemblies to perform in hot, humid climates at set point temperatures lower than 70°F, or to address the human comfort issues that cause low set points.

4.10 LOCAL COLD SPOTS

4.10.1 Background and interpretation of the topic literature

Localized surface areas inside the home may be at a temperature significantly lower than the average air temperature in the home. This can be caused by cool air discharged from supply registers directly hitting a wall or floor.

Air discharged from supply registers is typically 55 degrees F. If this air washes interior surfaces without first mixing with indoor air then these surfaces may be cooled far below the dew point of outdoor or even indoor air. When humid outdoor or indoor air comes into contact with these cold surfaces, condensation will occur on them.

4.10.2 Data

The data suggests a possible link between local cold spots on floors and floor moisture problems. Field investigators reported that floor moisture problems were often located under a ceiling air supply. The location of supply registers was noted in 15 homes. Five of the 11 homes with ceiling-mounted registers had floor moisture problems, as did only one of the five homes with floor registers (Figure 5-20). Looking at it in reverse, five of the six homes with floor moisture problems in this subset had ceiling mounted registers.

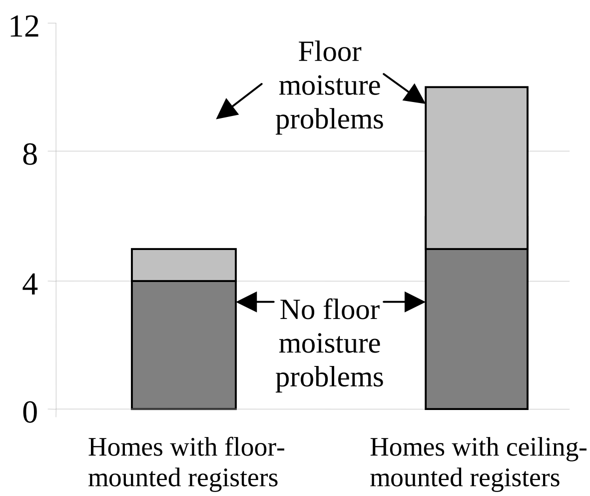

Figure 4-20. Floor moisture problems in homes with ceiling mounted registers

Field investigators also reported that floor problems were typically underneath a vinyl floor covering and in homes with bottom board holes. One possible mechanism for these moisture problems is that cool air was dropping directly from the supply register to the floor and cooling the floor surface. Moist air rising up into the floor system through holes in the bottom board permeated through the floor deck (whose permeability may have increased as its moisture content did), and condensed as it met the cool underside of the vinyl flooring.

Local cold spots was not included in the neural network analysis, as the necessary data, comprehensive surface temperature readings, was not collected.

4.10.3 Discussion

Both the data and field observations support the hypothesis that local cold spots can trigger moisture damage. This was noted particularly in the case of floors cooled by ceiling-mounted air conditioning registers. An alternative (or contributing) explanation for the correlation of attic duct systems with floor moisture problems may be the beneficial effect of in-floor duct systems in preventing floor moisture problems. Conditioned air leaking into the floor cavity from floor duct systems may tend to pressurize the floor cavity with dehumidified, conditioned air and prevent the entry of moist outdoor air.

4.10.4 Interim Conclusions

Though temperature mapping was not performed, it was clear from the data analysis that colder houses tended to have more moisture problems. By extrapolation, it is logical that cold spots (surface temperatures less than 71 degrees F) within building cavities and on interior surfaces should be avoided.

4.11 OVERSIZED AIR CONDITIONING EQUIPMENT

4.11.1 Background and interpretation of the topic literature

Air conditioning equipment is typically sized according to the size of the home and the climate in which the home is located. Equipment with greater capacity cools the home faster and so runs less frequently and for shorter periods of time. Pressures within the home generated by the air handler unit will therefore exist for shorter periods of time in homes equipped with air conditioners of greater capacity.

Additionally, air conditioning operation serves both to cool and to dehumidify the indoor air. Research suggests that oversized air conditioning equipment often does not operate long enough to dehumidify the indoor air and can result in elevated indoor humidity[39]. Equipment that has a low moisture removal capacity or whose indoor blower fan is set too high will also not dehumidify well. Higher humidity levels can increase moisture problems, and elevated humidity tends to cause homeowners to lower thermostat set points and increases the risk of condensation. Lower temperatures bring building materials that come in contact with the outdoor air closer to conditions that support condensation..

4.11.2 Data

Air conditioners among the homes in the sample typically were oversized. Cooling capacity ranged from 1.5 to 3.8 tons per 1000 square feet of floor area, with an average of 2.3 tons per 1000 square feet. The maximum air conditioner capacity recommended by MHRA sizing charts for the hottest climates in Louisiana and Florida is 2.2 tons for a 1000 square foot home[40].

Data collected in the field show that homes with moisture problems had oversized cooling equipment. On average, the cooling capacity found in the 67 homes was 1.5 tons oversized compared to the recommendations of the MHRA sizing chart.

Although the latent load fraction (the percent of moisture removal compared to the total cooling sensible and latent) was not examined, typically air conditioners with higher moisture removal capacity have an additional 3rd row of cooling coils. Out of the 36 homes for which the equipment was examined, 8 had 2-row coils, 23 had 3-row coils and 5 had 4-row coils (Figure 5-21).

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[39] "Grossly oversized equipment can cause discomfort due to short on-times, wide indoor temperature swings, and inadequate dehumidification when cooling. Gross oversizing may also contribute to higher energy use due to an increase in cyclic thermal losses and off-cycle losses." ASHRAE Applications 1999 Chapter A1.2 Residences -Equipment Sizing

[40] MHRA cooling equipment sizing chart

Figure 4-21. Cooling coils

The cooling fan speeds were set at all levels from low to high. Without measuring the return air flow it is difficult to ascertain if the air flow was detrimental to moisture removal. A lower fan setting generally indicates superior moisture removal capacity. Not all homes were measured for relative humidity levels, and as levels fluctuate during the day, a one-point measurement is not a reliable indicator of typical relative humidity; however 24 of the homes were reported by the field investigators to have indoor relative humidity over 65%.

Data also showed that a third of the homes had dirty or very dirty air filters (Figure 5-22). Although this results in inefficient operation, the lower air flow may increase moisture removal[41].

Figure 4-22. Dirty A/C filter

Data subjected to the neural network analysis suggests that air conditioner sizing strongly correlates with moisture problems, but in the opposite direction of the hypothesized relationship. Table 5-2

[41] "Although equipment efficiency is decreased, lower airflow due to dirty filter or other causes increases the moisture removal rate. This is demonstrated using the ORNL Heat Pump model for both TXV and Capillary tube controller designs." S. K. Fischer and C. K. Rice, 1983. *The Oak Ridge Heat Pump Models: I. A Steady-State Computer Design Model for Air-to-Air Heat Pumps*, ORNL/CON-80/R1, August, 185 pages. http://www.ornl.gov/cgi-bin/cgiwrap?user=wlj&script=hpdm/doehpdm.pl

shows that as the air conditioning capacity goes up (for a fixed floor area), the level of moisture damage (as indicated by the neural network analysis) goes down. Oversized air conditioners in this data set correlate with lower levels of moisture problems, according to the neural network model.

Table 4-2. Air Conditioner sizing and degree of moisture problem according to the neural network model

Degree of Moisture Problem	Tons of cooling capacity per 1000 ft^2 floor area
0.0	3.4
0.0	2.9
0.1	2.5
0.6	2.2
1.0	2.0
1.5	1.8
1.9	1.6
2.3	1.6

4.11.3 Discussion

The prevailing theory is that oversized air conditioners run for shorter periods of time and that dehumidification of the indoor air depends more on equipment runtime than equipment capacity. Therefore, homes with oversized equipment tend to have higher indoor humidity and a correspondingly greater propensity to experience moisture problems. In this data set, however, moisture problems correlate with smaller capacity equipment – not oversized equipment.

This apparent discrepancy may be explained by pressure differentials. If operating the air handler fan causes the house to experience negative pressures, then a home with oversized equipment will be subjected to shorter periods of negative pressure. If the effect of negative pressure is more problematic than high relative humidity of the indoor air, then oversized equipment that runs less frequently may protect some homes from certain types of moisture problems (particularly problems within concealed cavities).

Another issue relates to whole house ventilation systems. Many of the homes in this study had ventilation systems that bring air into the home only when the air handler is operating. Oversized systems will run less and will bring in smaller amounts of humid outside air through the ventilation system. This counterintuitive result may be characteristic only of homes with ventilation systems of this type.

This data set had a high percentage of difficult to diagnose and repair moisture problems located inside building cavities. There were moisture problems found in homes both with oversized equipment and properly sized equipment. Over-sizing cooling equipment cannot be recommended as a measure to reduce moisture problems. This result does suggest, however, that the duration over which a home experiences negative pressures may be a very important factor, thus air conditioners that have a long run time or homeowners who operate with the thermostat set for continuous fan operations are expected to have increased levels of moisture problems on average (assuming their air distribution systems generate negative pressure in the home).

4.11.4 Interim Conclusions

The analysis indicates that air conditioning system sizing does not have as big an effect on moisture problems as do pressure imbalances. Instead, it suggests that a properly sized air conditioning system coupled with a well-balanced air distribution system may reduce air conditioning system-induced moisture problems.

4.12 INTRODUCTION OF UNCONDITIONED OUTSIDE AIR

4.12.1 Background and interpretation of the topic literature

Unconditioned outside air can enter the home either through shell leakage or through the home's whole-house ventilation system. A whole-house ventilation system is required by the HUD-code[42]. It is intended to provide a quantity of fresh air that, combined with infiltrated air, meets the ASHRAE minimum ventilation recommendation of 0.35 air changes per hour for residential buildings[43].

Ventilation systems designed to satisfy the HUD Standards requirement for fresh outside air may add significant moisture to the home. Some types of ventilation systems supply air that bypasses the dehumidification system of the air conditioner (or furnace chamber in the case of heating climates) – Others supply significantly more ventilation air than can be accommodated by the air conditioner dehumidification system. This problem can be significant for ventilation systems that experience long operating periods and air conditioners with poor dehumidification capacity. Measurements of individual homes have found as much as 200 cubic feet per minute of unconditioned air being added to the home by this process[44]. Whole house ventilation systems are distinct from spot ventilation systems in kitchens and bathrooms that are intended to exhaust humid air created by periodic intense use of these areas.

A special example of the introduction of unconditioned air is through the phenomenon commonly referred to as "night flushing". In the evening, when the outside air cools faster than the home's interior, flushing of the inside air that has accumulated heat during the day can cool a house more quickly than air conditioning. A high volume of cool air moving through open windows and circulated by fans often feels more comfortable.

Despite its contribution to moisture, some consumer organizations recommend night flushing as a simple energy conservation measure. Although there are times when the combined thermal energy and energy associated with water vapor (enthalpy) is lower in the outside air than that inside (some commercial buildings use enthalpy controllers to determine when to increase ventilation to obtain the "free cooling"), enthalpy level measurement requires instrumentation that is not practical for homeowners. Therefore, in most cases, night flushing can contribute moisture to the building envelope and is not recommended by most building scientists.

4.12.2 Data

Data collected on ventilation systems was limited. No measurements were made to determine airflow or other operating parameters.

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[42] MHCSS § 3280.103

[43] 1997 ASHRAE Fundamentals Handbook Chapter 25.14, Residential Infiltration. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta GA.

[44] Manufactured Housing Fresh Air Ventilation System Field Test – Report to Michael Cammarosano, Louisiana Office of State Fire Marshall, Administer of Manufactured Homes, by Bobby Parks, Parks Air and Heat, Monroe LA, August 15, 1999

Of the 38 homes where ventilation system data was collected, 60% of the ventilation systems had either failed, were intentionally disabled, or, in the case of manually controlled fans, were reported by the residents as unused.

Thirteen homes were reported to have a ventilation system bringing air from the outside into the air handler unit via one branch duct, and into the attic via another, thereby pressurizing the attic.. This type of system can work on a variety of independent control strategies that may be tied into the operation of the air handler, a timer or a combination of the two. Twelve homes were reported to have had dedicated hall fans. These typically are switch operated and bring outside air directly into the home. Only two homes were reported as having dampered intakes to the air handler unit. This type of system brings air into the home from the outside when the air handler is operating. A number of other ventilation strategies were noted, including a passive system, a manual vent, and two homes with bedroom fans. No homes in this study were reported as having fresh air intake bypassing the cooling coils.

Occupants were not questioned as to whether they practiced night flushing.

Introduction of unconditioned outside air was not included in the neural network analysis, as it was not possible to collect reliable data on either the introduction of air from whole house ventilation systems or from night flushing.

4.12.3 Discussion

Whether coincidental (infiltration) or intentional (ventilation), outside air brought into the home will have the same effect in hot, humid climates; introduction of unconditioned outside air will increase the moisture load of the indoor air, and may find a path into the cavities of building assemblies. Typical residential air conditioning systems are not designed to remove the large amounts of moisture present in large volumes of unconditioned air.

4.12.4 Interim Conclusions

The data collected indicates that there a wide variety of methods of introducing ventilation air into the home. Because pressure balances can be affected by ventilation system operation, further analysis should include a detailed evaluation of ventilation issues.

5

INTERIM FINDINGS

The results of the first phase of the study indicate that there are several contributors to moisture problems that can be addressed through design, manufacturing and operating changes. The work performed to date has assisted in evaluating the relative importance of these factors to moisture problems. Some strategies are relatively easy to implement, while others are more challenging and deserve additional attention before definitive recommendations can be developed.

5.1 POSSIBLE CONTRIBUTORS TO MOISTURE PROBLEMS

Possible Contributor
Pressure imbalances
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 be significantly associated with moisture problems, particularly when they were amplified by closed interior doors.
2. ***Duct leakage to the outside.*** Despite the fact that specific duct leakage test data did not correlate strongly with moisture problems, results did indicate that air distribution imbalances (to which duct leakage contributes), manifested as pressure imbalances, have a significant impact on moisture problems.
3. ***High rate of shell leakage.*** Shell leakage alone did not correlate strongly with moisture problems; however theory states that it will contribute to humidification of the home if negative pressures with respect to the outside exist within the living area.
Non-continuous vapor retarder and air barrier
1. ***No ground vapor retarder under the home.*** Findings indicate that ground vapor retarders are effective in protecting homes from moisture damage, but only where a sufficiently designed drainage system prevents the accumulation of water under the home.
2. ***Damage to the bottom board.*** Data indicated that the bottom boards of many homes experiencing floor moisture problems were damaged, indicating a need to develop guidelines for manufacturers, installers and owners to prevent damage to bottom boards and to facilitate repairs of those already damaged.
3. ***Interior wall vapor retarder ineffectiveness.*** The literature review indicated that there is merit to a waiver allowing vapor permeable interior wall surfaces that will allow wall cavities to dry toward the interior of the home, in conjunction with a vapor retarder on the exterior in hot, humid climates. Further testing should be conducted to verify this recommendation.
4. ***Lack of exterior air barrier.*** Analysis of the data and review of the pertinent literature

indicates that air barriers should be located on the exterior wall surface in hot, humid climates to prevent the introduction of hot, humid air into building cavities that can contribute to condensation. Measures to limit outside air movement into building cavities should be explored.

5. ***Ventilated attic space.*** From the limited data collected in this study on the effects of attic ventilation on moisture problems , it does not appear that ventilating attics contributes to ceiling moisture problems in hot, humid climates.

Occupant Comfort

1. ***Low thermostat setting.*** As hypothesized at the beginning of the data collection process, low interior temperatures contribute to moisture problems. Interim findings indicate that thermostat set points should be no lower than 71°F.

2. ***Local cold spots.*** Local cold spots such as those created by cold air registers directed on floor surfaces, though not specifically studied in the field, are hypothesized to contribute to certain moisture problems.

3. ***Introduction of unconditioned outside air***. Introduction of unconditioned outside air into the home through the whole house ventilation system was not specifically part of the data collection effort in the initial phase of the study.

4. ***Oversized air conditioning equipment.*** The results indicated that proper sizing air conditioning equipment would be effective in addressing moisture problems only when combined with good air distribution design practices, i.e. a balanced system.

6

NEXT STEPS

This study has established the effective limit of understanding condensation-related moisture problems from field data gathering efforts. More comprehensive data collection efforts would require invasive and destructive probes and tests of occupied homes, which would be impractical. Further data collection and analysis will not likely produce superior results, however, the results of the current work suggests several fruitful areas for further investigation.

Nine out of the twelve contributors to moisture problems evaluated in this report related to physical characteristics of the home for which measurements of varying precision could be made, while three contributors were dependent on the activities of the inhabitants. This suggests that there are opportunities to make changes in design, production and installation that reduce the chances of moisture problems. Changing the habits of homeowners is a more difficult task but some strategies for reaching the end user must be attempted.

The following efforts will enable this project to move from a diagnostic phase to developing and testing solutions to moisture problems. The suggestions for future research follow the three major source areas described in Section 6: pressure imbalances, non-continuous vapor retarder and air barrier, and occupant comfort.

6.1 PRESSURE IMBALANCES

The results of the literature review, data analysis and field observations indicate that pressure imbalances significantly contribute to moisture problems. Imbalances are characterized by differential pressures between interior spaces (including wall cavities) having a negative pressure relative to the exterior. The ideal condition is a uniform inside air pressure that is slightly positive relative to the exterior. Research into this area would be structured as follows:

6.1.1 Objective

Describe the design and operational conditions that result in pressure imbalances and develop and test approaches that provide internal air pressure balances that minimize moisture problems. Develop design guidelines and installation practices based on these findings.

6.1.2 Process / Methods

- Characterize through analysis and testing how the components that impact the overall pressure balance in the home—including but not limited to return air flow path, architectural features that interrupt interior air movement, duct system design, air handler operation and location, duct leakage, shell leakage, and other factors—contribute to pressure imbalances.
- Develop design strategies that create air flow mechanics that minimize moisture problems, and assess cost effectiveness of alternative approaches. Perform comprehensive tests of specific designs which may include testing duct configurations, transfer grill design issues and return air system design considerations.

- Develop and publish recommendations for manufacturers to improve installation techniques that will reduce pressure imbalances in housing, potentially including duct and shell sealing practices, testing protocols and field pressure balancing techniques.

6.1.3 Deliverables

- Characterization of systems configurations that result in balanced air pressures within the home and positive pressures relative to the outside. Descriptions of ways in which current systems are not meeting design goals.
- Testing protocol for whole houses and component systems based on target design specifications.
- Cost effective system designs to achieve target air flow and pressure characteristics.
- Manufacturing and installation guidelines to help reduce pressure imbalances.
- In-plant training program to help disseminate the design guidelines.
- A simple diagnostic field testing protocol and or tool for use by service personnel to determine pressure balance that minimizes moisture problems.

6.2 NON-CONTINUOUS VAPOR RETARDERS AND AIR BARRIERS

The data, observations and literature also suggest that the lack in continuity of an exterior vapor retarder and air barrier (outside the insulation), as the first line of defense in limiting moisture flow into the home, significantly contributes to the potential for moisture problems.

6.2.1 Objective

Better understand how vapor retarders and air barriers in the floor, walls and ceiling of homes in hot, humid climates function under dynamic conditions and develop strategies to improve the resistance of envelope components to moisture penetration.

6.2.2 Process / Methods

- Perform a review of vapor retarder and air barrier design issues including an analysis of their role as a continuous envelope around the home and the impact of moving them from the inside to the outside of the wall cavity. Individual investigations and testing of floor, wall and attic systems is anticipated in the field and/or lab.
- Conduct a project tie-in with the attic ventilation study to look at how sealed attics function as vapor retarders and air barriers to minimize moisture problems in hot, humid climates
- Develop a testing plan and perform comprehensive tests for different locations and configurations of vapor retarders and air barriers, including on the interior walls, outside the wall cavities, in the ceiling and the bottom board. Testing should distinguish between the functions of vapor retarders and air barriers. This should be done primarily in test cells to determine effectiveness in a controlled environment.
- Issue specific vapor retarder and air barrier design recommendations based on design review and testing.
- Determine the relative importance of air movement versus vapor diffusion as a moisture transport mechanism in contributing to moisture problems.

6.2.3 Deliverables

- Assessment of the performance of vapor retarders and air barriers in walls, ceilings/attics and floors (including the foundation).
- Design strategies intended to improve the management of vapor and air flow through the major components of the home.
- Test cell protocol and controlled-environment tests assessing the performance of the wall, floor and ceilings/attics strategies. Various configurations and material applications will be considered for each component.
- Vapor retarder and air barrier design recommendation report based on design review and testing results.

6.2.4 Occupant comfort

Occupant comfort is affected by a combination of indoor temperature and humidity levels. Poor occupant comfort can spur occupants to lower their thermostat, an action that was found to strongly correlate with moisture problems, particularly at temperatures below 70°F. The purpose of this research area is to investigate ways to prevent this chain of events from being set off by ensuring that occupant comfort is maintained.

6.2.5 Objective

Develop strategies to improve comfort and reduce the frequency of low temperature areas in homes. These will include the development of mechanical space conditioning and ventilation systems that effectively minimize build-up of moisture in the indoor air before it can condense on building surfaces.

6.2.6 Process / Methods

- Evaluate the most likely causes of low temperatures in housing, including occupant attitudes toward temperature. Include a literature review, homeowner interviews and a design review of materials that can reduce the impact of hot, humid climates on indoor comfort.
- Establish the relative importance of factors that relate to comfort, such as air temperature, direct sunlight, air distribution balance, humidity and mean radiant temperatures for typical manufactured homes.
- Based on these findings, develop recommendations for methods to increase comfort and educate users on options to reducing air temperatures.
- Perform a review of ventilation system design issues including an analysis of the role of ventilation system in controlling the amount of unconditioned air into a typical home. Dovetail these investigations with MHRA's ongoing ventilation research.
- Assess how the current design of air distribution systems may create local cold spots and recommend guidelines to avoid them.
- Develop and test integrated space conditioning and ventilation systems that provide efficient cooling, humidity and air exchange.
- Demonstrate these strategies in homes along the Gulf Coast.
- Issue specific recommendations for actions that will reduce the occurrence of low temperatures and the resulting problems.

6.2.7 Deliverables

- Recommendation report on causes of low temperature behavior of occupants, materials and methods that will reduce radiation heat transfer, and potential solutions to both issues.

- Equipment designs and configurations that are more effective at humidity control than current practices.

- Recommendation report on design guidelines and best practices for ventilation systems that mitigate the introduction of unconditioned outside air into the home.