



BUILDING MOISTURE AND DURABILITY

PAST, PRESENT AND FUTURE WORK

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BUILDING MOISTURE AND DURABILITY

NOTICE

This report was prepared as an account of work sponsored by the U.S. Department of Housing and Urban Development. Views and opinions expressed herein are the responsibility of the authors. References herein to any product, process or system do not constitute an endorsement, but are included solely because they are considered essential to the object of the report.

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EXECUTIVE SUMMARY

Moisture, in all its physical forms, is commonly regarded as the single greatest threat to durability and long-term performance of the housing stock. Excessive exposure to moisture is not only a common cause of significant damage to many types of building components and materials, it also can lead to unhealthy indoor living environments. A long list of serious adverse effects can result from moisture problems in houses. There is wide agreement that successful management of moisture in its various forms is essential for houses to be durable, safe, and energy efficient.

This project set out to develop a set of recommendations for future research on moisture problems in housing that will help to prevent such problems or resolve them once they have occurred. The research recommendations were developed following a review and analysis of the extensive technical literature concerning the problems created by bulk water and excessive water vapor in houses, and the solutions to those problems. The literature review was supplemented with information about ongoing public and private research into moisture problems prior to developing research recommendations. Detailed input was also provided by a panel of experts active in this field.

The recommendations for future research developed for this project are presented in the body of this report. Recommended research topics are organized under three overarching goals: building improved knowledge about the nature, extent and implications of moisture problems, pursuing a variety of methods for preventing and detecting moisture problems, and taking greater advantage of the potential offered by moisture modeling tools. Project ideas are summarized descriptively with an explanation of the need for the work and other information including responsibility for heading up the work, and the timing and level of funding anticipated. The projects considered very high and high priority are also identified, based on input from participants at the Expert Panel meeting.

Relevant background information developed during the project appears in the Appendices. Results of the literature review and analysis are in Appendix A, which includes separate sections on bulk moisture issues; problems associated with water vapor, condensation and humidity control; and tools for moisture modeling. Summaries of ongoing research projects relevant to moisture in housing and compiled during this study are in Appendix B. Finally, a discussion of issues and possible approaches to improving overall coordination of work among public agencies and with interested private-sector groups is in Appendix C.

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1. Introduction

Moisture, in all its physical forms, is commonly regarded as the single greatest threat to durability and long-term performance of the housing stock. Excessive exposure to moisture is not only a common cause of significant damage to many types of building components and materials, it also can lead to unhealthy indoor living environments. Some of the more serious effects resulting from moisture problems in houses include:

- decay of wood and corrosion of metals
- infestation by termites, carpenter ants and other insects
- negative impacts on indoor air quality
- the growth of mold, mildew and other biological contaminants
- reduced strength in building materials
- expansion/contraction damage to materials
- reduced thermal resistance of wet insulation
- premature failures of paints and coatings
- damage to building contents
- negative effects on building aesthetics

There is wide agreement that successful management of moisture in its various forms is essential for houses to be durable, safe, and energy efficient.

In recognition of the importance of improving durability of the U.S. housing stock, the Partnership for Advancing Technology in Housing, a public-private initiative involving the U.S. Department of Housing and Urban Development and a wide range of private organizations, sponsored this study of moisture problems that affect durability of housing. The scope of the project includes water problems due to leaks, condensation and water vapor in single-family houses of all ages, particularly detached houses of conventional light-frame construction in climates characteristic of the continental U.S. Multifamily low-rise buildings and other types of construction such as SIPS and steel framing are only addressed occasionally, as are buildings located in extremely cold or extremely hot climates. Water damage from flooding of surface waters, while a major cause of property loss in its own right, is not specifically considered.

The principal goal of the project is to develop a set of recommendations for future research on moisture problems in housing that will contribute to preventing such problems or solving them once they have occurred. The research recommendations were developed following an extensive review of the technical literature concerning the problems created in housing by bulk water and water vapor and the solutions to those problems. The literature review was supplemented by interviews with practitioners about problems observed in the field, and interviews with researchers to compile information about ongoing public and private research into moisture problems.

The recommendations for future research developed during this project are presented in the body of this report. Section 2 identifies a series of goals providing a framework for organizing future research on moisture control and related issues, while Sections 3, 4 and 5 describe the candidate research projects under each of the goals. Each project description presents a brief rationale for the work and a discussion of desired outputs. Where feasible they also include qualitative

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information about timing, level of effort and whether the project should properly be pursued by the public sector, the private sector, or a combination of the two. Some of these project concepts were drawn from the literature or developed by the project team, while others were suggested by participants in an Expert Panel on Moisture Research. Participants at the Expert Panel meeting also provided input on prioritization of these topics, and the identification of certain projects in the text as "very high" priority or "high" priority has been based on this input.

Additional materials developed during the project appear in the three Appendices to this report. Appendix A presents the review and analysis of the literature, organized into major sections on bulk moisture, water vapor, and moisture modeling. Appendix B includes summaries of ongoing moisture research projects, which were compiled to provide a context for preparing the agenda for future work. Appendix C discusses recommendations for improving the coordination of research among the many groups interested in moisture problems in housing.

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2. Research Goals

Notwithstanding decades of work by architects, designers and practitioners, the persistence of moisture problems in housing and the apparent emergence of new types of moisture-related problems both highlight the need for developing or compiling a comprehensive research agenda for future work on moisture control. In this context the overall purpose of future work is to minimize detrimental effects of moisture, through pure and applied research and through demonstration and deployment of new products, systems or methods of construction. All of these activities are encompassed within the research plan presented in this document. Although this project was sponsored by HUD, there are a variety of other public and private organizations performing research in this area that might also sponsor work described in this report. In other words, the scope of research presented here is determined primarily by the nature and scope of the problem, not solely by the mission of HUD.

There are many component steps that can contribute to achieving the overall purpose of minimizing detrimental effects of moisture. These steps can be best organized and explained as they relate to a series of more detailed research goals. These goals are divided into three categories. The first category are goals that fill in knowledge on key points that affect scientific and policy priorities. The second category are goals that involve steps to prevent and correct specific moisture problems in houses. The third category relate to future development and deployment of moisture modeling tools, which have considerable potential to improve designs and prevent moisture problems. The order of presentation is for purposes of discussion, and is not intended to reflect priorities, which will be considered in the project descriptions. Under each category of goals there exist a mix of opportunities for the near-term along with others that will require more time and greater effort. Some of the goals are not so discrete as to be specifically achieved at a known point in time; rather, greater or lesser progress can be made in the indicated direction.

Many specific research opportunities are set forth in the following pages. These are collectively presented as a good starting point, but each should ultimately be considered on its own merits and all should be understood in the proper context. There are stand-alone projects and interrelated projects. Success does not necessarily require pursuing every idea that is described; indeed, prioritization is critical because the total cost of all these activities would far exceed the resources of all the organizations with an interest in moisture problems. There also are undoubtedly other areas of work, not described herein, that would be beneficial and could be identified through further study. The most important thing is for the overall portfolio of moisture-related research to address the broad categories of goals mentioned above: enhancing understanding of the problem, avoiding and addressing specific moisture problems, and realizing the full potential of moisture modeling tools.

The balance of Section 2 describes the goals underlying the research plan and briefly explains the rationale underlying each. Sections 3, 4 and 5 describe the recommended projects under each of the goals.

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2.1 Build Additional Knowledge about the Moisture Problem in Housing

Despite widespread attention to and concern about building moisture, much of what is known about this problem is qualitative, conceptual or anecdotal. A clear, authoritative, quantitative picture would serve several important purposes. It would help to attract funding from many sources for R&D, and to prioritize this problem relative to others. It would also help funding sources to allocate their resources across different areas of potential study under the overall moisture heading. There are two principal goals included under this area.

- **Develop Reliable Quantitative Information Documenting the Nature, Frequency, Severity and Impacts of Moisture Problems in Housing.** This first goal is the most basic. It reflects the frustrating lack of quantitative data on how common different types of moisture problems in housing actually are, or how they relate to design and occupant variables, age of house and geographic location. Examples include prevalence of leaks through roofs and walls; wet basements; standing water in crawl spaces; plumbing fixture overflows; oversized cooling equipment; condensation in building cavities or on slabs, and so forth. While the prevalence of these types of problems is in itself of considerable interest, this information also needs to be supplemented with reliable estimates of the economic and non-economic impacts of moisture problems.
- **Improve Scientific Understanding of the Relationship Between Moisture in Homes and Health Outcomes.** This second goal complements the first. Recent years have seen growing awareness of the possibility that moisture in buildings is not just a structural and maintenance issue, but under some conditions may also be related to the health and well-being of the occupants. Several organizations have already shifted their focus from physical effects to health effects. This trend has certainly raised awareness and concern among the public, producers of building materials and systems, and the home building community. Ultimately health impacts will be treated as one of the spectrum of impacts of moisture problems in buildings. But even the latest research highlights major gaps in knowledge and understanding about how moisture and occupant health are related. These gaps must be resolved before a complete picture can be painted and the overall magnitude of the moisture problem can be understood.

2.2 Prevent and Correct Specific Moisture Problems

The central features of a sound plan for moisture research should be to minimize the impact of moisture on the built environment. A great deal is already known in this area, much of it incorporated in building codes and standards as well as in rules of practice. Yet there is reason to believe that problems arise when things are overlooked or communications fail, allowing moisture to accumulate in building environments that are susceptible to its effects.

The general approach here is to strengthen various layers of protection or lines of defense. There are four corresponding goals under this heading. These goals reinforce one another and, in combination, have the potential to significantly reduce the incidence and detrimental impacts of building moisture. They are as follows:

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- **Build in Moisture Protection through Proper Design and Construction Detailing.** The first line of defense against moisture problems is undoubtedly good design and the proper execution of design details that prevent moisture intrusion.
- **Identify Improper Work while it can be Corrected Easily.** Where execution is improper, defects should be identified and corrected before construction is complete. Incorporating specific requirements in building codes and enforcing them through design review and inspection play a large part in this effort.
- **Detect and Correct Moisture Problems Before they Cause Serious Damage.** To the extent moisture problems do arise in spite of these measures, they should be caught and corrected quickly, before they can cause serious damage.
- **Use New Technologies to Reduce Vulnerability to Moisture Damage.** Where moisture problems arise and are not detected and corrected quickly, the final line of defense is building materials and systems that have greater resistance to moisture.

2.3 Realize the Potential of Moisture Modeling Tools

Traditional approaches to preventing moisture problems have been based on rules of thumb and generations of field experience. Over the last twenty years a wide range of moisture modeling software tools have become available, and shown great potential for improving building designs. These tools now can model vapor diffusion, flows of humid air, bulk water intrusion, wetting, drying and moisture storage of different materials and phase change phenomena. They can also deal with a growing number of building material and assembly types. Note that models can be used in several ways, e.g. to develop or test general design guidelines or requirements, to assess moisture vulnerabilities of specific designs, and to derive ideal material properties. Note that some of these outputs will feed back into the previous goal of building in moisture protection through proper design and detailing. Specific goals are as follows:

- **Fill in Data Gaps that Limit Modeling Accuracy.** The physics that underlie moisture modeling are relatively well understood, but the output of a model is only as accurate as the input data. At present there are several types of input data that are poorly defined, which creates ambiguity or uncertainty in interpreting modeling outputs.
- **Demonstrate Robustness and Extend Modeling Capabilities.** Modeling outputs will not be widely relied upon for general design purposes or specific decisions until their accuracy has been demonstrated through rigorous validation studies, which are an ongoing process. Outputs will be more useful if they can specifically report whether critical conditions for the development of biological contaminants or physical deterioration will be exceeded, rather than simply predicting physical parameters. And modeling results would provide users with more insights if results were presented in probabilistic terms (e.g., "most likely" values with ranges or associated uncertainties), rather than as absolute, deterministic outputs.
- **Translate Modeling Results into Practice.** Current models tend to be complex, difficult to use and hard to interpret, or so simplified that their results may be unreliable. Experts can make good use of state-of-the-art models, but typical building designers face a much greater barrier. In the near term, models can and should be used by the experts to do comparative

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studies of building assemblies, reducing or eliminating the need for field testing. These results can be used to create design guidance, which in turn can be disseminated to and used by practitioners. However, in the long term models should be applied to analyze individual building designs. The best route to this result involves integration of models with widely-used design tools. Tight integration will give users insights into the results of modeling without requiring them to become familiar with operation of specialized moisture software or re-enter building information.

2.4 Summary of Suggested Moisture Research Projects

A list of all the research projects identified under these headings and discussed in subsequent sections of this paper appears on the next page. The projects designated as very high priority and high priority based on input from the Expert Panel are also identified.

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Summary List of Moisture Research Projects

Goal or Project Title	Priority
Build Additional Knowledge about the Moisture Problem in Housing (Section 3)	
Compile statistically valid data on the relative frequencies and severity of different types of moisture problems, in both new and existing homes	Very high
Perform an in-depth analysis of existing AHS data on moisture problems.	Very high
Quantify the physical damage resulting from different types of moisture problems	
Characterize the moisture performance of existing homes through a field testing protocol	Very high
Investigate the evolution of legal and insurance claims relating to mold and moisture problems	
Improve understanding of the health effects of indoor moisture problems, especially mold	
Update recommendations of appropriate target indoor humidity levels to reflect health and other effects	
Prevent and Correct Specific Moisture Problems (Section 4)	
Gather, disseminate and transfer residential flashing know-how to user audiences	High
Determine optimum foundation drainage practices	
Develop guidelines for building material moisture content prior to building enclosure	
Assess the drying performance of typical wall systems in U.S. climates and disseminate the results	Very high
Develop educational tools to enable and certification programs to recognize good moisture control practices	Very high
Review current building code flashing and overhang requirements, and develop code changes to fill gaps	
Develop gutter scoping requirements and design criteria for pitched roofs	
Clarify requirements for crawl space ventilation and moisture protection design details	
Develop inexpensive, unobtrusive moisture sensors and data collection devices	
Promote the development of technology for passive detection of moisture problems	
Create and publish a model building envelope maintenance and repair guide for owners and property managers	
Introduce improved structural and finish materials that are resistant to moisture and decay	
Validate the performance benefits of a "smart" vapor retarder, and work to promote appropriate use of improved vapor retarder technologies	High
Determine feasibility and cost of residential air-conditioning systems capable of meeting latent loads under part-load conditions	
Work to ensure that expanded use of mechanical ventilation systems helps reduce rather than worsens moisture problems	
Develop a mold resistance rating and associated moisture performance test procedures for air handling equipment	High
Realize the Potential of Moisture Modeling Tools (Section 5)	
Compile specialized weather data sets	
Develop statistically validated procedures to assess internal moisture loads for use in hygrothermal analyses and related engineering studies	Very high
Develop a generalized approach to determine cladding pressure differential for purpose of cladding structural and rain-penetration design	
Development and maintenance of material properties by industry for use by designers	
Generate information on the "aged" properties of common building and insulating materials	
Strengthen validation studies and incorporate consensus standards for accuracy	
Establish "threshold" values for temperature, relative humidity and duration to initiate biological, chemical and mechanical damage of building materials and components	
Develop a generalized approach to determine cladding pressure differential for purpose of cladding structural and rain-penetration design	
Develop stochastic moisture models using probabilistic outputs (ranges) to reflect errors due to weather (external loads), material variations, and internal load variations	High
Use models to develop design guidance and disseminate the results	
Use models to identify optimum properties of specific building materials	
Integrate models tightly with standard design tools	

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3. Building Knowledge about Moisture Problems

This section and the next two each describe a series of research activities that could, individually and collectively, help to address moisture problems in low-rise housing. The research projects are based on issues and recommendations found in the published literature or developed by the project team. Individual research items are organized under a series of themes or objectives to be achieved in the future, although some suggestions are cross-cutting. Project descriptions also indicate whether the suggested work is most appropriately the responsibility of the public sector, the private sector, or a combination of the two. In many cases the most appropriate private-sector participants are noted. Qualitative indicators of cost (low, medium and high) and time required (short, medium, long) are also included, based on judgments of the project team. In round numbers, low cost was considered to be under \$200,000, medium cost between \$200,000 and \$500,000, and high cost would be above \$500,000, while short-term was up to two years, medium-term was two to five years, and long term was more than five years. Finally, the items selected by vote of the Expert Panel as very high priority and high priority are so identified.

This section includes research activities designed to fill in missing knowledge about different aspects of the moisture problem. The first sub-goal focuses on basic data about the nature and frequency of moisture problems, while the second addresses understanding of the relationship between moisture and the health of the occupants.

3.1 Develop Reliable Quantitative Information Documenting the Nature, Frequency, Severity and Impacts of Moisture Problems in Housing

- ***Compile statistically valid data on the relative frequencies and severity of different types of moisture problems, in both new and existing homes.*** Most descriptions of moisture-related problems in housing are either theoretical in nature, or based on data compiled through field studies and investigations of problem homes. Little if any attention is given to how commonly they arise. There are some statistical studies of moisture problems in smaller geographic areas, especially in the Pacific Northwest, as well CMHC/NRCC studies from the early 1980's (further described in Appendix A). All these sources vary in scope and definition of what constitutes a "moisture problem." In this environment it is difficult or even impossible to make educated decisions about what types of mitigating steps are most important, especially when those steps add significant cost or complicate the building process. Additional data is badly needed.

There may be no need to field a new survey in order to address this topic. The HUD-sponsored American Housing Survey (AHS), which is performed every two years and based on a random sample of over 60,000 U.S. housing units, provides the necessary mechanism. Indeed, the AHS already collects some very general data about roof, wall, basement, water heater and pipe leaks. For example, the 2001 AHS found that about 12 percent of the occupied housing stock had experienced leaks in the roof, basement, walls, or other exterior shell components during the last 12 months. For homes less than 4 years old this figure was 7 percent. However, the current AHS does not attempt to determine the severity of these problems, nor does it touch upon any of the variety of water vapor-related problems. The AHS could readily be revised to expand the scope of moisture problems covered, add additional questions about phenomena such as condensation leading to puddling of water and cooling season humidity control, and to inquire as to the severity of other leaks reported by

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the occupant. Ideally the information collected would allow determining whether problems were caused by design, workmanship or product failure. Other survey vehicles could also be used, but not as easily as the AHS.

Responsibility: Public sector.

Cost: Low. Modification of the AHS to expand coverage of moisture problems would be relatively inexpensive since the survey is already in place.

Time: Short to medium. Development of survey modifications could be completed in less than one year, but due to time lags the implementation of a modified survey and analysis of the results would take several years.

Priority: This project was identified as very high priority by the Expert Panel.

- ***Perform an in-depth analysis of existing AHS data on moisture problems.*** Complete data sets from the AHS are available for analysis. This data source could be used to create a statistical picture of those aspects of the moisture problem that have historically been included within the AHS. Such a picture could go well beyond information in the published tables. Two major themes could be explored. First, data on homes with moisture problems could be analyzed using housing characteristics and occupant data, to identify factors associated with reported leaks from external and internal sources. This would be, in effect, a multivariate predictive model of conditions associated with moisture problems. Second, since the AHS is longitudinal in design (i.e., it surveys the same sample of homes over time), data from multiple administrations of the AHS could be analyzed to investigate whether the reported moisture problems appear to occur randomly in different homes over time, or whether they tend to recur in particular homes. Both of these themes have implications for identifying the best strategies for addressing the problem.

Responsibility: Public sector.

Cost: Low.

Time: Short.

Priority: This project was identified as very high priority by the Expert Panel.

- ***Quantify the physical damage resulting from different types of moisture problems.*** Determining the incidence of leaks and moisture accumulation only tells part of the story. The follow-up topic for study is to develop estimates of the resulting types of damage to buildings and their contents. How common is structural damage such as deterioration of roof or wall sheathing? What about insect infestation, visible mold and mildew, or damage to interior finishes requiring replacement of drywall, carpeting or other components? Or what about damage to personal property stored in houses? These are the physical outcomes of interest. They require time and money to correct. Reliable estimates of the economic costs associated with these effects of unwanted moisture would round out incidence data and help to pin down the parameters of a presumably serious but poorly documented problem. This topic would be more difficult than the survey items discussed above, and different methods or a combination of methods might be required, so cost and time frame are correspondingly extended.

Responsibility: Public sector.

Cost: Medium.

Time: Medium.

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- ***Characterize the moisture performance of existing homes through a field testing protocol.*** This project would be a more intensive version of data collection than described under the discussion of the American Housing Survey (above). It would focus exclusively on moisture-related issues in a smaller sample of newly-built homes (several hundred homes up to 5 years old) around the country. It would include field measurements and possibly data monitoring (up to 1 year) in addition to survey questions for the occupants. The goals would be to collect basic data about the type of construction and mechanical systems of the property, to look for evidence of "hidden" or concealed moisture problems, and to characterize indoor conditions (temperature and RH in the living space, attic, and foundation space), outdoor weather, and internally generated moisture loads (type and amount). It would be highly desirable for the data collected from each home to be sufficient to study with modeling tools, (e.g. given the location, construction, outdoor conditions and internal loads, can the monitored internal conditions be accurately predicted with a particular model?). Steps in the project would be development of a comprehensive inspection and monitoring protocol, survey design, field execution, and data analysis.

Responsibility: Public sector.

Cost: High.

Time: Medium to long.

Priority: This project was identified as very high priority by the Expert Panel.

- ***Investigate the evolution of legal and insurance claims relating to mold and moisture problems.*** There is a perception that lawsuits involving moisture problems (particularly mold) and related product liability claims have grown significantly in recent years. Publicity over large jury awards has been intense. These trends have led property insurers and builders' risk insurers to modify policy language, and prompted manufacturers, retailers and home builders to change warranty terms. There have also been a range of product recalls and class-action settlements in the last fifteen years that were driven by moisture or moisture-related product failures, including EIFS, hardboard siding and OSB siding. Finally, there have been changes in some state warranty laws extending coverage for new homes that alter incentives for builders. This would be a project to identify and document trends in litigation, warranty claims and insurance claims, nationally or for selected jurisdictions, to the extent data on these topics is available. Whether or not such trends represent any change in the underlying moisture problem, they tell a very important story to businesses throughout the supply chain.

Responsibility: Public sector.

Cost: Low to medium.

Time: Short to medium.

3.2 Improve Scientific Understanding of the Relationship Between Moisture in Homes and Health Outcomes

- ***Improve understanding of the health effects of indoor moisture problems, especially mold.*** There is great uncertainty about the actual effects of exposure to moisture and its by-products such as mold in typical residential environments. Reported effects range from allergic reactions and sinusitis, to asthmatic attacks, to acute pulmonary hemorrhage (bleeding from

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the lungs) in infants (although the study reporting this latter effect was subsequently withdrawn). While this has surely increased interest in management of indoor moisture (which may offer other benefits as well), it has also created unnecessary fear about common phenomena such as small spots of mold or mildew in shower compartments. One result has been to leave some occupants afraid to take common-sense cleanup actions.

The latest study on the subject, *Damp Indoor Spaces and Health*, was commissioned by the Centers for Disease Control, developed by a committee operating under the National Academy of Sciences, and published in early 2004. While that report concluded that a variety of health outcomes were associated with exposure to damp indoor environments, including upper respiratory tract symptoms, cough, wheeze, and asthma attacks in asthmatics, it also found that there was insufficient information to assign a causal relationship between dampness and any of those outcomes. It concluded that excessive indoor dampness was a public health problem, although the word "excessive" appears key to this conclusion. Finally, the report also acknowledged that as yet there was no basis for recommending appropriate levels of dampness reduction or "safe" levels of exposure to dampness-related agents. Numerous recommendations for further research appear in the study. Some are covered elsewhere in this report (e.g. reviewing HVAC systems as a potential site for growth and dispersal of microbial contaminants, or development of designs, construction and maintenance practices for buildings that reduce moisture problems, and development of building materials that resist microbial contamination when wet), but many others are not.

The additional work needed on health relationships would be to identify causal relationships, where they exist, between indoor dampness and health outcomes, and to assess the contribution of residential dampness or moisture to the overall burden of relevant diseases such as asthma and sinusitis. Of course, the building science community will only play a peripheral role in this kind of research. And while the unanswered questions are undoubtedly important, given that the impacts of moisture problems are multifaceted and go well beyond health effects, such studies should not be allowed to distract attention from the challenge of preventing moisture problems in the first place.

Responsibility: Public sector.

Cost: High. Broad epidemiological studies are difficult and expensive.

Time: Ongoing/long-term.

- ***Update recommendations of appropriate target indoor humidity levels to reflect health and other effects.*** Appropriate indoor relative humidities were originally based on occupant comfort, with recommendations in the 30% to 60% range dating back many years in ASHRAE Standard 55. A more comprehensive basis would also reflect health considerations and material durability. For example, it has been argued that to prevent microbial growth and minimize allergens (e.g. dust mite control) the lower the humidity the better. Recently recommendations have been published calling for RH as low as 15% in very cold climates. Yet the occupants of extremely dry homes are also familiar with the unpleasant effects of extremely low relative humidity. One relatively complex factor is the variation of humidity within the conditioned space, which can lead to mold growth on cold (underinsulated) exterior walls in winter, even if humidity is acceptable in the space as a whole. Seasonal swings in humidity also create stresses in building assemblies as moisture concentrations change, which causes cracks and splits to appear and disappear. The

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importance of conditions within building microclimates promoting undesirable localized effects serves to complicate this question. A comprehensive re-evaluation of target indoor humidity levels under different conditions that reconciles these variables as much as possible and produces consensus recommendations (which might vary by type of occupancy, occupant characteristics, climate and other factors) would be a valuable resource for designers and building operators, including consumers.

Responsibility: Public-private, including involvement of the design and public health communities.

Cost: Medium.

Time: Medium.

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4. Prevent and Correct Specific Moisture Problems

4.1 Encourage Moisture Protection in Building Design and Construction

- ***Gather, disseminate and transfer residential flashing know-how to user audiences.*** Flashings are an essential component of building envelopes, especially roofs and walls. They come in many different varieties, each tailored for specific conditions, and they may be installed by several different subcontractors on a single house. Improperly formed or installed flashing can lead to significant bulk water leakage, and can be costly to repair once the home is completed. Improving the quality and workmanship of flashing would be a major step towards reducing leaks through building envelopes. Flashing practices are described in many different sources; some in the public domain and many others under the control of different industry associations. The first part of this project would involve inventorying existing flashing resources, identifying the most useful ones and working with the sources to compile a concise, accurate guide to flashing aimed at audiences who actually select and install them in housing. Coverage would include roof penetrations, valleys, chimney flashing, drip edges, step-flashing, counterflashing, and flashing of window and doors. Such a guide would be quite valuable even if it did not cover every possible combination of roofing and siding systems. The second part of the project involves outreach designed to transfer this knowledge to workers responsible for flashing installation. This represents a major challenge given the dynamic nature of the workforce and the multiple trades involved. It will require a sustained effort through multiple avenues including trade associations and building firms.

Responsibility: Public sector, in collaboration with major product and material interests.

Cost: Low to develop materials; medium to high to perform outreach.

Time: Short to develop materials, then ongoing.

Priority: This project was designated high priority by the Expert Panel.

- ***Determine optimum foundation drainage practices.*** Foundation drainage is an important determinant of overall exposure to moisture. It is essential that rainwater and roof drainage be diverted away from the building perimeter to prevent leaks into basements or crawl spaces, or saturation of the ground around slab-on-grade construction. Many sub-areas are included in this topic, beginning with site development and rough grading, and extending to backfilling, compaction, finish grading and termination of downspouts. Houses that are very close together complicate the problem, as do sloping parcels that fail to divert water from the buildings. The possibility of gutter overflow due to obstruction (or lack of gutters) is another variable to be considered at the design stage, as is the best approach to compaction of backfill, since too much compaction can damage the foundation while too little can allow settlement over time that alters drainage patterns. The building code includes minimum requirements for slope away from the foundation, but these are not always achieved and may be frustrated by settlement. The research would investigate optimum backfilling practice (compaction as a function of soil type and backfill material), threshold criteria for site grading, and criteria for rainwater discharge through downspouts. Recommended practices would be developed for wet and dry climates, based on anticipated impacts on moisture intrusion and soil moisture levels at the foundation.

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Responsibility: Shared between the public sector, the building industry and material interests for concrete and masonry.

Cost: Medium.

Time: Medium.

- ***Develop guidelines for building material moisture content prior to building enclosure.*** Some building materials including framing lumber and wood panels naturally contain moisture that may dry out early in their service lives. Others become wet during construction, are naturally wet (fresh concrete) or are even applied wet intentionally (wet-spray cellulose). In most situations this is not a problem, but it is possible for a wall or an entire house to be closed up while materials are overly wet. If they remain damp for prolonged periods, mold growth is possible. Drying through dehumidification or desiccant systems is possible, but expensive, and the question remains "how wet is too wet?" The problem is most serious in the Pacific Northwest, where high humidities and rain can continue for days or weeks on end. The goal of this research would be to develop guidelines for how dry moisture-sensitive building materials should be before they are enclosed from the outdoor weather or within unventilated assemblies.

Responsibility: Public sector and material interests.

Cost: Unknown.

Time: Unknown.

- ***Assess the drying performance of typical wall systems in U.S. climates and disseminate the results.*** Occasional bulk water leakage into walls is difficult to eliminate, but (most) walls also have an inherent ability to dry. The drying performance of a wall is a function of many climate and construction variables. There has been extensive Canadian work to test and model the moisture performance of exterior walls (the "MEWS" project), which has included modeling in various U.S. climates. Unfortunately, the results can be hard to interpret because they are based primarily on modeling, and are often characterized as relative rather than absolute. But even relative results can be useful in design. To be relevant, the testing and modeling needs to reflect current construction materials, and realistic indoor and outdoor moisture levels. It also must model air movement through walls, vapor diffusion, and moisture storage and release. Comparative rating of various wall systems in terms of drying potential and climate would be one very useful result, assuming differences of practical significance can be identified in such studies. If reliable ratings can be developed, then communicating the findings to building designers would be a valuable and important exercise. Work to date has included characterization of the performance of several common wall types (brick, vinyl and stucco claddings), and benchmarking of modeling tools to field results. In order to complete this process the testing and benchmarking should be extended to include other types of siding such as fiber-cement and wood products. Then modeling can be done to extend results to other climates, and comparative performance can be determined. This work will need to be revisited periodically as modeling tools evolve and underlying data sets become more complete.

Responsibility: Public sector, although broad-based material interests would probably collaborate.

Cost: Medium to high, depending on scope and required field work.

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Time: Medium to long-term.

Priority: This project was identified as very high priority by the Expert Panel.

- ***Develop educational tools to enable and certification programs to recognize good moisture control practices.*** One way to encourage builders and trade contractors to "go the extra mile" involves creating educational programs to raise awareness and communicate key information about good building practices, and reinforcing this with certification programs that document successful completion of a basic program of education. While there is a wealth of information on moisture control details and a growing body of "best practices," these are aimed largely at an audience with more education than the bulk of the construction workforce. Finding a method for packaging and delivering this information to users where it can do some real good presents a significant challenge. Certification represents one potential motivating force. Certification can be a marketable credential in a competitive environment, especially an environment that views moisture problems as a threat and moisture control as a priority. Some certification programs involve ongoing third-party oversight and can be difficult and costly to create and operate, while others simply attest to education and skill. These activities should be carried out in conjunction with private sector associations, possibly with some manufacturer sponsorship. Key tasks under this topic include: identifying key topics and compiling content, developing a delivery vehicle or vehicles, defining criteria for certification, putting a certification mechanism in place, and promotion.

Responsibility: Public-private.

Cost: Low to medium.

Time: Medium.

Priority: This project was identified as very high priority by the Expert Panel.

4.2 Improve Moisture Protection Through Codes and Standards

- ***Review current building code flashing and overhang requirements, and develop code changes to fill gaps.*** As codes have become more "performance oriented" they have stripped out information about traditional building envelope detailing intended to prevent moisture problems. It is hard to see just how this has improved building performance, but much easier to imagine how it may have contributed to problems. An alternative, much more informative approach is represented by documents such as the 1958 FHA *Minimum Property Standards*, and *Wood Frame House Construction* (USDA Handbook No. 73). The possibility of incorporating improved concept details for envelope flashing and simplified design recommendations for roof overhangs into building codes deserves close consideration and appropriate follow-up. While any resulting code changes should not limit innovation, evolution in the code should not undermine the use of traditional practices.

Responsibility: Public sector.

Cost: Low.

Time: Short time to develop changes; uncertain time to incorporate changes into codes.

- ***Develop gutter scoping requirements and design criteria for pitched roofs.*** Working gutters and downspouts are a critical line of defense against foundation moisture problems in large parts of the country. Lack of gutters causes problems ranging from wet basements to foundation wall failure. Clogged downspouts or clogged gutters due to lack of maintenance

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result in overflows with similar consequences. Yet the *International Residential Code* has no requirements for installing gutters on pitched roofs, and no placement or sizing requirements for downspouts. This project would identify criteria for determining when gutters should be installed, information on proper attachment and detailing at the roof edge, a methodology for placing and sizing downspouts, and criteria for drainage at ground level. It would also compile information about different ways to protect gutters from accumulation of debris that impedes or prevents performance. Some of this information may be available in state or local building codes, or scattered throughout other publications.

Responsibility: Public sector, together with producers of gutter guard systems.

Cost: Low.

Time: Short.

- ***Clarify requirements for crawl space ventilation and moisture protection design details.*** The problem of how to build dry crawl spaces consistently has been debated for decades. Much of the discussion has focused on whether crawl space ventilation is necessary, although several other factors clearly can contribute to moisture problems. Typical code requirements for fixed ventilation openings are said to be antiquated or unsubstantiated, based on successful experience with unvented crawl spaces in a few climates. There is no long-term U.S. experience with unventilated crawl space construction (outside of parts of Alaska where such designs are more common). It is clear that ventilated crawl spaces can and sometimes do experience serious moisture problems, but it is not known whether this results from ventilation or from other factors including poor site drainage, release of water vapor from the ground, or marginal hydrologic conditions at the site. Thus far there is no accurate way to predict which crawl spaces will perform satisfactorily and which will not. Changes to the *International Residential Code* approved in 2004 are intended to simplify the use of unventilated crawl spaces, yet the requirements are exacting and performance-oriented which will not facilitate their use. There remains a continuing need for testing, monitoring and demonstration of crawl spaces with and without ventilation, positive drainage and other moisture protection strategies to identify the essential site, design, and construction details for acceptable performance. There is also a potentially important role for modeling in extending this research, given the high cost and long time required for field demonstrations, assuming that models can be shown to accurately predict failures that occur in practice.

Responsibility: Public sector.

Cost: Medium.

Time: Medium.

4.3 Detect and Correct Moisture Problems Before Serious Damage Occurs

- ***Develop inexpensive, unobtrusive moisture sensors and data collection devices.*** Some destructive moisture problems involve slow, hidden processes in concealed spaces that can continue for years before they are discovered. For example, there is no simple way to monitor wall cavities for moisture intrusion or internal condensation. The same is true for concealed water pipes, which can drip or leak slowly for months or even years before causing visible damage. By that time the mold is established, the wood is decaying, the insulation is saturated, the paint is peeling, etc. Early detection and repair is usually the most economical way to deal with these problems. There is ongoing work to develop non-destructive methods

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for sensing moisture (or even mold) in building assemblies, using broadband radar and other means. These tools will be useful for diagnostic work and home inspectors, but they will also be expensive and require expertise. The miniaturization of electronic components for sensing and data storage makes another approach feasible. Very small devices could be placed to measure temperature and relative humidity and log the results for entire seasons. Such devices could be placed into a wall below a window, beneath plumbing connections for a tub or shower, or just in a crawl space or attic. Once removed, the data could be downloaded and scanned very quickly for any indication of moisture intrusion or systematically elevated humidity.

Responsibility: Private sector.

Cost: Low.

Time: Short.

- ***Promote the development of technology for passive detection of moisture problems.*** As an extension to the previous item, it seems clear that the ideal method of monitoring and detecting moisture problems (especially in concealed spaces) would be completely passive, requiring no intervention by the user but providing a warning when conditions warrant. One example is an air conditioner condensate pump with an overflow switch that shuts off the compressor before allowing condensate spillage. In terms of detection, for less than \$20 a consumer can already buy a battery-powered thermometer with a wireless remote temperature sensor that has a 100-foot range. Up to three temperature sensors can be used with a single base station, and relative humidity sensing could easily be added. It might also be possible to use active RFID tags (chips with antennas and an embedded power source) to send distress signals when crawl spaces or wall cavities become excessively damp. There is ample room for other approaches. The key is for the user to be notified of hostile conditions automatically, rather than relying on destructive inspections or diagnostic equipment used by experts.

Responsibility: Public-private. The private sector has a role because this could lead to marketable products.

Cost: Unknown.

Time: Unknown.

- ***Create and publish a model building envelope maintenance and repair guide for owners and property managers.*** It is not realistic to think that improved design and construction practices will eliminate all moisture problems, especially as buildings age. Responsibility for preventing and correcting problems ultimately falls on the owner or property manager, who may not fully appreciate the issues or understand the best approach to any particular situation. A building envelope maintenance and repair guide directed at this audience should include (1) a schedule of generic inspection procedures with recommended frequencies, (2) information about how to correct problems identified during the inspection or when to bring in a specialist, and (3) a troubleshooting guide for identifying the cause of known or suspected water intrusion problems. As a supplement or alternative to a printed guide it would also reasonably straightforward to develop and deploy a "moisture problem troubleshooter" over the internet. Such a tool would allow users to identify a problem, then probe them with questions to narrow down potential causes, and finally present information

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about possible approaches to remediation, with advantages and disadvantages of each. Given that one problem can have many causes and one cause can lead to many problems, a publication with a linear structure would be highly repetitious. Use of hyperlinks in a web-based tool provides a simpler way to tailor information to the user's specific situation.

Responsibility: Public-private. Numerous product, material, financial and insurance interests have a stake in this activity.

Cost: Low.

Time: Short.

4.4 Use New Technologies to Reduce Vulnerability to Moisture Damage

- ***Introduce improved structural and finish materials that are resistant to moisture and decay.*** Over time, building products have evolved or new products have been introduced in order to address moisture problems. Vinyl siding is a good example; it is essentially invulnerable to moisture and has largely replaced wood-based siding products which require rigorous maintenance or they will decay or rot after sufficient exposure to moisture. Cement-based panels, treated lumber and membrane roof underlayments are other examples. In terms of current products, gypsum board is just one obvious example where improved resistance to the detrimental effects of moisture could be highly beneficial. Paints are another; paints that adhere more tenaciously to damp substrates would greatly reduce maintenance requirements. The potential research needs in this area should focus on evaluating the overall performance of new or alternative materials that are proposed because they appear to be more resilient in the face of on-site moisture. Systems for treating framing and truss lumber to enhance resistance to mold would also be beneficial to lumberyards, builders and buyers. Assessments of alternative products should consider moisture, structural, fire, thermal performance and toxicity (depending on the particular item) as well as other practical considerations like cost, installation issues, and integration with other building materials.

Responsibility: Private sector firms.

Cost: Moderate for incremental improvements; high for major product changes.

Time: Ongoing.

- ***Validate the performance benefits of a "smart" vapor retarder, and work to promote appropriate use of improved vapor retarder technologies.*** A vapor retarder that exhibits low permeance under dry conditions and much higher permeance under damp conditions ("MemBrain") is now commercially available in the U.S (it has been marketed in Europe since the 1990's). In cold weather the product is designed to function much like a conventional vapor retarder, blocking vapor diffusion from inside the house into the wall cavity. However, during hot weather it would permit a damp wall cavity to dry towards the indoors. The product can also be used in mixed-humid climates where conventional vapor retarder placement is problematic, but it is not recommended for hot-humid climates. This technology should be studied in real-world applications to see if its benefits can be demonstrated, or if they are merely theoretical. Other approaches to smart vapor retarders (e.g. one-way vapor transmission), as well as the general question of optimal vapor retarder properties, also merit investigation. For example, if a membrane that only allowed vapor transmission in one direction could be commercialized, then it could be installed on both

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sides of a wall in any climate and positioned to allow drying from the inside in either direction. This would resolve many problems that arise today.

Responsibility: Private sector.

Cost: Low to medium.

Time: Medium.

Priority: This project was designated high priority by the Expert Panel.

- ***Determine feasibility and cost of residential air-conditioning systems capable of meeting latent loads under part-load conditions.*** The oversizing of air conditioners is widely cited as a contributor to moisture problems in hot weather, since an oversized system will meet sensible loads and cycle off before extracting sufficient moisture from the air. The result is a cool house with high humidity. But even a "properly" sized system can experience similar problems when operating below design outdoor temperature; in effect under those conditions it performs like an oversized system. As a result, removing humidity on days when temperatures are only slightly elevated can require cooling the house to an uncomfortable degree, even with a properly sized system. Reheating the output air can be done, but only at a high energy penalty. Campaigns to discourage equipment oversizing have been attempted with limited success since there are evidently institutional reasons for oversizing equipment. In much of the U.S., the trend to include mechanical ventilation may only increase latent loads and make the problem worse. Engineering solutions to the latent load problem deserve to be investigated. If the latent capacity of equipment cannot be increased then supplemental dehumidification in some form seems logical, but it needs to be integrated with operation of the air conditioning. The ideal technology would provide satisfactory dehumidification and cooling under the whole range of load/operating conditions, not just at design conditions. An interim approach would be to use a stand-alone dehumidifier with combined controls so that the air conditioner runs to meet sensible loads, while the dehumidifier runs to meet latent loads once sensible load is low or nonexistent.

Responsibility: Private sector HVAC firms.

Cost: Medium to high.

Time: Medium to long.

- ***Work to ensure that expanded use of mechanical ventilation systems helps reduce rather than worsens moisture problems.*** Endorsements of mechanical ventilation have come from many corners. Mechanical ventilation is often cited as a way to improve indoor air quality, and to prevent moisture problems, although this view is not universal and the practice is not yet mainstream in low-rise residential construction. It is clear that the use of different types of mechanical ventilation systems seems likely to grow as builders move to market "healthy" features in homes, and as codes and standards evolve. And while ventilation systems can dilute indoor moisture levels under some conditions, they can also have the opposite effect, creating or worsening moisture problems. Several needs that could be addressed by research are apparent. For example, Chuck Murray of Washington State University Energy Extension points out that experience to date suggests that system designs have to be particularly simple if they are to be installed correctly and perform reliably. This suggests a need for systems that come pre-wired and do not require connections of multiple components in the field, even if this limits performance. Design tools integrated with HVAC load calculations are also

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needed, since a ventilation system can dramatically affect load. Performance monitoring systems would help ensure proper ventilation that improves (or at least does not compromise) moisture performance, given that uncontrolled operation can unnecessarily humidify homes and increase moisture loads. Finally, it would be very helpful to have a greater understanding of when and how mechanical ventilation systems can be retrofit into existing houses in order to address existing moisture problems.

Responsibility: Public-private. Many public agencies advocate use of these systems, and private entities benefit from their use.

Cost: Low to moderate.

Time: Short to medium.

- ***Develop a mold resistance rating and associated moisture performance test procedures for air handling equipment.***¹ The accumulation of moisture in concealed spaces is a general concern in building science, but most of the emphasis in housing has been on building cavities. One very common concealed space that warrants special concern, especially in humid southern climates, is the air handler of a forced-air HVAC system. This environment is not only dark, damp and concealed from view, it also becomes wet during the cooling season from condensate removed from humid air during normal operation. Under some circumstances this can add unnecessarily to humidity in the output air stream. It can also allow biological contaminants to become established in the air handler and be spread throughout the house whenever the fan runs. Differences in energy performance are captured with standardized efficiency ratings, but at this time consumers have no easy way to tell how well different units collect and dispose of moisture extracted from the air.

A whole range of variables determine the vulnerability of an air handler to internal moisture problems. Examples include spacing of fins on the A-coil (tight spacing impedes drainage), the extent to which the fan tends to blow water off the A-coil into the duct system rather than allowing it to drain, the efficiency of condensate drainage, the efficiency of air filtration that prevents dust from accumulating in this part of the system, the presence or absence of a time delay relay that keeps the fan running after the compressor shuts off (thereby improving SEER but also delivering more humid air), or a similar relay to delay turning on the fan until after the compressor has run for a short time (improving latent capacity), and the presence or absence of fibrous internal surfaces that can encourage biological growth in the air handler. Some of these variables involve trade-offs between equipment efficiency and moisture performance. The research challenges here include development of test methods that will accurately assess different aspects of moisture performance of an air handler, devising a generally acceptable way of combining multiple indices of moisture control into a single index (e.g., a scale of 0-20) that can be easily communicated to and understood by the consuming public, and applying these methods in an environment of "mix and match" equipment and site-fabricated ducts. Associated topics include development of equipment designs with better ability to handle moisture or, to the extent moisture control remains problematic, incorporation of technologies that prevent the moisture from fostering biological contamination (e.g. UV irradiation or anti-microbial surface linings).

¹ Suggested by Dr. Subrato Chandra.

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Responsibility: Public sector, in collaboration with HVAC equipment manufacturers and associations.

Cost: Medium.

Time: Medium to develop, long to implement.

Priority: This project was designated high priority by the Expert Panel.

5. Realize the Potential of Moisture Modeling Tools

5.1 Fill in Data Gaps that Limit Modeling Accuracy

The physics that underlie moisture modeling are relatively well understood, but the output of a model is only as accurate as the input data. At present there are several types of input data that are poorly defined, which creates ambiguity or uncertainty in interpreting modeling outputs.

- ***Compile specialized weather data sets.*** There are many gaps in the weather data that will ultimately be necessary for accurate modeling of key phenomena such as wind-driven rain around the U.S. This requires high-resolution data on coincident wind speed, wind direction and rate of precipitation. The kinds of extreme events that may play a large part in water intrusion are probably poorly captured even by hourly data based on averages. This is problematic because when leaks occur they can easily dwarf moisture contributions of humid air or vapor diffusion.

Responsibility: Private sector (ASHRAE), with public sector support.

Cost: Low to medium, depending on scope, resolution and number of locations.

Time: Medium for initial development; further refinement will be needed over the long-term.

- ***Develop statistically validated procedures to assess internal moisture loads for use in hygrothermal analyses and related engineering studies.*** One component of this research is documenting internal moisture load profiles for U.S. houses. The amount of moisture released by normal occupant and household activities must be used in order to model the overall moisture balance of the building. There is very little field data available on this question, but modeling suggests that the difference between best case and worst case can correspond to a building that functions acceptably versus an impending disaster. Field measurements of moisture generation and levels are needed to provide improved data. The results of field studies should ultimately be incorporated into consensus standards as a way of ensuring they are used consistently throughout the modeling and design communities. The standards should specify internal loads, address the proper treatment of combination of loads, and specify whether and when to model using "worst case" loads, "best case" loads, "average" loads or some other variation. These steps would not only be of value for modeling, they would go far towards putting the emerging science of "moisture engineering" onto a sound basis.

Responsibility: Public sector.

Cost: Medium to develop data.

Time: Medium for data gathering, long for standards development.

Priority: This project was identified as very high priority by the Expert Panel.

- ***Development and maintenance of material properties by industry for use by designers.***² Some published data exists (ORNL, Canadian, ASTM) but there are no consensus properties and few labs equipped to do the relevant testing. The relevant parameters are not widely used, e.g. curves relating moisture absorption and release to ambient humidity. Developing a database through centralized testing is labor intensive, slow and costly. What is needed is a system where it is the responsibility of manufacturers or trade groups to measure and

² Suggested by Andre Desjarlais and Dr. Achilles Karagiozis.

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disseminate information about moisture-related performance properties of their materials. These properties would then be used in design by moisture-modeling software. The analogy is to structural performance properties, as well as thermal performance values, both of which are routinely obtained from manufacturers.

Responsibility: Private sector.

Cost: Low to medium.

Time: Short to medium, depending on capacity of qualified test laboratories.

- ***Generate information on the "aged" properties of common building and insulating materials.***³ Most of the current models deal with idealized assemblies based on the performance properties of new materials. They have little or no ability to analyze how performance changes over time as materials undergo cycles of heat and cold or damp and dry, and degrade with age and the passage of time. Obviously most systems will perform very well when they are new. They may perform very differently after five, ten or twenty years of exposure to the elements. And once deterioration sets in, it may be a rapidly accelerating process. Of course, while it is straightforward to test properties of aged materials, deterioration is by its nature very difficult to model accurately.

Responsibility: Public-private.

Cost: Medium to high, depending on number of materials and variations.

Time: Medium.

5.2 Demonstrate Robustness and Extend Modeling Capabilities

- ***Strengthen validation studies and incorporate consensus standards for accuracy.*** Numerous simulation tools have been developed. Most have been abandoned or are no longer supported; they served a research need at a point in time, but have no lasting value. Of the tools that are currently available, notwithstanding claims of being "easy to use", most or all have a very steep learning curve and a few are effectively unusable by anybody but the developer. Where validation has been attempted this usually involves lab tests under idealized conditions. Not only does this not necessarily imply accurate results in real-world applications, such results are particularly hard to interpret because there are no recognized standards for what constitutes "validation", i.e. how accurate is "good enough"? Before users will voluntarily rely on modeling outputs for making important decisions, they will demand better evidence that the results are meaningful. This task is naturally an ongoing one, since models are constantly being revised, updated and extended.

Responsibility: Public sector. Model developers typically perform these studies.

Cost: Medium.

Time: Medium.

- ***Establish "threshold" values for temperature, relative humidity and duration to initiate biological, chemical and mechanical damage of building materials and components.***⁴ While experience has shown that buildings can easily survive brief excursions into temperature and moisture regimes that would be destructive if sustained over prolonged

³ Suggested by Dr. Kumar Kumaran.

⁴ Suggested by Dr. Kumar Kumaran.

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periods, there are no generally accepted criteria specifying how much is too much, and how long is too long. These criteria, which could be developed with input from microbiologists and material scientists, can be used to "filter" modeling outputs, i.e. identify modeling results that include combinations of conditions likely to lead to destructive outcomes. Using combinations of criteria is less conservative and probably much more accurate than interpretation based on single-variable rules of thumb, e.g. whether or not condensation occurs at design conditions (since short-lived condensation may not cause any damage at all), or whether peak relative humidity inside an assembly exceeds 70 percent. The criteria may also be useful outside the modeling community, as part of an overall framework for moisture engineering in design that parallels accepted approaches to structural engineering, and they would be a valuable resource for manufacturers seeking to develop high-performance products.

Responsibility: Public sector with input from product manufacturers.

Cost: Low to medium, depending on scope and testing required.

Time: Short for basic criteria.

- ***Develop a generalized approach to determine cladding pressure differential for purpose of cladding structural and rain-penetration design.*** The pressure difference across the cladding is not just an issue in structural design for wind load resistance, it is also an important modeling parameter for determining the degree to which pressure differentials drive rainwater past cladding and into wall assemblies. This is a complex but important part of the overall moisture equation; many sources suggest that far more water can enter walls through this type of method than through air flow or vapor diffusion. A computerized method has been developed in Canada ('RAIN' model by NRC-IRC). As with hygrothermal material properties, test methods are necessary to determine how pressure differences vary with wind speed, direction and other parameters. Then a range of assemblies (ideal and real world) should be tested or monitored to benchmark modeling of pressure differentials across claddings. Monitoring and measuring of this type could be included in the wall system testing programs that are currently underway. This could be done inexpensively using existing demonstration buildings. Laboratory testing is another approach, which would require a test protocol that should ideally be developed in light of field data from demonstration homes.

Responsibility: Private-public. Trade associations and manufacturers should lead these efforts, which are relevant to structural design as well as moisture penetration.

Cost: Medium to high.

Time: Medium.

- ***Develop stochastic moisture models using probabilistic outputs (ranges) to reflect errors due to weather (external loads), material variations, and internal load variations.***⁵ Current moisture models treat physical outcomes as deterministic, rather than probabilistic, phenomena. This means they provide no information to users about the inherent level of uncertainty in modeling results, uncertainties that reflect variability in factors such as material properties, workmanship, external loads and internal loads. Explicitly modeling key inputs as random variables would support developing results as ranges or bands rather than

⁵ Suggested by Dr. Achilles Karagiozis.

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point estimates. This would highlight some of the uncertainty inherent in attempting to analyze moisture, and help users distinguish meaningful differences from small, unimportant differences. The research challenges are to identify and characterize the major sources of uncertainty in the modeling, and coping with the computational demands of monte carlo approaches that would likely be required to determine how the uncertainties propagate into modeling results.

Responsibility: Public, as with model development in general.

Cost: Medium.

Time: Medium.

Priority: This project was designated high priority by the Expert Panel.

5.3 Translate Modeling Results into Practice

- ***Use models to develop design guidance and disseminate the results.*** Current models tend to be complex, difficult to use and hard to interpret, or so simplified that their results may be unreliable. Experts can make good use of state-of-the-art models, but typical building designers face a much greater barrier. In the near term, models can be used by the experts to do comparative studies of building assemblies, reducing or eliminating the need for field testing. This is best done when some baseline field results are available that can be used to benchmark or calibrate the model. Modeling then provides a quick, efficient tool for extending results to other geographic locations or climates, or to address small variations in building construction or materials. Results can be condensed into simplified guidance for practitioners about when particular types of assemblies work well, or which assemblies are most resistant to moisture accumulation. One specific application of this topic was previously discussed in Section 4.1 under "Assess the drying performance of typical wall systems in U.S. climates and disseminate the results."

Responsibility: Public sector, possibly in cooperation with affected product interests.

Cost: Medium for modeling; higher if field testing is also required.

Time: Medium for modeling; longer if field testing is also required.

- ***Use models to identify optimum properties of specific building materials.***⁶ Moisture modeling tools have been developed to assist researchers and designers in understanding how different types of structures respond to moisture loads. The goal has always been to model these phenomena as accurately as possible. Yet once a model is developed, it can often be used to answer a related question: what are the "ideal" properties of different building materials. In effect the model can iterate through different possible properties of a given layer, such as a vapor retarder and find the combination of properties that demonstrates the best resistance to moisture. Once these properties are determined, they can be shared with material scientists who may be able to modify their current products to more nearly approximate the ideal. This approach could be useful whenever the ideal properties are reasonably stable or invariant to small changes in other components and modeling inputs.

Responsibility: Public sector, since intimate knowledge of the models is required.

Cost: Low to medium.

Time: Short.

⁶ Suggested by Andre Desjarlais.

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- *Integrate models tightly with standard design tools.* In the medium to long term, if modeling tools are to improve the design of specific buildings they must be far better integrated with the standard design (CAD) software tools used by the design community. In other words, the moisture analysis software must take little or nothing more than a building design file (with the building in a given orientation and geographic location) as input, analyze the susceptibility of the design to moisture problems, and present results to the designer without requiring additional steps or input data. Then the analysis can be done in the background, without any request by the user, let alone specialized knowledge. Even this may be of little value if the software cannot also present suggestions for design improvements to improve moisture tolerance. This problem has been recognized in other contexts; for example, several years ago there was an effort to improve integration of energy analysis software with design software through the use of object-oriented CAD techniques. See, for example, <http://eetd.lbl.gov/Search.html>, and <http://gaia.lbl.gov/vbe/>. Unfortunately, most CAD programs do not model using 3-D objects, and some use proprietary file formats. For these and other reasons, little progress seems to have been made in this area.

Responsibility: Public sector, ultimately becoming a shared public-private activity.

Cost: Medium to demonstrate the concept.

Time: Medium to demonstrate the concept.

APPENDIX A

LITERATURE REVIEW AND ANALYSIS

APPENDIX A: LITERATURE REVIEW AND ANALYSIS

A.1 Introduction

Moisture is commonly regarded as the single greatest threat to durability and long-term performance of the housing stock. Excessive exposure to moisture is not only a common cause of significant damage to all types of building components and materials, it also can lead to unhealthy indoor living environments. Some of the more serious effects resulting from moisture problems in houses include:

- decay of wood and corrosion of metals
- infestation by termites, carpenter ants and other insects
- negative impacts on indoor air quality
- the growth of mold and mildew
- reduced strength in building materials
- expansion/contraction damage to materials
- reduced thermal resistance of wet insulation
- premature failures of paints and coatings
- damage to building contents
- negative effects on building aesthetics

There is wide agreement that successful management of moisture in all its forms is essential for houses to be durable, safe, and energy efficient.

In recognition of the relationship between moisture and durability the Partnership for Advancing Technology in Housing, a public-private initiative involving the U.S. Department of Housing and Urban Development and a wide range of private organizations, commissioned this project. The focus of the project is on water problems due to leaks, condensation and water vapor in single-family houses, particularly detached houses of conventional light-frame construction in climates characteristic of the continental U.S. Both newly built and older homes are included. Multifamily low-rise buildings and other types of construction such as SIPS and steel framing are only addressed occasionally. The same is true of extremely cold or hot climates. Water damage from flooding of surface waters, while a major cause of property loss in its own right, is not specifically considered.

This Appendix includes a review and analysis of published literature on moisture problems in housing. It is organized as follows. Sections A.2, A.3 and A.4 review the literature and explain the various house systems implicated in moisture problems. Section A.2 deals with bulk moisture problems resulting from rain, snow, groundwater and similar exterior sources. It focuses on organizing and summarizing specific reference materials as they relate to different parts of the building or building system. Section A.3 is focused on water vapor, whether generated internally or admitted from outside, and the problems it can cause inside buildings and within building components. It too is loosely organized into wall, roof and foundation sections, as well as sections on the indoor environment and on moisture problems as they relate to HVAC systems. Section A.4 reviews recent reports and papers addressing the rapidly evolving field of moisture analysis models and software tools, both for the building designer and for the researcher.

The following steps were used in obtaining relevant literature to review in this report:

- Identify key documents addressing bulk moisture problems and water vapor problems
- Review key documents and identify additional references
- Conduct information searches including web-based searches, database inquiries, and targeted sources such as institutions known to be involved in moisture-related research.⁷

⁷ One particularly extensive collection of references to moisture research and numerous related topics can be found at: <http://alcor.concordia.ca/~raojw/crd/>.

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A.2 Bulk Moisture Problems

A.2.1 Introduction

This section of the literature review focuses on the topic of bulk moisture or water in liquid form and its effects on buildings. Bulk moisture is often considered in the literature to be the most frequent and widespread cause of building moisture problems. The primary sources of bulk moisture are external to the building and come from the climate (e.g. precipitation) and the earth (e.g., ground water). However, internal sources, such as plumbing leaks, are also considered bulk moisture. Note that bulk water intrusion can also contribute to internal moisture loads by way of evaporation and then transmission by vapor diffusion and air movement to other distant parts of the building. These effects are discussed below in Section A.3.

In building assessments, case studies, and surveys, bulk moisture problems are most commonly associated with rainwater and groundwater intrusion and the resistance of the building envelope system and materials to these sources of bulk moisture. The magnitude of a bulk moisture source (bulk moisture load) ultimately depends on two factors that are not changeable, namely climatic and site hydrologic characteristics. Therefore, bulk moisture loads and their effect must be controlled, managed, or resisted in a manner consistent with the climatic and site hydrologic conditions. This process is achieved through building design and construction by implementing a multitude of decisions, practices, and requirements. Sometimes these decisions are relegated to judgment and experience and in other cases they are regulated by building code and standards. In any event, the goal for building envelope design (including roof, wall, foundation, and site design considerations) has been to minimize the moisture load where possible and to prevent moisture intrusion or access to materials that are subject to degradation due to moisture. Conventional building envelope design practices for prevention of bulk moisture intrusion and accumulation are relied upon with the assumption that, in the event that water intrusion occurs, the problem will be promptly corrected or otherwise have a non-consequential or incidental effect.

Following the above logic, the Bulk Moisture part of the literature review is broken into four major sections. These sections are as follows:

Section A.2.2 General Literature surveys information on bulk moisture from commonly available sources that are used by designers, builders, consultants, manufacturers, and trades. The types of resources addressed include technical manuals devoted to the topic moisture, building codes, material and test standards, practice guidelines, and other documents that are generally intended to give technical and practical guidance. Thus, this section of the literature review is largely a broad survey of current practical knowledge that may typically affect the way that designers, builders, consultants, manufacturers, and trades approach their respective roles in the construction process.

Section A.2.3 Assessment of Bulk Moisture Problems reviews current understanding regarding the nature and extent of bulk moisture problems from the standpoint of actual experience. This section may be viewed as a “problem identification” exercise intended to place an appropriate emphasis on important causes and effects related to bulk moisture. The section includes examples of studies that are anecdotal or qualitative in nature, but gives special attention to those studies that provide quantitative information on bulk moisture problems.

Section A.2.4 Bulk Moisture Hazards focuses on sources of bulk moisture and their quantification in terms of potential moisture loads experienced by various parts of a building’s exterior envelop. Therefore, literature that addresses climatic conditions, extreme weather events, and ground and surface water characteristics is reviewed. This information is predominantly associated with environmental research or related studies.

Section A.2.5 Bulk Moisture Effects and Solutions addresses literature related specifically to knowledge on the performance (response) of a building’s exterior envelope systems in protecting against the effects of bulk moisture. The topical areas addressed include roofs, walls, foundations, flashings, sealants, and materials. This section attempts to focus on available quantitative research, but also refers to established building design and construction practices (or enhanced practices) addressed in the literature covered in Section A.2.2.

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Key findings or conclusions are summarized in Section A.2.6.

The authors emphasize that this part of the literature review is by no means exhaustive. Instead, an attempt has been made to identify important, accessible literature that addresses the specific scope of this overall literature review. Therefore, a preference has been placed on sources of information that are particularly relevant to typical one- and two-family dwellings and multi-family low-rise construction. The content of this part of the literature review reflects that focus. In some cases, multiple documents have been identified that essentially cover the same information. In these cases, either a representative document has been selected for inclusion or a list of similar documents is discussed as a whole. In addition, where an almost limitless set of building materials and methods may exist, those that are most common or representative of current residential construction characteristics are usually highlighted to provide a relevant example for the particular topic of interest. The section on standards is a good example where such a representative rather than exhaustive approach is taken.

A.2.2 General Literature

A.2.2.1 Authoritative Building Moisture References

There are several key moisture-related references that may be regarded as authoritative and comprehensive technical resources on the issue of building moisture. They also serve as repositories for building science research in relation to moisture, and are referred to at multiple points in this report. The primary audiences for these documents include researchers, designers, and building science specialists. Short reviews of four of these documents as they relate to the topic of bulk moisture follows.

- **ASTM, *Moisture Control in Buildings*, MNL 18, 1994.**

ASTM Manual 18, *Moisture Control in Buildings* [MCB, 1994] covers a wide range of issues, fundamental theory, concepts, material property data, climate data, research, experience, and supplemental references related to the occurrence and effects of moisture in buildings. In Chapter 5, climate data is discussed and presented, but it is recognized that there is “no single answer on what climate criteria to use for moisture analysis.” Rainfall or wind-driven rain climate data are not presented in detail, perhaps because there is not a means to use this information objectively as a practical design tool in the United States. In Chapter 8, moisture sources are discussed and available data presented. For bulk moisture sources, causes are discussed and plausible (or worst case) moisture loads are reported from select studies or by estimation. Construction moisture is also discussed (i.e., moisture stored in construction materials that will be released into the air as the materials equilibrate over the first couple of years in a new building). In Chapter 14, particularly severe cases of construction moisture problems are often associated with excessive wetting of materials by rain during the construction process. Additional case studies of building moisture problems in Chapter 14 focus predominantly on northern climate issues and suggest that moisture problems (including various manifestations such as window condensation, mildew on walls, and others more serious) are primarily related to problems in controlling indoor humidity levels. Therefore, it is concluded by the author that the tendency to focus on moisture in walls is misplaced. Ground cover in crawlspace foundations is emphasized in relation to limiting interior moisture vapor load. Apparently, little emphasis is placed on the role of water intrusion in moisture problems experienced by buildings.

Part III of MNL 18 addresses construction practices to reduce or control various types of moisture problems. In relation to bulk water, conventional practices are discussed (e.g., use of flashing and sealants, proper site grading, etc.). In addition, the rain-screen wall method is noted as a suitable solution for climates prone to wind-driven rain. Windows and doors are considered as major contributors to bulk moisture problems, mainly in relation to joint detailing (e.g., flashing and sealants) and window frame leakage. Recommendations include use of proper flashing and sealing details and specification of properly tested units. Moisture problems specific to other parts of the building are also discussed (e.g., roof drainage, ice dam prevention, foundation drainage and moisture proofing, etc.). For residential construction, the information is essentially identical to that found in another comprehensive reference, this one aimed at builders and designers, the *Moisture Control Handbook* (see below). Chapter 19 on remedial actions stresses the logic of a prioritized sequence for addressing moisture problems: (1) identify and reduce moisture source, (2) modify building envelope, (3) provide mechanical equipment and controls. It is also noted that the cost increases in this order. In many recommended practices, there is a lack of definitive guidance and understanding as to what extent certain practices are necessary (e.g., in what climate condition is a rain-screen

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wall needed to provide equivalent performance to other “conventional” wall systems in less severe climates). In other cases, the recommendations are clearly understood to be necessary from experience and sound logic (e.g., proper flashing of roofing and wall penetrations). Chapter 24 addresses codes and standards with some important observations: (1) a standard terminology for communicating moisture principles does not exist and leads to ambiguity and confusion, (2) there is little direct association between index test methods and in-situ envelop system performance in varying actual moisture loading conditions, (3) an uncontested and universal design guideline that is derived from and reconciles field and laboratory observations and experience is lacking, and (4) most of the referenced guidelines focus on moisture diffusion, insulation and infiltration, with little information on bulk water management. The ASTM E241 standard guide ("Standard Guide for Limiting Moisture-Induced Water Damage to Buildings") also covers similar information in a much-abbreviated but well-organized fashion.

- **Lstiburek and Carmody, *Moisture Control Handbook*, John Wiley and Sons, Inc., 1994**

The Moisture Control Handbook [MCH, 1994] is a revised and expanded version of a handbook developed under sponsorship of the U.S. Department of Energy. The primary focus of the book is on the design and construction of wall, roof and foundation sections to control moisture. While bulk moisture control is covered, the book pays a great deal of attention to methods for managing water vapor and avoiding problems resulting from vapor condensation and capillary movement. Early chapters discuss (1) moisture on interior surfaces and the relationship between condensation and mold/mildew problems, (2) the physical mechanisms of moisture transport in and around buildings, and (3) basic moisture-related concepts for use in the design of walls and roofs. Subsequent chapters present more detailed recommendations for moisture control in wall, roof and foundation assemblies with individual chapters devoted to heating climates, mixed climates, and cooling climates. The final chapter presents results of six "case studies" where specific moisture problems are investigated and causes diagnosed. Numerous diagrams and illustrations appear throughout the text, including many detailed construction sections.

- **ASHRAE, *ASHRAE Handbook 2001 Fundamentals*, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA, 2001.**

The ASHRAE 2001 *Handbook of Fundamentals* [HOF, 2001] is a well-established, widely known standard reference for the design of indoor environments. It primarily focuses on moisture from the perspective of vapor and its role in controlling the indoor environment. It gives a brief treatment of the effects of bulk water intrusion in Chapter 24 (Section 24.3), while recognizing that it is a frequent problem. Causes of water entry mentioned include foundation or roof leaks, wind-driven rain, and splashing rain. Poor flashing is also mentioned as often being a major cause. Only one solution each for the foundation and above-grade walls is briefly described: (1) remove rain water from the foundation with gutters, downspouts, and positive grading and (2) use rain-screen wall systems to minimize water penetration due to raindrop momentum, capillarity, gravity, and air pressure difference. Prescriptive conceptual wall and foundation details are also discussed and illustrated based on information in MCH. Prevention of burst pipes due to freezing is discussed in Section 24.14, although this is from the perspective of industrial applications. For agricultural applications, including wood-frame house construction, a comprehensive treatment of heating, ventilation, climate control, moisture protection, climate data, and many other structural and environmental design topics (beyond those addressed in *Fundamentals*) is found in the *Structures and Environment Handbook, Eleventh Edition* produced by a consortium of Universities, agricultural engineers, and the U.S. Department of Agriculture (**Structures and Environment Handbook, Eleventh Edition, Midwest Plan Service, Iowa State University, Ames, Iowa, 1986**).

- **HUD, *Durability by Design - A Guide for Residential Builders and Designers*, U.S. Department of Housing and Urban Development, Washington, D.C., 2002. [DBD]**

Durability by Design [DBD, 2002] contains comprehensive information about many different aspects of housing durability, with a primary focus on steps that designers and builders can take to create structures that successfully resist deterioration due to forces such as rain, ground water, sunlight, insects, decay and natural hazards. It is aimed at an audience of practitioners rather than researchers, focusing more on the practical than the theoretical. The document begins with an overview discussion of factors affecting durability and lists of common problem areas, most common warranty claims, and dollar expenditures for different types of maintenance and repair. The remainder of the document describes and explains a series of recommended practices to improve housing durability with respect to each of the following areas:

Ground and Surface Water

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Rain and Water Vapor
Sunlight
Insects
Decay and Corrosion
Natural Hazards
Plumbing, HVAC and Exterior Finishes

Methods to protect against bulk water intrusion through design and construction details (e.g. grading, guttering, flashing, overhangs) are dealt with extensively in this document, and related topics such as ventilation of crawl spaces and attics, vapor retarders and housewraps are also discussed at length.

A.2.2.2 Building Codes

Selected References:

- *International Residential Code 2003*, International Code Council, Falls Church, VA. 2003 [IRC 2003]
- *CABO One- and Two-Family Dwelling Code*, Council of American Building Officials, Falls Church, VA, 1995 [CABO 1995]
- *Minimum Property Standards*, Department of Housing and Urban Development, Federal Housing Administration, Washington, DC. 1958 [MPS 1958]
- *Recommendations for the Prevention of Water Intrusion and Mold Infestation in Residential Construction*, Texas Association of Home Builders, Austin, TX. 12/16/2001 [TAHB 2001]

Building codes have a direct influence on building material selections and building practices. For this reason, a general overview of the functional aspects of building codes in the United States is in order. This section provides background information about how building codes address (or do not address) topics such as bulk moisture. While some information about typical requirements of this type is included, the section is not intended to be a comprehensive review of building code regulations related to building envelope materials, systems, and installation.

Building codes provide minimum requirements for the purpose of public health, safety and welfare. While the primary focus is on life-safety concerns, aspects of durability are also addressed from the perspective of “fitness for use” and longevity. The interpretation of these goals in terms of building code content are influenced by a number of interests based on quantitative and qualitative decision-making factors. Model building codes serve as a model for building regulation and only become law once adopted as such by state or local governmental authorities. In general, they represent a “standard of care” and are often referenced for that purpose. However, they are often amended when adopted at local levels. Building codes also do not address all possible materials and methods of construction. Code officials often rely on other sources such as code evaluation reports and standards for alternatives. Finally, building codes also do not directly address all possible criteria for acceptable performance of products, materials, and assemblies used in construction. To avoid the voluminous information that this would require, model building codes make frequent reference to standards maintained by other standards writing organizations.

The most current model residential building code in the United States is the *International Residential Code* [IRC 2003]. It has been adopted with or without amendments in a large number of local political jurisdictions. The IRC draws extensively on several prior building codes, most notably the CABO One- and Two-Family Dwelling Code [CABO 1995], which in turn was based in part on predecessors, such as the HUD *Minimum Property Standards* [MPS 1958]. In this manner, experience is passed down and new criteria are incorporated through periodic development of “new” building codes and maintenance of existing building codes through a structured code development process operated by the organization(s) that publish a particular model building code. In addition, local code adoption processes generally also have a formal hearing process or committee to make decisions in regard to model building code adoption and local amendments. Thus, there are several opportunities for different interests, experiences, and opinions to influence the provisions of a locally adopted building code. Some states prohibit or otherwise regulate local amendments, while other states allow local political jurisdictions complete freedom.

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The situation as described above is relevant to the manner in which bulk moisture issues are addressed. For example, many issues in regard to protecting buildings from the effects of bulk moisture are “judgmental” in nature. Thus, disagreement often exists on the combination of moisture control strategies that should be considered as “minimum practice” in any given situation. In some cases, the building code provides options based on building official discretion or based on site specific conditions. For example, foundation drainage may not be provided (at the code official's discretion) provided that the foundation is placed on a naturally well-drained site. In other cases, local building code amendments may implement more conservative strategies that assume that all buildings are placed on “wet” sites (for an example, see Article 21 of the Anne Arundel County [Maryland] Code). These differences may be related to local experience, differences in level of risk aversion, or other special interests. For example, in reaction to growing litigation over the occurrence of mold in buildings, a series of moisture-related building code amendments has been adopted in the State of Texas that enhance a selection of minimum construction provisions found in the IRC. See TAHB 2001 for more information..

In some cases, building code requirements in relation to bulk moisture resistance are vague. One example is in the area of flashing where a list of typical conditions requiring flashing is provided and the goal of preventing moisture intrusion is mentioned, but specific details or illustrative guidance is not included [IRC, 2003]. This is an area where older building codes, (such as [MPS 1958]), appear to have provided a much greater level of attention and guidance on preventing bulk moisture intrusion problems. While reasons for the reduction of information in newer building codes in relation to this topic are not documented in the literature, the general desire to move towards performance-oriented requirements in the model codes may have played a part. Material property requirements for resistance to bulk moisture intrusion may be similarly vague. For example, a particular fastener or device may be required to be “corrosion resistant” without any indication of how this requirement is met. However, in most instances, specific test or material standards are referenced to address a particular minimum requirement. The topic of standards is covered in the next section. Installation requirements may be completely detailed or may rely extensively on approved manufacturers guidelines and accepted practice.

For products that are not specifically addressed in the building code provisions, code evaluation reports are usually required before approval for use is obtained at the level of local political jurisdictions. The model code evaluation services, now operating jointly as the ICC-ES (International Code Council Evaluation Service, Inc.), issue reports for approved products that have been evaluated under contract with a particular product manufacturer. These reports evaluate products relative to minimum performance expectations expressed in the building code. Note that final approval for use still remains at the discretion of the local building official. Sometimes these evaluations are based on "intent" of the code, while in other cases they are based on specific criteria or referenced standards drawn directly from the code. In the absence of clearly defined criteria in the building code or in referenced standards, the evaluation service may develop unique test requirements and pass/fail criteria. These requirements are then published as “acceptance criteria” and provide a means for subsequent evaluations to be performed on similar products. In some cases, the content of the acceptance criteria are eventually addressed in new or modified material standards. This process is one that follows the maturity and successful growth of products as they evolve in the building market. Various current acceptance criteria are found at www.icc-es.org. Many relate to building envelope products, such as Exterior Insulation Finish Systems (EIFS), that are currently available but which may only be briefly mentioned in the building code. There are exceptions to this rule, such as an acceptance criteria for fiberglass mat reinforced asphalt shingles (which seems to replicate information in building codes and standards, except in the matter of quality assurance requirements during production).

The issue of quality assurance for building products has its own network of requirements, certifications, and periodic audits conducted by accredited quality assurance agencies. These requirements may be specifically established in the building code, in referenced standards or in evaluation service acceptance criteria, or they may be less formal in nature. In the process of constructing a home using code-approved materials, quality assurance varies further according to the nature and rigor of governmental inspections. The model building codes provide guidance on required inspections for consideration in the local building code adoption process, but administrative practices such as these are frequently modified during the adoption process. Finally, many aspects of a home’s quality relate to the skill and business practices of the builder and the various trades involved, including detailing of requirements on construction plans, trade subcontractor scopes of work, worker training, and conducting internal inspections. Many states or localities, and some manufacturers, require some form of licensing or certification in an attempt to establish at least a minimum expectation for contractor skill and knowledge. However, the installation of building envelope

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components such as shingles, siding, flashing, and sealants are rarely subject to any significant scrutiny during the process of designing and building a house. Perhaps this is because building envelope features are determined primarily on the bases of architectural preference and appearance with the expectation that “if it looks good” and it’s on the market and code-recognized then it will also perform adequately without any serious consideration of the details required to ensure adequate performance or adequate support to construction quality control in the field.

A.2.2.3 Standards

Standards provide supporting information to building codes and are used by manufacturers and specifiers (designers) as a basis for establishing minimum testing and performance requirements for building products. Many (but not all) of the relevant standards are developed under sponsorship of the American Society for Testing and Materials (ASTM). There are many hundreds, if not thousands, of standards related to building products used in housing construction. Therefore, this section is not intended to be a comprehensive review of building-related construction standards. Instead, it provides a review of some representative standards and related information applicable to typical residential building envelopes and bulk moisture concerns. For this reason, many important building envelope material standards are intentionally not addressed (e.g., metal, brick, stone, slate, wood-based roofing and siding, fiber cement, etc.) to avoid greatly expanding the content of this review.

It should be realized that material standards and related test standards are developed for the purpose of establishing a relatively manageable means to evaluate the performance of a given product under a specified test condition. Often, the results are considered on the basis of “pass/fail” criteria and, at best, provide an indication of acceptable performance in actual use. However, they are indices which are only as reliable as the experience associated with a particular material in actual use. In this sense, they are not a replacement for actual experience, nor can they be considered as an absolute predictor of actual performance. While some test methods intend to test “representative samples,” actual conditions experienced in field installations are very difficult to replicate or anticipate in a laboratory setting. Therefore, index test results must often be interpreted in this context. Some of these issues are discussed in the following review of selected standards associated with asphalt shingles and underlayment, vinyl siding, and windows/doors/skylights, all very common residential building materials that serve important functions in regard to protecting a building from bulk moisture problems.

Selected Standards for Asphalt Shingle Roofing and Underlayment

- **ASTM D3462-03 Standard Specification for Asphalt Shingles made from Glass Felt and Surfaced with Mineral Granules**
- **ASTM D225-03 Standard Specification for Asphalt Shingles (Organic Felt) Surfaced With Mineral Granules**
- **ASTM D3161-03b Standard Test Method for Evaluating Wind Resistance of Asphalt Shingles (Fan-Induced Method)**
- **ASTM D4869-03 Standard Specification for Asphalt-Saturated Organic Felt Underlayment Used in Steep Slope Roofing**
- **ASTM D1970-01 Standard Specification for Self-Adhering Polymer Modified Bituminous Sheet Materials Used as Steep Roofing Underlayment for Ice Dam Protection**

The ASTM D3462-03 standard addresses the most commonly used asphalt shingle roofing product class using glass felt reinforcement mat. It provides for fire testing requirements, wind resistance, tear resistance, and other physical properties. Another similar standard, ASTM D225-03, addresses products with organic felt reinforcement mat that are usually recommended for use in cold or windy climates. These standards apply to asphalt shingle products with a minimum head lap of 2 inches which may be considered as a prescribed minimum resistance to water intrusion, along with minimum roof slope and underlayment requirements that are generally specified in the governing building code and by manufacturer installation requirements. Therefore, this standard does not address water intrusion testing. However, there is at least one local product acceptance standard that does address wind-driven rain penetration (i.e., Miami-Dade PA 100). Wind resistance requirements are based on the ASTM D3161 test

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standard with a 60-mph fan-induced wind speed pass/fail criterion. In recent model building code revisions, this test standard criterion has been increased to 110 mph for high wind zones (e.g., hurricane coastal areas) [IRC 2003]. Roofing underlayments, which are critical to long-term protection from roof leaks, are typically specified in accordance with ASTM D 4869-03 and, for special ice dam protection materials, ASTM D1970-01.

Selected Standards for Vinyl Siding

- **ASTM D3679-96a Standard Specification for Rigid Poly(Vinyl Chloride (PVC) Siding**
- **ASTM D4756 Practice for the Installation of Poly(Vinyl Chloride) (PVC) Siding and Soffit**

The ASTM D3679-96a standard addresses wind loading, impact loading, and various physical properties of PVC siding products. It also references ASTM D4756 (an installation practice standard) as well as mentioning manufacturer installation instructions. The D3679 standard does not address water penetration criteria or characteristics of products complying with the standard. However, the standard's wind loading criteria include reductions to account for air-permeability of the siding systems (although this particular provision is rejected by some local building authorities and HUD in regard to its manufactured housing regulations). This characteristic is synonymous with pressure-equalization effects considered important to the performance of rainscreen cladding systems that attempt to additionally limit water penetration through a cladding system by reducing inward driving pressure differential across the cladding due to wind effects. This characteristic of vinyl cladding, and other typical cladding systems, has been evidenced in recent wall system research addressed in Section A.2.5.

Siding underlayment as a secondary water barrier or drainage plane membrane is not always required by current building codes, but it is generally a recommended practice, particularly in rainy and wind-exposed building climates. A variety of water-resistant materials are used for this purpose including asphalt impregnated felts, building paper, building wraps (various types, also known as air-retarders), and water-resistant sheathing products. There are a number of standards addressing these materials. Because these materials also have different levels of vapor permeability, the selection of a siding underlayment should be coordinated with proper design of the wall for climate specific vapor pressure differentials. Even within material types, vapor permeability characteristics may vary considerably (see, for example, DBD 2001). For some materials, like asphalt-saturated felt underlayment, material standards require a water spray test to ensure that a sample does not allow water to diffuse or leak through the sheet; but, there is no requirement to test or maintain a specific range of vapor permeance (see ASTM D4869, discussed above under standards for roofing). In addition, vapor permeability data required in this standard is associated with a property of the underlayment itself and not the product as installed on a typical building application.

Selected Standards for Windows, Doors and Skylights

- **101/IS2/NAFS-02 North American Fenestration Standard, Voluntary Performance Specification for Windows, Skylights, and Glass Doors, Window and Door Manufacturers Association (WDMA)**
- **ASTM E331-00 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure**
- **ASTM E547-00, Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference**
- **ASTM E2112-01, Standard Practice for Installation of Exterior Windows, Doors, and Skylights**
- **ASTM E1105-00, Standard Test Method for Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Static Air Pressure Difference**

The 101/IS2/NAFS-02 standard is a voluntary performance standard sponsored jointly by the Window and Door Manufacturers Association (WDMA, formerly the National Wood Window and Door Association or NWWDA), the American Architectural Manufacturers Association (AAMA), the Canadian Window and Door Manufacturer's Association (CWDMA), and the Canadian Standards Association (CSA). It integrates several prior standards for

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windows, doors, and skylights that were once separate standards distinguished by window frame material (e.g., aluminum or wood). It also addresses vinyl windows which have become very popular in recent years. This standard establishes performance criteria for water leakage, air leakage, and deflections under pressure loading, and addresses other structural, serviceability, and durability issues. Other ASTM and CSA standards are also referenced.

The ASTM E331-00 standard is the most commonly applied standard for testing water penetration resistance of windows, skylights, doors, and curtain walls. Similar standards for cyclic pressure testing as found in ASTM E547 are also sometimes applied. In addition, a test standard to address water penetration under a “rapid pulsed” air pressure difference is being developed by ASTM. These standards, however, establish index pass/fail criteria that do not address all possible leakage paths resulting in water intrusion into a particular wall system under field installation conditions. Considered failure modes primarily address the manufactured unit performance itself. To address this issue as well as water intrusion problems associated with the installation of these manufactured units, a standard practice for installation of these products, ASTM E2112, has also been developed. This standard practice features numerous installation and flashing details for integrating units with various cladding and walls systems. The practices are generally developed with the mindset that at least an “incidental” amount of water leakage should be anticipated around or through window and door frames. Finally, the ASTM E1105-00 standard test method has also been developed for field determination of water penetration in installed units under a uniform or cyclic static pressure differential. This later standard may be used to evaluate a known leakage problem in the field or for the purpose of commissioning a new building construction.

A.2.2.4 Standard Guides and Practices

Selected References

- **ASTM E241-00 Standard Guide for Limiting Water-Induced Damage to Buildings**
- **ASTM C1193-00 Standard Guide for Use of Joint Sealants**

"Standard Guides" are documents published by standards-writing organizations that serve a unique role. They are not technically considered as standards suitable for reference in building codes or contracts, but rather are consensus-based guidelines or practices that are intended to represent current knowledge and recommended practices. Such guides are particularly relevant to topics like building moisture control where practices usually involve a blend of judgment, experience, and interpretation of established theory. A few relevant standard guides or practices are addressed in this section.

The ASTM E241 standard guide is intended to provide guidance for building design, construction, commissioning, operation, and maintenance for the purpose of limiting water-induced damage to buildings. It is most applicable to typical low-rise building construction. It does not provide actual material performance limits or moisture load criteria which are considered to be too variable, subjective, or not well understood to be of practical use. Instead the guide is conceptual and is based on knowledge largely gained by experience. It addresses definitions, key moisture sources and effects, design methods and concepts, moisture management practices, construction examples, and field check lists, often referring to other documents such as MCB 1994 and HOF 2001 for more detailed information. This guide is an excellent summary of important moisture considerations in building design, construction, operation, and maintenance. However, it is not a definitive tool for judging whether or not a particular building envelope system is acceptable or unacceptable. Such a tool, independent of experience and judgment that define the practice of building “arts”, does not currently exist.

Other standard guides and practices of interest in regard to wall envelope systems and moisture include:

- ASTM E2112-01 "Standard Practice for Installation of Exterior Windows, Doors, and Skylights"
- ASTM E1825-96(2003) "Standard Guide for Evaluation of Exterior Building Wall Materials, Products, and Systems"
- ASTM E2099-00 "Standard Practice for the Specification and Evaluation of Pre-Construction Laboratory Mockups of Exterior Wall Systems"
- ASTM E2128-01a "Standard Guide for Evaluating Water Leakage of Building Walls"

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In regard to sealants and flashing, various standards for metal, plastic, and membrane materials are available. However, information on how to incorporate these materials in various systems is widely dispersed. A significant amount of information is available from sources such as manufacturers, industry organizations, and architectural detailing manuals. In addition, flashing and sealant recommendations and details are featured in many other sources of literature, such as ASTM C1193 and the guides identified in the following section. In many cases, guidelines are conceptual in nature and must be “translated” to a specific application, building detail, or combination of materials and components.

A.2.2.5 Design and Construction Guides

Other useful and practical guidelines related to bulk moisture control include a number of industry recommended practice guides, texts, and government-sponsored manuals. Two good examples are the *Moisture Control Handbook* [MCH 1994] and *Durability by Design* [DBD 2001], both discussed in section A.2.2.1 above. A list of other resources is below. These guidelines are generally based on conventional practices, but may also include other information related to research, individual experience, and design theory. As a result, the objectives of these documents are similar, but the scope, detail, and level of recommended practice may vary. For example, the listed resources generally all agree that proper flashing of the exterior envelope is a major concern in providing protection against bulk moisture intrusion. However, the documents give widely varying levels of attention to this topic.

- *Controlling Moisture in Homes*, National Association of Home Builders, Washington, DC. 1987
- APA, Build-A-Better-Home Program, “Designing Roofs to Prevent Moisture Infiltration”, May 2001
- APA, Build-A-Better-Home Program, “Avoiding Moisture Penetration in Walls”, May 2001
- APA, Build-A-Better-Home Program, “Steps to Constructing a Moisture-Resistant Foundation”, May 2001
- *Moisture and Wood-Frame Buildings*, Building Performance Series No.1, Canadian Wood Council, Ottawa, Ontario, Canada, 2000
- *Design of Wood Frame Structures for Permanence*, National Forest Products Association, Washington, DC. 1988
- *Moisture Protection of Wood Sheathing: An Installer’s Guide*, NAHB Research Center, Inc., no date.
- *Moisture Control: System Performance*, United States Gypsum Company, 2003
- *Building Foundation Design Handbook*, Oak Ridge National Laboratory, DOE, May 1998
- *Wood-Frame House Construction*, Agriculture Handbook No. 73, U.S. Department of Agriculture, Forest Service, (US GPO: Washington, DC) July 1970 (slightly revised April 1975, extensively revised 1989)
- Verrall, A.F. and T. L. Amburgey, *Prevention and Control of Decay in Homes*, prepared for U.S. Department of Housing and Urban Development by Southern Forest Experiment Station, Gulfport, MS, 1978

Some additional unique features within the above construction guidance documents also deserve mention. In those documents presenting rain-screen wall cladding systems as a solution for wind-driven rain problems, guidance on flashing details necessary for proper execution around various types of wall penetrations is not addressed or even mentioned as a concern. Also, guidance on climatic conditions that provide a definitive means to determine wind-driven rain potential and appropriate action is limited to very few of the above documents, and recommendations are based mainly on the judgment of the authors. In some cases, exterior insulation sheathing products are recommended for reason of energy efficiency and potentially improved resistance to condensation in wall cavities, but little is mentioned in regard to consequences of water intrusion (and accumulation due to potentially lower drying potential of such a wall system). Varying degrees of action in terms of foundation waterproofing, dampproofing, and drainage are also addressed, but all agree on the important practice of providing adequate removal of roof drainage and surface water from the vicinity of a building foundation. Other factors addressed include the conventional wisdom of separating non-moisture-resistant wood materials from sources of ground moisture or rising damp through porous foundation materials such as concrete and masonry. Only two of the documents give quantitative recommendations in relation to designing roof overhangs to reduce bulk moisture loading on walls. In terms of a comprehensive approach to integrating moisture protection strategies with all other important building design and construction considerations, only one of the listed documents may be considered to take this approach. *Prevention and Control of Decay in Homes*, gives comprehensive treatment of the topic of protecting wood materials from moisture and provides additional evidence and support for the approach taken in older documents such as *Wood Frame House Construction* and MPS 1958. Also, *Controlling Moisture in Homes* (NAHB, 1987)

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gives an excellent summary of building moisture principles, problems, and solutions for a builder or trade audience. However, it would benefit from an update, including more specific guidance for various parts of a building related to causes of common moisture problems.

A.2.2.6 Miscellaneous Resources

A variety of articles, technical briefs, fact sheets, extension service bulletins, and other information address various aspects of bulk moisture and avoiding related moisture problems in homes. This type of information is readily found on the internet. A few examples are as follows:

- PATH/AHRC, Tips and Techniques, “Controlling Moisture in Homes”, May 2000, www.pathnet.org
- Clemson Extension Service Bulletin HL 239 “The Billion Dollar Thief: Moisture”, July 1991
- Clemson Extension Service Bulletin HL 254 “Controlling Moisture with Overhangs and Flashings”, April 1997
- Straube, John F. “Moisture in Buildings,” *ASHRAE Journal*, January 2002
- Zylkowski, S. and K. Hayes, “To Build a Better Home: Improvements in design and construction practices hold the key to moisture management, mold mitigation”, *Wood Design Focus*, Forest Products Society, Madison, WI, Summer 2003

These types of documents generally provide a cursory review of moisture issues and concepts. They also tend to provide a mix of actionable practices or solutions for various audiences including builders, designers, and homeowners. In some cases, however, the guidance requires experience and additional knowledge to implement except in the simplest of recommendations (e.g., clean gutters periodically, or call plumber to fix a plumbing leak). In other cases, the recommendations are directed to specific recommendations for new construction (e.g., use roof overhangs of minimum 3 feet or provide a 5% slope of grade away from foundation). Remediation of water problems in existing buildings is also a popular topic (e.g., restore proper surface and gutter water drainage around foundation). These documents are generally based on conventional experience, but sometimes suggest implementation of newer research findings reported elsewhere. For some issues such as crawlspace ventilation in humid climates, the recommendations may be in conflict with newer research findings (discussed elsewhere in this report).

Conferences, symposiums, and workshops provide an exchange of information and ideas in regard to bulk moisture issues and solutions and generally serve a “special interest” audience. There are several examples of such conferences and some may have published proceedings while others are less well documented. In most cases, there are relatively few such events that are dedicated especially to bulk moisture issues in building construction. One Workshop proceedings and one paper from another conference are discussed below.

- **NIBS/BETEC Workshop on Rain Penetration Control, June 13, 2002, www.nibs.org.**

This Workshop was conducted by the Building Environment and Thermal Envelope Council (BETEC) of the National Institute of Building Sciences (NIBS). Participants discussed rain penetration issues and research including topics such as rain screen walls, wind-driven rain, various wall design strategies, and moisture intrusion problems. Jacques Rousseau simplified the issue by commenting that designing to control rain penetration is “not rocket science.” By eliminating or reducing the moisture source (rain), leakage paths, and forces to drive water into the wall, problems can be avoided. The various classifications of wall design strategies in terms of rain penetration control were discussed: mass walls, cavity walls, face-sealed walls, and pressure-equalized rainscreen (PER) walls. One participant also simplified the issues being considered by commenting that most builder call-backs are related to rain penetration that the problems often appear to be associated with improper installation. The “4-Ds” of wall design were mentioned as key strategies to address moisture penetration: deflection, drainage, drying, and durability. One concern voiced in regard to rainscreen walls is related to identifying and repairing leaks should they occur, since the leakage problem would be concealed behind the rainscreen cladding which might need to be removed for repair or maintenance. Similarly, concerns about corrosion of components within the wall cavity, such as brick ties, were mentioned as a major concern. It was felt that many brick ties may only last about 30 years, whereas industry expectations are in the range of 50 to 100 years. Problems with EIFS wall systems, in relation to installation and related moisture intrusion, were also discussed.

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- **Carll, Charles, “Rainwater Intrusion in Light-Frame Building Walls, *Proceedings of the 2nd Annual Conference on Durability and Disaster Mitigation in Wood-Frame Housing*, November 6-8, 2000, Forest Products Society, Madison, WI.**

In this conference paper, the current state-of-the-art and issues related to rainwater intrusion have been summarized with a view toward developing a design rationale. Water intrusion is recognized as the primary source of durability concern related to moisture in light-frame construction. It is suggested that this has possibly become somewhat more important in recent years due to changes in building design (e.g., increased energy efficiency, reduced overhang, increased use of vulnerable architectural wall details, differences in durability of newer materials, etc.). However, the problems with water intrusion are related to the same factors that have always been present in building design, namely proper installation of materials, flashing, building exposure, and others. The author also recognizes that these factors are considered as a building “art” that is guided by conceptual knowledge, experience, and opinions of practitioners. As such, the terminology used is not consistent. In addition, there is no “established” methodology for designing light-frame buildings to resist damage from rainwater intrusion. No standardized methodology to characterize rain exposure of a given low-rise wall or building is available. Therefore, the general design principle and expectation is that water should not intrude into the wall as far as the framing members.

A.2.3 Assessment of Bulk Moisture Problems

A.2.3.1 Introduction

This section focuses on select literature that provides useful information regarding the nature and extent of bulk moisture problems documented in building case studies (qualitative) and representative samples of the housing stock (quantitative). In some cases, the data is obtained directly through visual assessments while in other cases the data may be obtained by indirect means such as surveys of builders or occupants. Quantitative data provides that greatest insight in terms of understanding the frequency of bulk moisture problems associated with various causes. Case study information usually complements this information with more detailed insights from one or more buildings, but with little information on how the observations may related to a larger sample of buildings or the housing stock as a whole. Relatively little information was found that focused primarily on roof system leakage and related bulk moisture problems. Information on water intrusion in wall systems was most abundant. Limited information was found in regard to quantifying the nature and extent of foundation water leakage problems, but case studies and indirect sources such as industry experience indicate that this moisture problem may occur more frequently than bulk water intrusion in the above-ground structure.

A.2.3.2 Moisture Damage Assessments, Case Studies, and Surveys

A wide variety of case studies found in the literature provide information on specific occurrences of moisture problems. Most case studies are anecdotal in nature and deal with a specific construction or a select group of structures that have experienced moisture-related performance problems. Only a few studies actually assess moisture damage in a representative sample of the building stock and in a manner that would allow for an objective characterization of the nature and extent of moisture problems. A large number of case studies of moisture problems are addressed or summarized in a few sources and many are related to indoor moisture problems and related effect of vapor transmission by air-leakage and diffusion. A few of the most relevant assessments and case studies related to the occurrence and significance of bulk moisture problems are summarized in this section.

- **Jacques Rousseau, *Rain Penetration and Moisture Damage in Residential Construction, Building Science Insight, National Research Council Canada / Institute for Research in Construction (NRC-IRC)*, [http://irc.nrc-cnrc.gc.ca/bsi/83-1.CMHC 1982](http://irc.nrc-cnrc.gc.ca/bsi/83-1.CMHC%201982) (based on *Moisture Induced Problems in NHA Housing, 3 Parts, Canada Mortgage and Housing Corporation. Report prepared by Marshall Macklin Monaghan Limited, Cat. No. NH20-1/2-1983-IE, ISBN 0-662-12662, Ottawa, June 1983*).**

This study was prompted by indications of moisture problems in CMHC-financed housing built between the years of 1973 and 1981 (689,000 total housing units representing about 35% of housing production in Canada during that period). Thus, the housing units ranged from 1 to 8 years old at the time of the study. Comments here are based on review of the published summary of the study, cited above.

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This study stands out as one of the most extensive and quantitative field studies found in the literature for moisture problems in North American, cold-climate housing. Moisture problems were classified into five different categories: (1) mold and mildew, (2) window condensation, (3) attic condensation, (4) condensation in wall cavities, and (5) exterior siding damage. Within these classifications, a rating of “serious” was described as follows:

Serious Condensation in Attic – wood moisture content exceeding 22% or mold and mildew growth covers more than 50% of the attic sheathing and roof joists.

Serious Wall Cavity Moisture – wood moisture content exceeding 22%

Serious Exterior Siding Moisture – buckling or warping of more than 50% of the wall area, or paint damage affecting more than 0.3 square meters

Based on the above categorization and rating of moisture problems the following geographic distribution of all “serious” moisture-related problems was found:

FREQUENCY OF SERIOUS MOISTURE-RELATED PROBLEMS BY LOCATION

Newfoundland	27.0% of 10,400 units
Maritimes	1.4% of 32,800 units
Quebec	0.7% of 164,000 units
Ontario	0.7% of 276,000 units
Prairies	1.4% of 135,000 units
British Columbia	3.0% of 71,300 units

The study concludes that there are at least 10,000 housing units in Canada which have problems serious enough to cause financial loss.

In cases where mold and mildew formation was involved, two primary causes were identified: (1) high indoor humidity (over 50%) and (2) cold wall surfaces. Mold and mildew problems were found across all climatic regions at the following frequencies:

FREQUENCY OF MOLD AND MILDEW PROBLEMS BY LOCATION

Newfoundland	3.0% of 10,400 units
Maritimes	0.6% of 32,800 units
Quebec	0.3% of 164,000 units
Ontario	0.4% of 276,000 units
Prairies	0.1% of 135,000 units
British Columbia	1.3% of 71,300 units

Window condensation problems included staining or damage to window sills, plasterboard edges below windows, rotted or moldy floor coverings below windows, corrosion of wall connections for baseboard heaters, rotting of wall framing, and freeze-thaw damage of masonry materials. Occurrences of serious window condensation problems by region or province in Canada were reported as follows:

FREQUENCY OF SERIOUS WINDOW CONDENSATION PROBLEMS BY LOCATION

Newfoundland	1.2% of 10,400 units
Maritimes	0.3% of 32,800 units
Quebec	0.2% of 164,000 units
Ontario	0.2% of 276,000 units
Prairies	1.3% of 135,000 units
British Columbia	0.2% of 71,300 units

The frequency of attic condensation problems was high for two types of climatic regions: (1) northern regions with very cold conditions and (2) coastal regions with milder, but more humid and prolonged winter conditions. The more severe cases were associated with the second climate condition. In addition, houses with attic condensation problems tended to have high indoor humidity levels. In cases with major attic damage, poor ventilation of the attic was a significant factor (e.g., covered or non-existent soffit vents). The observed frequency of serious condensation problems were reported as follows:

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FREQUENCY OF SERIOUS ATTIC CONDENSATION PROBLEMS BY LOCATION

Newfoundland	2.2% of 10,400 units
Maritimes	0.2% of 32,800 units
Quebec	0.6% of 164,000 units
Ontario	0.4% of 276,000 units
Prairies	0.7% of 135,000 units
British Columbia	2.7% of 71,300 units

Wall cavity moisture problems were mostly localized (e.g., elements near an electrical outlet often combined with moisture saturation of the sole plate and wall sheathing). Wall cavity moisture problems were associated with the following climate conditions: (1) cold temperatures especially in April and May, (2) high incidence of driving rain during winter and spring, and (3) high wind exposure. There was also a higher incidence of this problem in walls of the second floor, indicating possible contribution of indoor moisture transported by stack effect and air leakage. Unfortunately, frequency of wall cavity moisture problems were not given in the summary report and should be further investigated in the full report listed above.

Siding damage included buckling, rot, paint damage, and spalling brick. The Newfoundland climate was found to produce the greatest frequency of these types of problems (low temperature and windy during spring, high incidence of driving rain during winter and spring, and very little sunshine, especially during the spring). The frequency of serious moisture problems with sidings (of all types) were reported as follows:

FREQUENCY OF SERIOUS SIDING MOISTURE PROBLEMS BY LOCATION

Newfoundland	24% of 10,400 units
Maritimes	0.8% of 32,800 units
Quebec	0% of 164,000 units
Ontario	0.004% of 276,000 units
Prairies	0.04% of 135,000 units
British Columbia	0% of 71,300 units

It would be more helpful if, within the different regions, the frequencies were further categorized by siding type (e.g., wood lap, hardboard, brick, stucco, etc.). The original report should be investigated more carefully in this respect.

Two major causal factors for serious moisture problems are evident from the study: (1) high indoor humidity and (2) rainy/windy climate with low drying potential. With all other factors equal, removing the rainy climates from the data sets gives some indication of the frequency of moisture problems that are primarily related to high indoor humidity. In this scenario, about 0.9% of the sampled homes have “serious” moisture problems that are primarily related to higher than normal indoor humidity levels for various causes (e.g., inadequate ventilation, high internal moisture load) with various consequences (e.g. mold on cold wall or window surfaces, excessive condensation on windows, and internal wall condensation). Even so, the incidence of serious moisture problems (as defined in this study) for the non-rainy, interior climate regimes indicates that current design and construction practices result in about 99% of sampled homes without serious moisture problems. Conversely, considering only the coastal climates, the incidence of moisture problems is dramatically higher (e.g., Newfoundland at 27% and British Columbia at 3%) and is typically 3 to more than 20 times more frequent in these climates than in other inland climates. This comparison indicates the significance of rainy climates with low drying potential as a dominant source of building moisture problems.

This type of quantitative data is unusually valuable because it allows cost-benefit principles to be applied in addressing moisture problems for new and existing construction. However, such an approach has not been reported or investigated in the literature which generally tends to focus on anecdotal experiences and estimates of non-normalized or absolute damages (e.g., “study finds more than 10,000 homes with serious moisture problems” or “cost impact of \$7.5 billion/yr for roofing and wall system repairs”). The following discussion is hypothetical, but is included to make the possibilities clearer.

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Assuming the incidence of serious moisture problems for the non-coastal climates could be reduced by 50%, what added cost for new construction could be justified given the frequency of problems and estimated repair costs? Assuming the repair costs are the only costs associated with the moisture problems, and assuming the repair cost may be conservatively estimated to average \$10,000 per damaged unit, then for the 5,429 units with serious damage the repair cost may be conservatively estimated at \$54,290,000. Dividing by the total number of units (607,800) gives a value of \$89/unit associated with a 1 to 8 year period (about \$22/unit/year assuming the average age is 4 years). Thus, the actions taken on new construction to resolve 50% of the problem would need to provide a return equivalent to about \$11/unit/year of future expenditure. While the time value of money is not considered and repair costs have been conservatively assumed, this hypothetical analysis suggests that an initial expenditure of \$300 to \$500 dollars (e.g., present worth) may be justified if serious moisture damage problems can be reduced in frequency or severity by about 50% depending on the pay-back time period assumed. Depending on the causes, solutions within this price range could include a special inspection of attic ventilation, exterior flashing, and air sealing; a modest increase in window/door glazing R-value; owner purchase of a portable dehumidification unit (or humidistat controls on bath and kitchen exhaust fans) should indoor humidity levels approach 50% RH or more in a given unit; and/or provision for a building owners guide for rehab and maintenance of the building envelope.

The details of the foregoing calculation are not the point. The point is that a more objective process is needed for interpreting quantitative moisture damage information and placing reasonable economic constraints on actions to address what may appear as a large problem to some and a small problem to others. Such an approach should also consider regional climate and construction differences, potential litigation costs, and human health implications as appropriate to specific moisture related issues.

As with structural engineering, a goal of zero probability of failure is impractical and unjustified. Even for life-safety consideration, a theoretically low annual probability of failure is accepted for building design. For moisture-related “failures”, generally accepted limit states and exceedance probabilities have not been defined, and analytical tools and moisture load data are not developed to the point to provide meaningful assurances even if acceptable moisture limit states and exceedance probabilities were defined as performance goals. Additional work in this area will be necessary to gain maximum benefit from new modeling approaches and to identify prudent public policy.

- *Survey of Building Envelope Failures in the Coastal Climate of British Columbia*, Technical Series 98-102, CMHC, Ottawa, Ontario, Canada. 1998 (based on full report by the same title)
- *Comparative Analysis of Residential Construction in Seattle, WA and Vancouver, B.C.*, Technical Series 99-111, CMHC, Ottawa, Canada, 1999. www.cmhc.schl-gc.ca

Technical Series 98-102 reports findings of a study of 37 problem buildings and 9 control buildings (without problems), prompted by reported moisture problems with multi-family low-rise residential buildings in British Columbia. The study found that the primary source of moisture leading to performance problems was rainwater intrusion rather than interior sources of construction moisture. About 90% of the problems were associated with interface details between wall components at penetrations, including leaking window frames. Defective drainage membrane installation on balconies was also cited as a common cause. Of the cladding types observed, the problems were most prevalent with conventional 3-coat stucco siding (face barrier system). On average, vinyl siding was found to present the least amount of problem and lower repair cost (about \$1800 on average). Problem buildings with wood sidings were about 2 to 3 times more costly to repair than those with vinyl. Problems with conventional 3-coat stucco were nearly 5 times more costly to repair. The main differences between problem and control buildings were associated with wind exposure (control buildings were less exposed to wind-driven rain), size of overhang (control buildings had wider overhangs), number of architectural features (control buildings had fewer architectural features and more of these features were flashed), and siding material choice (fewer of the control buildings used conventional 3-coat stucco barrier system). Control and problem buildings were similar in the level of design detailing provided on the plans, indicating the importance of trade knowledge and installation care in preventing water intrusion problems. The study concludes that face-sealed siding systems are difficult to achieve acceptable performance in the field and that, in wind-driven rain environments, rainscreen wall assemblies offer the best opportunity to achieve acceptable performance. It also concluded that greater attention needs to be paid to water management principles (e.g., moisture entry, drying potential, and drainage) and that local climate conditions need to be taken into account when establishing effective water management strategies in construction.

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Similar findings appear in Technical Series 99-111 (cited above), which presents a comparison between multi-family low-rise buildings in Seattle, Washington and Vancouver, British Columbia.

- ***Wall Moisture Problems in Alberta Dwellings, Technical Series 00-112, CMHC, Ottawa, Canada, 2000***

In this study of residential buildings in the province of Alberta (a non-coastal environment), similar but less extensive moisture problems. The difference presumably reflected a less severe climate (less rainfall and greater drying potential). For example, 91% of the problems were related to direct rain penetration, most of which occurred at window and door perimeters and decks. By comparison, condensation moisture, caused by occupants trying to maintain indoor humidity above 30% during the winter, contributed to 14% of all problems. Again, stucco-clad buildings had more reported moisture problems than vinyl-clad buildings. In fact, vinyl siding only accounted for about 4% of cited construction detailing problems whereas conventional 3-coat stucco wall claddings accounted for about 95% of the construction detailing problems associated with water intrusion. Problematic construction details included parapets at roof edges, soffits that slope toward walls, vertical transitions, rail attachments, and scuppers. In most cases, severity of water damage was classified as minor or moderate. All of the severe water damage incidents were associated with stucco cladding systems. Recommendations addressed proper construction practices to shed and drain water from claddings and to consider the use of rainscreen systems.

This study and the others cited earlier in this section provide strong evidence that bulk moisture from wind-driven rain penetration is the dominant factor explaining building moisture problems. The strength of this finding is greatest for the coastal climates, but also applies to samples of homes from inland climates. These findings appear to form the basis for the Canadian Moisture in Exterior Wall Systems (MEWS) research program (discussed later in this review) which focuses on key climatic conditions related to bulk moisture intrusion (e.g., wind-driven rain and drying potential) and moisture damage potential related to common wood-frame wall cladding systems with varying degrees of water intrusion caused by representative “defects”, such as a failed or missing caulk joint, under pressure and water spray conditions.

- ***Chouinard, K.L. and Lawton, M.D., Rotting Wood Framed Apartments – Not Just a Vancouver Problem, Morrison Hershfield Limited, Canada***

While based primarily on professional experience in remediation of moisture-related problems in multi-family low-rise wood frame buildings, the authors claim that moisture problems are not just limited to wet, coastal climates such as British Columbia. They present a few representative case studies of buildings in the provinces of Ontario and Nova Scotia demonstrating that particularly poor detailing and installation of cladding systems in less severe climates can also result in extensive moisture damage due to rainwater intrusion. It was noted that interior moisture sources and condensation were not a contributor to the observed damages. In most cases, the damage was associated with leaking windows, poor or absent flashing details, inadequate lapping of water-resistant membranes underlying cladding materials, and improper cladding installation. Joints in the weather barrier system created at exterior balcony and deck attachments (and at the bottom of sliding doors) were particularly problematic. The authors noted that severe internal wall damage was not usually detected until window replacement or other action was initiated due to outward effects of moisture damage. In one case, the moisture damage discovery was initiated by an upper balcony or deck collapse. In these special detailing cases, the implication is that proper water management of claddings is associated with structural safety. The authors also note the seeming lack of detail and guidance provided on construction documents in relation to building envelop detailing. However, the authors do not provide an indication of the frequency of such severe moisture problems relative to the building population at large.

- ***May, J.C., Moisture Problems: From Case Studies and Home Inspections, Proceedings of Bugs, Mold, and Rot I, BETEC, BSSC, Washington, DC. 1991.***

In this paper, the author addresses the types of moisture problems routinely seen in inspections of existing homes. Based on his experience, the most common causes for moisture problems include improper handling of roof water (e.g., improper maintenance of gutters and downspouts to direct water away from roof eaves, walls, and foundations) and homeowner ignorance of the consequences of various practices (e.g., venting dryers to interior spaces and inadequate maintenance of furnaces and humidifiers). The author also demonstrates through several examples that moisture damage is more dependent on management of rainwater (e.g., prevention of intrusion caused by careless or absent flashing details and leaking window/door frames) and is less dependent on condensation of vapor in walls.

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- ***Assessing Housing Durability: A Pilot Study*, U.S. Department of Housing and Urban Development, Washington, DC. November 2001.**

This study was prompted by the need to quantitatively benchmark the durability characteristics of housing in the United States as a part of the PATH program. A sample of 208 homes within two age groups (5 to 10 years old and 25 to 30 years old) was randomly selected from the housing stock in Anne Arundel County, Maryland. An extensive survey of the exterior characteristics and condition of the homes and surrounding site conditions was conducted. In addition, occupants were interviewed to gain additional information, including interior conditions or frequency of problems such as flooding or visible leaking of windows. Only a few of the most important findings related to bulk moisture effects are addressed in this review.

Foundation/Site – Site grading and drainage problems (surface depressions or negative slopes adjacent to foundations) were observed on 20 percent of the 1970's sample and 11 percent of the 1990's sample. This problem was found to be associated with a much higher incidence of foundation cracking. In terms of bulk moisture loading this finding points to a potential interaction with compounding effects on potential for bulk water intrusion. First, improper grading increases moisture load on the exterior of foundation walls. This moisture load also increases the structural load on foundation walls (either through higher lateral soil pressure or greater tendency for differential settlement). Moisture cycling will also tend to increase settlement of foundation backfill in a natural process of consolidation (further aggravating the moisture load due to loss of surface drainage away from the building). Increased structural loads or settlement over time increase the likelihood of foundation cracks. Finally, when cracks form, an additional moisture transport mechanism to the interior of the building becomes possible (e.g., liquid flow). In addition, a high percentage of homes experienced problems with improper maintenance of guttering (e.g., plant growth in gutters, missing downspouts, damaged or reversed slope gutters, etc.).

Above-grade Walls – Rot of exterior wood components, mainly siding trim, was observed in 31 percent of the 1970's homes and 22 percent of the 1990's homes. The causal factors included inadequate detailing, protective coating, ground or concrete clearances, non-rot resistant wood species, and others. While the difference in the frequency of rot in the two samples may be closely related to time effects, other indirect causes such as changes in wood characteristics, construction practices, and wall protection by overhangs may have contributed. For example, overhang widths greater than 12 inches dropped from 60% in the 1970's sample to 18% in the 1990's sample. This factor alone may account for a significant increase in bulk moisture load on exterior wall surfaces. In addition, the newer housing stock was comprised of taller homes (e.g., 93% 2 story or greater in 1990's compared to 71% 2 story or greater in 1970's sample; or 29 % less than 2 stories in 1970's and 7% less than 2 stories in 1990's). There was also more multi-unit (townhome) construction in the 1990's sample. At the same time, dramatically increased use of vinyl siding and windows were observed in the newer housing which would tend to reduce moisture problems with the siding material itself, but not necessarily with internal moisture loads from moisture penetrating siding, particularly at joints with windows and doors. Vinyl siding may also tend to improve drying potential or other factors that improve envelop durability. Several of these findings are consistent with the Canadian research into building envelope failures in British Columbia, discussed above. Also, most homes were in shielded exposures from the wind (e.g., reduced wind driven rain effects, but also possibly reduced amount of solar drying effect).

Roofing – While asphalt composition roof shingles dominated the sample in both age groups, differences in roof slope and number of valleys were found. For example, roofs in newer homes tended to be of slightly greater slope which would serve to modestly improve water shedding even in the presence of minor roofing defects or degradation. However, newer homes also exhibited a much higher use of valleys (indicating greater complexity of roof design) which tends to give greater opportunity for flashing problems to result in roof leaks. For example, only 18% of the 1970's sample had 2 or more roof valleys, while this number increased to 49% for the 1990's sample.

Home Owner Survey – In a related survey of homeowners, the most frequent moisture problems cited were standing water in the basement or crawlspace, leaks or water stains around windows, and, to a lesser extent attic water problems.

In general, the survey identified changes in housing characteristics that may be associated with greater bulk moisture exposure of the building envelope (e.g., more complex roof shapes, less roof overhang, taller walls). The observed frequency of site grading problems and a higher percentage of homeowners indicating standing water in basements

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over other moisture intrusion problems gives evidence that basement water problems continue to be a significant moisture intrusion problem.

- **Crandell, J. H., *Exterior Insulation Finish Systems (EIFS): Lessons Learned, Advancements, and Challenges*, prepared for Institute for Business and Home Safety (IBHS), Tampa, FL. 2003 (available at www.ibhs.org).**

In this study, experience with use of Exterior Insulation Finishes Systems (EIFS) on commercial and residential buildings in North America (United States and Canada) is summarized. Moisture problems experienced with EIFS have provided especially useful insights into the effects of water intrusion combined with the drying potential of wall systems and climates in the United States. Most of the water intrusion and decay in wood frame housing with EIFS cladding systems is associated with leaking windows, improper using of flashing, and missing or inadequate sealant specification and installation. As with other moisture problems reported in Canada and the United States, severe moisture problems are commonly associated with the interface of EIFS with other wall components such as windows, doors, roof details, etc. In addition, EIFS was initially manufactured and installed as a face-sealed or barrier cladding system on homes and commercial buildings. With recent introduction of "drainable" EIFS and related building code changes, EIFS on one- and two-family dwellings are now required to use a secondary drainage plane and water barrier to remove water than may penetrate EIFS at joints with other wall components. On new commercial buildings, continued use of face-sealed or barrier EIFS requires special inspections and installation certifications. Essentially, this drainage component with a secondary weather barrier are the key features that define a rainscreen wall system (for which there are a number of variations depending on exterior cladding type, degree of drainage space provided, and effectiveness of pressure moderation across the exterior cladding under wind-driven rain conditions).

- **Crandell, J.H. and Kenney, T.M., *Investigation of Moisture Damage in Single-Family Detached Houses Sided with Exterior Insulation Finish Systems in Wilmington, NC*, 2nd Edition, NAHB Research Center, Inc., Upper Marlboro, MD, January 1996.**

In Wilmington, North Carolina, particularly severe and frequent cases of moisture damage to wood frame homes with barrier EIFS cladding were discovered in 1995 by Alan Golden of the Wilmington Building Department. A monitoring program was instituted to document the nature of damages and performance of implemented repair strategies. The monitoring of repairs on 100 homes of 3 to 5 years old with EIFS documented the frequency of rot and extent of repair required according to building feature or component, as shown in the Table below. In addition, homes in Wilmington, NC were required by the building code to also have in interior vapor barrier (e.g., polyethylene film) which dramatically decreased the drying potential of the wall system during warm summer months and accelerated the wood degradation process.

**Repair Statistics for 100 Barrier EIFS Homes
In New Hanover County, North Carolina
with Moisture Intrusion Problems**

Number of Features in Sample of EIFS Homes	Percent Requiring Replacement of Substrate	Average Amount of Substrate Replaced
2,751 Windows	18%	16 ft ²
574 Kick-outs	23%	38 ft ²
97 Chimneys	15%	48 ft ²
105 Decks	19%	74 ft ²

Source: *Moisture Testing Guide for Wood Frame Construction Clad with Exterior Insulation Finish Systems (EIFS)*, prepared for the EIFS Review Committee by the New Hanover County Inspection Department, Wilmington, NC, August 4, 1998

- **Crandell, J.H., *Investigation of Moisture Damage in Insulating Concrete Form Homes Sided with Exterior Insulation Finish Systems in Eugene, Oregon*, Portland Cement Association, Skokie, IL, 1996.**

Moisture intrusion problems were also reported in a study of houses with insulating concrete form walls and EIFS cladding. Again, rainwater intrusion was usually associated with interfacing of the cladding with other wall components (e.g., decks, windows, doors, roofs, etc.) and leaky windows. Homes that were sheltered from wind and

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having longer roof overhangs (particularly one story homes) exhibited less likelihood of water penetration, with all other factors being equal.

In general, the three foregoing studies of EIFS homes (similar to studies of homes with other claddings) indicate that rainwater intrusion is the primary cause of moisture problems. As with other face-sealed or barrier cladding systems, any fault in the flashing and sealing and general water-tightness of wall components penetrating the cladding will result in aggravated moisture problems, particularly if the drying potential of the wall system and/or climate is low. Therefore, it is generally understood that with barrier EIFS and other face-sealed cladding systems, a much greater degree of care in construction detailing and quality control is necessary to achieve acceptable performance. In addition, it may be argued that adherence to good building maintenance practices (e.g., periodic inspection and sealant replacement) are equally important to long-term performance. Significant litigation has resulted from bulk moisture intrusion and accumulation problems experienced with barrier EIFS on homes and other buildings. Newer drainable EIFS products are now being used, but it may be too soon to judge the actual effectiveness of this improved moisture management strategy.

- **Tsongas, G.A., Govan, D.P., and McGillis, J.A., “Field observations and laboratory tests of water migration in walls with shiplap hardboard siding” *Thermal Performance of the Exterior Envelopes of Buildings VII*, Clearwater Beach, FL, p.469. 1998.**

While most studies in this section have focused on rainwater intrusion through walls, other effects of bulk moisture are also reported in the literature in regard to the durability of siding products. One such product is hardboard siding which, in the past, has suffered premature damage from bulk moisture exposure. The main expression of the problem was in edge swelling of the siding material, which resulted in additional exposure and eventual fungal growth in many cases. Aside from the susceptibility of hardboard siding to moisture damage, other factors contributing to the damage were related to water penetration at joints, improper installation, and overly demanding installation requirements. As with barrier EIFS claddings, a significant amount of litigation has arisen involving hardboard siding.

A.2.3.3 Indirect Sources Identifying Bulk Moisture Problems

Selected References

- **"Housewrecked" *Consumer Reports*, January 2004**
- **Fowler, P., "Common Construction Defects" *Journal of Light Construction*, October, 1998**
- **March 1999 *National Forum on PATH Durability Research*, NAHB Research Center, Inc., May 12, 1999**
- ***Basement Water Leakage ... causes, prevention, and correction*. National Association of Home Builders, Washington, DC. 1978.**

Case studies and other reports on moisture problems are also a common topic in the popular press; recent examples in *Consumer Reports* and the *Journal of Light Construction* are listed above. These reports provide case study evidence of the types of construction defects that are commonly observed in home inspections or that often result in litigation. Many are related to moisture intrusion problems. In addition, some broad quantification of importance of moisture problems based on building industry experience has been summarized for HUD under the PATH program, both in a March 1999 report, *National Forum on PATH Durability Research*, and DBD 2001, which is directed at builders. The indirect sources of information in these reports to HUD include builder and home inspection surveys, compilation of ToolBase technical hotline service inquiries, and investigation of remodeling industry activity.

An early NAHB study of wet basements, *Basement Water Leakage*, includes extensive data on this long-standing problem. While there is no shortage of anecdotal information indicating that basement water leakage is a major and continuing issue, quantitative sources of data on this problem are scant. This publication included a survey of the building industry, a literature review, input from building experts, and a series of practical observations and suggestions regarding basement water leakage problems. The study was based on questionnaires from builders across the country concerning 135 basements that leaked. A total of 70 builders (30 percent response rate) replied

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and about 85 percent reported one or more basement leakage problems. Most responses were from the Midwestern and Eastern builders in areas where basement construction is common. The key findings were as follows:

- About two-thirds of the of the leakage problems were classified as “light,” indicating only surface wetting, and the other one-third were classified as “heavy,” indicating standing water on the basement floor slab.
- Heavy leakage tended to be associated with high ground water whereas light leakage was associated with failure to control of surface water.
- About 85% of the leaks appeared only after rainstorms or melting snow, indicating that some of the heavy leaks may have been associated with a combination of shallow ground water recharge and surface water drainage.
- Masonry and poured concrete foundations were almost equally susceptible to leakage.
- Topography was level in 50% of the leakage cases reported, gently rolling in about 40 percent, and hilly in about 10 percent. However, note that these percentages may be associated simply with the distribution of all basement homes, rather than differences of potential for water leakage due to topography alone.
- Surface slopes of $\frac{1}{4}$ ” per foot to over $\frac{1}{2}$ ” per foot (2% to over 4%) were reported for 78% of the homes with basement leakage; however, this information was considered contradictory and may have overlooked other factors such as small areas of deficiency in grading.
- Clay and silt soils were reported below the top soil in about 85% of the houses with basement leakage. The corresponding percentages for all other homes are not known.
- Some 75% of the builders reporting leaking basements did not make water table tests before construction and 28% believed that high ground water was the factor causing leakage.
- The builders surveyed believed that poor control of surface water was the most important factor, which agreed with the causes associated with the predominant cases of “light” leakage and may have contributed to some of the “heavy” cases.
- There was less agreement on appropriate prevention strategies. However, builders who had experienced no problems were in closer agreement. Nine out of the ten builders who reported having had no basement leakage problems emphasized the need for positive drainage beneath the basement slab as well as on the outside of the basement wall. Their approach included a deep layer of porous fill under the slab (6” thick or more) with the drainage layer extending 1 to 2 inches above the top of the footing, allowing water penetrating the wall-footing joint to be drained under the slab. Some builders used weep holes in addition to extending the porous fill above the footing. Areas underneath the slab were positively drained.

Assuming typical builder levels of production, this study may suggest that about 4 to 8% of basement homes experience some form of leakage problem. Based on the “heavy” and “light” leakage data, this would imply that about 3 to 5% of basement homes may experience “light” leakage (surface wetness on walls and floors) and 1 to 3% may experience “heavy” leakage (standing water). These numbers are only suggestive since builder production data was not collected in the survey to compare with the number of reported leakage cases.

Some of the more significant findings, based on experience with basement water intrusion problems, were as follows:

- While the literature generally advocated sealing out hydrostatic pressure and draining the water through tile, the study found that eliminating hydrostatic pressure by discharging excess water beneath the slab and to a point of positive drainage was more effective than relying on exterior drains alone (2:1 difference in potential for leakage based on evaluation of house construction data and leakage data obtained in the survey).
- While the literature advocated parging with or without additional liquid sealant coatings, the substitution of plastic films seemed to be more effective (11:1 difference in leakage potential based on evaluation of house construction data and leakage data obtained in the survey).

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- While the literature advocates drain tile sometimes on the inside and sometimes on the outside of foundation walls, the study indicated that providing a means for positive drainage for ground water to escape without drain tile may be more effective and less costly.

A.2.3.4 Summary

The reviewed sources of information on bulk moisture problems experienced in the building stock indicate several key issues:

1. Wind-driven rain is associated with most cases of building envelope moisture problems.
2. Building characteristics and site characteristics that establish variation in levels of vulnerability to wind-driven rain penetration, accumulation and damage were significant contributing factors to leaks, based on field assessments of the existing housing stock.
3. Envelope construction quality has varying degrees of importance depending on the above two factors.
4. Most foundation bulk water intrusion problems are associated with inadequate management of surface water (e.g., site and roof water drainage) while a smaller but still significant problem with ground water also exists due to insufficient practices in relation to site-specific conditions.
5. Owner maintenance is a significant factor in long-term performance and varies in level of importance (and amount of effort required) in accordance with several items listed above.
6. Trends in residential building characteristics, materials, and methods suggest that vulnerability to bulk moisture intrusion has potentially increased in the recent past; however, this finding is based on interpretation of very limited data and deserves to be studied more carefully.

A.2.4 Bulk Moisture Hazards (Sources and Loads)

A.2.4.1 Introduction

This section focuses on literature related to the quantification of bulk moisture sources and the loads they impose on the building envelope. For external moisture loads climate is the dominant factor, and specifically precipitation amounts and coincidence of wind and precipitation. Precipitation moisture loads on a building and their consequences are complicated by climate factors such as wind, temperature, and humidity that may affect how the moisture is deposited on the building, as well as whether the precipitation is liquid or solid. Other potential external loads such as landscape irrigation are not specifically considered in this literature review and the solution is relatively straight-forward (i.e., don't direct sprinkler water onto house walls and control the amount of irrigation water applied adjacent to the foundation). Internal bulk moisture loads such as plumbing leaks are also addressed in a cursory fashion as there is little information on frequency and quantity. They are generally considered to be "accidental" even though they can cause significant damage to building contents. Furthermore, there is little quantitative information on internal bulk moisture loads for some of the more common causes, such as leaky plumbing or burst washer hoses. Therefore, most of the information on internal bulk moisture loads can be considered anecdotal. Insurance industry data was not reviewed; it may provide some useful insights into the nature and extent of these types of bulk moisture problems. However, no insurance or related data was found in regard to plumbing leaks after several hours of searching on the Internet and inquiries directed to plumbing industry trade organizations.

A.2.4.2 Climate Data and Indices

Basic climatic and geologic data related to moisture is readily available from the National Oceanic and Atmospheric Administration, and is often reported or used in other sources. Relevant data climate or geologic data from direct measurement of rainfall amounts, wind speed, temperature, humidity, evaporation rate, ground water level, snowfall depth or weight, and flooding events (overland, riverine, and coastal). From these data, statistics such as annual averages, monthly averages, and extremes are often determined. Rain, and particularly wind-driven rain, is widely considered the most important factor related to the performance of building envelopes and protecting them against moisture damage. While several methods of quantifying climate effects in relation to this concern have been developed, it is still an area of active research and advancement. Knowledge regarding wind-driven rain climate and

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related moisture loads on building envelopes is important in to the development of performance test standards, general building envelope design decision-making, building envelope moisture assessment and remediation strategies, and establishing input or boundary conditions for sophisticated HAM modeling of building envelope systems. Climate indices that have been developed for one or more of these purposes are reviewed in this section.

- **Sheffer, T.C., “A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground,” *Forest Products Journal*, Vol. 21, No. 13, Madison, WI, October 1971**

The Sheffer paper describes a *Decay Index* (DI), developed as a means for estimating the decay potential of exposed above-grade wood materials in structures. The index uses monthly mean temperatures and the mean number of days with 0.01 inch or more precipitation to develop an annual index. It does not consider climatic variations in the combined effect of wind with “wet” days. Therefore, in terms of potential rainwater loads on building walls, it may be either conservative or unconservative in some climates depending on climatic difference in coincidence of rain events and wind of various magnitudes. A simplified version of the original DI map is found in the *International Residential Code 2003* as Figure R301.2(7) – Decay Probability Map; however, its only use in the code relates to conventional wood decay protection requirements in Section R319 of the IRC. In that section, the wood protection requirements apply wherever a decay probability exists as shown in the Decay Probability Map. It is notable that at least a “slight” decay probably is shown in the figure for all areas of the United States. Therefore, the map is of very limited value in current U.S. building codes and is not generally used as a decision making factor in terms of building envelope design, installation, inspection, and maintenance.

- **BS 8104: Code of practice for assessing exposure of walls to wind-driven rain, British Standards Institute, 1992)**
- **van Mook, F.J.R., Driving rain on building envelopes, published as issue 69 in the Bouwstenen series of the Faculty of Architecture, Planning and Building of Eindhoven University of Technology, ISBN 90-6814-569-X, 2002**
- **Technical Note 7 – Water Resistance of Brick Masonry, Design and Detailing, Brick Industry Association, Reston, VA. April 2001**

The *Driving Rain Index* (DRI) was introduced in England in 1962, then later improved and eventually implemented in BS 8104. DRI is a measure of the rainfall intensity (rate) passing a vertical plane due to a horizontal component of raindrop motion caused by wind. Standard rainfall intensities are reported for rain passing through a horizontal plane (e.g., the ground or the opening of a rain gauge). Two driving rain indices were calculated for 52 weather stations throughout the UK for each of 12 wind directions: (a) an average annual driving rain index and (b) a driving rain spell index associated with a frequency of once in three years. The first index (based on hourly products of rainfall and wind speed) was thought to be relevant for the weathering of building envelopes, and the latter index for assessing the risk of rain penetration through masonry walls. It is reported by van Mook as being the only standard on driving rain estimations and is also in preparation as a European (EN) standard. A driving rain index has also been proposed by the Brick Industry Association for masonry wall design guidance in the United States. Their Technical Note 7 includes a map based on wind and rainfall amounts along with a classification system based on building wall exposure conditions.

- **Straube, J.F., and Burnett, E.F.P., Simplified prediction of driving rain deposition, Proc of International Building Physics Conference, Eindhoven, September 18-21, 2000, pp. 375-382**
- **Choi, E.C.C., 2001, Wind-driven rain and driving rain coefficient during thunderstorms and non-thunderstorms”, *Journal of Wind Engineering and Industrial Aerodynamics*, 89(3-4): 293-308.**

Many other studies involving wind-driven rain climate indices and moisture loads on building facades are reported in the literature, but there is a lack of quantitative data relating them to the actual magnitude, duration, and frequency of rain deposition on buildings. In Choi's study quantifying rain deposition during thunderstorm and non-thunderstorm rain events, results indicate that the short duration intensity can be 10-20 times the hourly average. Thus, a precise basis for determining wind driven rain indices for building envelop design purposes is unclear. The best approach is highly dependent on the duration over which driving rain intensities have disproportionate effects on building envelopes.

- **Underwood, S.J. and Meentemeyer, V. 1998. “Physical geography, climatology of wind-driven rain for the contiguous United States for the period 1971 to 1995,” *Physical Geography*, 19(6): 445-462.**

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The article by Underwood and Meentemeyer reports on development of a "wind-driven rain" (WDR) climatology of the contiguous United States. While the climatology lacks specific association to rain impingement on a given building façade and exposure condition, it does provide a reasonable indication of the hazard of wind-driven rain for the purpose of building envelope design decision-making. WDR intensity is estimated from a linear regression model that develops a relationship between rainfall on a horizontal surface and rainfall on a vertical surface. The WDR estimates are used to create maps of WDR intensity, event duration, annual frequency, total receipt, and direction. Areas of highest WDR intensity, duration, and frequency are found in the southern United States, especially along the Gulf Coast. Directional indices indicate that WDR occurs most often from easterly directions in locations in the southeast and central United States, while WDR is predominantly from the south along the West Coast.

- **An Exploratory Study of the Climatic Relationships Between Rain and Wind, Technical Series 96-208, CMHC, Ottawa, Canada, 1996**

The *Driving Rain Wind Pressure* (DRWP) is used in the Canadian window standard (CAN/CSA-A440-M90) for determining design or test requirements for window performance. It is based on estimates of annual extreme mean hourly wind speeds associated with what is considered sufficient rain to provide the quantity of water on the building surface from which leaks may occur (assumed to be 1.8 mm/hr). The applicability of this approach as well as a more thorough exploration of coincidence of wind and rain was subject to additional study in CMHC 96-208, which concluded that wind directional tendencies (i.e., wind roses) during periods of wet weather were often substantially different from those during all times. In the limited examination of weather data, it was felt that a simpler definition of the DRWP could be based on using a fraction of the 10-year return period wind pressures reported in the National Building Code of Canada.

- **Report from Task 4 of MEWS Project – *Environmental Conditions Final Report*, NRC-CNRC, Ottawa, Canada, October 2002, www.nrc.ca/irc/ircpubs**

In the Canadian "Moisture in Exterior Wall Systems" (MEWS), project an innovative "moisture index" (MI) was developed based on consideration of climate conditions that govern the potential for wetting as well as the potential for drying. A high MI represents a climate with high rain water loading potential and/or a low drying potential. The MI is comprised of two separate indices. One is based simply on total annual rainfall amount (the wetting index, WI) and the other is based on annual evaporation potential (the drying index, DI). Several different climate indexes are considered and compared in the study. The purpose of the climate study, in addition to providing categorization of North American climates by drying and wetting potential, was to provide climate data input for hygrothermal modeling and testing of various wood frame wall types in a number of representative cities in North America. Also, representative or reference years for hygrothermal analysis are investigated and recommended, although this is an area of ongoing debate internationally. In the MEWS project, years with the lowest, closest to average, and highest MI values were selected as moisture reference years for use in hygrothermal modeling. In addition, an impinging rain amount was used to modify the WI, based on a simplified methodology accounting for wind direction and water load impacting the upper corner of the worst-situated wall relative to selected representative moisture years for cities investigated. This information was used to determine wetting loads for the hygrothermal analysis. Furthermore, the sequencing of moisture reference years was somewhat arbitrarily selected (e.g., using a wet-wet-average sequence of moisture reference years). It is noted, however, that the MI was purposefully uncoupled from any characteristics of particular building sites or walls that may affect any quantitative representation of moisture effects. For climate zoning purposes, the MI was used in its simplest form described above. The authors recognize that additional work is needed, particularly on the correlation of such a climate index with the frequency of actual moisture related damage such as mold, decay or corrosion. Given the many uncertainties and additional work required, such zonation efforts are essentially qualitative indices (based on actual physical climate characteristics) depicting relative differences in potential moisture intrusion and damage. They do not provide absolute or quantitative design guidance at this time.

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A.2.4.3 Extreme Climatic and Hydrologic Events

Selected References

- *Development of Loss Relativities for Wind Resistive Features of Residential Structures*, Florida Department of Community Affairs, prepared by Applied Research Associates, Inc., Raleigh, NC, March 28, 2002
- *Coastal Construction Manual*, FEMA 55, Federal Emergency Management Agency, Washington, DC
- *Manual for the Construction of Residential Basements in Non-Coastal Flood Environs*, U.S. Department of Housing and Urban Development, Federal Insurance Administration, Washington, DC, March 1997

The effect of short duration wetting spells due to extreme wind events such as thunderstorms was mentioned previously. The report by Applied Research Associates focuses on rain intrusion during even more extreme events such as hurricanes, mainly from the standpoint of water damage to the building and contents and the resulting insurance losses. Probabilistic wind speed maps are available in building codes and design standards (such as ASCE-7, 2002), and hurricane prone regions are readily identified in coastal areas with high design wind speeds.

Long-term durability effects from short-term, extreme wetting episodes like hurricanes have not been the subject of significant research, probably due to the fact that moisture-sensitive materials (such as interior finishes, insulation, and other items) are often replaced after major events. Instead, studies on extreme events tend to focus on remediation practices to be employed immediately as part of disaster recovery (e.g., drying and repairing a building after a major flood event). Structural impacts have usually been of greater concern, although protection of building envelopes (particularly from a structural standpoint in regard to wind-borne debris resistance of glazing and connection of claddings) has received much greater increased attention in codes and standards during recent years.

The FEMA *Coastal Construction Manual* describe how flood-resistant construction practices are being implemented for protection of coastal homes, and the related HUD manual on basement construction provides similar information about homes built in inland flood plains. Their relevance is limited by the fact that most U.S. communities participate in the National Flood Insurance Program and restrict or prohibit new construction in the 100-yr flood plain as identified on FEMA flood insurance rate maps.

Window and door products tested to standards such as ASTM E1996 and ASTM E331 are often considered superior in climates subjected to hurricanes because of their improved ability to limit wind-driven rain penetration through seals, frames, and broken glazing due to potential debris impacts. In addition, increased testing requirements for wind-resistance of asphalt roof shingles in extreme wind environments has been recently added to national model building codes (see IRC 2003). This particular building code change is intended to minimize direct losses due to wind-related shingle damage (e.g., the largest single source of insured wind damage losses next to those associated with roof tie downs) and to minimize the potential for subsequent water damage to building contents (also a major source of insured building losses).

A.2.4.4 Ground and Surface Water

Ground Water -- Assessing the potential for ground water problems is usually addressed by means of local experience and varying degrees of site exploration, if any, by a geotechnical engineer. In some cases, ground water is not considered to be a problem unless it is discovered during foundation excavation or, alternatively, during percolation testing for drain fields if the site is to be served by a private drain field. However, building codes and construction practice often require that seasonally high ground water tables be at least some minimum distance below the foundation footing depth. See, for example, DOE/ORNL, *Building Foundation Design Handbook* (1988). The degree to which this is actually implemented is not known and, when even implemented, the level of uncertainty may be significant depending on the nature of the recent rainfall amounts and other factors. This same complication also affects decisions regarding percolation testing for acceptance and sizing of on-site sewage disposal systems (i.e., drainfields), which is a deciding factor on whether not some sites can even be considered developable. In practice, poor ground water conditions are often aggravated by insufficient elevation of the building on the site and poor drainage of surface water and roof run-off away from the immediate foundation area.

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- ***Lot Drainage Characteristics Study Natural Storm Events, prepared by CH2M Hill Engineering Ltd. for Alberta Municipal Affairs, Office of Housing and Consumer Affairs, Alberta, Canada, February 1994.***

This Canadian study was undertaken to quantify storm sewer flow contributions (foundation drain response) from residential foundation drainage systems due to natural storm events. The study included sites with various soil types (clay till, sandy, and silty) and various foundation backfill practices (tamped or unconsolidated). Foundation drains can contribute significant flow into sanitary sewers to which they are connected. This condition can cause sewer overloading, surcharging, and basement flooding. In addition, extra capital and operating costs are associated with collection and treatment of increased flows from residential foundation drains. Previous research identified lot grading, backfill practice, ground cover, and roof leader discharge location as factors affecting foundation drain flows. The testing procedure for this project involved: (1) applying a design storm to the test facility or monitoring a natural storm event, (2) measuring foundation drain response, and (3) measuring groundwater table response. A good correlation was found between natural or simulated rain events and foundation drain flows.

Foundation backfill soil type was found to be the most significant factor impacting foundation drain responses. Silty soils produced the lowest responses, followed by clay, then sandy soils. Significance of other parameters, in descending order of importance, was as follows: (1) degree of compaction, (2) backfill zone grading, and (3) roof leader location. Sometimes contrary to recommendations for foundation backfill practice in residential construction for reasons other than limiting foundation drain flows, the study made the following recommendations (see important qualifiers and discussion below):

- Silty soils should be considered as the preferred backfill material, followed by clay soils, and lastly sandy soils.
- Compaction of backfill for new construction is recommended.
- The width of the construction zone (foundation excavation) should be minimized, to maintain less permeable properties of surrounding undisturbed soil, and to reduce the potential for settlement.
- Good grading should be provided on all new homes, and in regarding of existing homes.
- Frozen material should not be used in backfilling.
- “Engineered backfill” is recommended where sand must be used.
- Roof leaders should be extended beyond the backfill zone, and at least 1.5 m from the foundation wall.
- In the design of drainage infrastructure, and in computer modeling of new and existing sewer systems, the flow rates provided in the study should be used.

There are some important qualifiers that may apply to interpreting the findings of this study. For example, in the clay soils studied it was found that grading was a less important factor when the clay and silty backfill soil was compacted. Grading may have been more important for an uncompacted backfill condition typical of residential construction, but this condition did not appear to have been investigated or emphasized in the study. A similar qualifier may also be appropriate for the lower ranking of the roof leader (gutter discharge) location in regard to backfill compaction condition. Thus, if backfill soil is uncompacted, the significance of parameters may tend to emphasize site grading and roof drainage as the important parameters with regard to foundation drain flows. This observation would place the findings in closer agreement with experience in conditions associated with residential foundation water problems rather than compaction or soil type. Regarding soil type, silty soils are generally not considered to be optimum backfill material for structural reasons (e.g., potential for frost heave and “jacking” of foundations inward or upward).

Perhaps the most important finding of the study was that under all conditions studied, there was a water flow response to the foundation drainage system due to rainfall which ranged from 0.01 L/s (best case) to 1.12 L/s (worst case) for the range of above-average or design rainfall events simulated or occurring during the testing program. The simulated rainfall events were selected primarily from an interest in impact on design flows from design storms typically used for storm water infrastructure design. The findings should be qualified by an understanding that the testing schedule also created a situation with wet antecedent soil moisture conditions in all cases. Therefore, possible effects of initial abstraction, storage, evaporation, and evapo-transpiration were not considered, even though these may be important in regard to foundation water loads associated with building moisture problems.

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Freezing and Thawing of Ground Water

Selected References

- ***Development of Frost Depth Maps for the United States*, U.S. Department of Housing and Urban Development, Washington, DC. July 2001**
- ***Frost-Protected Shallow Foundations, Phase II – Final Report*, U.S. Department of Housing and Urban Development, Washington, DC, June 1994**
- **Steurer, P.M., and Crandell, J.H., “Comparison of Methods used to Create Estimate of Air-Freezing Index,” *Journal of Cold Regions Engineering*, Vol. 9, No. 2, American Society of Civil Engineers, Reston, VA, June 1995**
- ***Design and Construction of Frost-Protected Shallow Foundations*, ASCE 32-01, ASCE Reston, VA, 2002;**
- **Crandell, J.H., “Frost Protected Shallow Foundations”, *Structure Magazine*, Vol. 11, No.1, Dec 2003/Jan 2004**

Potential problems associated with frozen, moist ground are generally resolved by placing foundation footings below a locally established design frost depth as required by model building codes. This moisture- and climate-related foundation practice is generally determined by local experience rather than any special analysis. Only recently has frost depth been investigated by evaluating actual weather station frost depth data and consistently modeling probabilistic frost depths based on important variable properties of climate and ground. Such information, in the form of probabilistic frost depth maps of the United States, is currently not found in model building codes or design standards. Various other maps of frost depth, often based on conservative assumptions appropriate for special applications such as utilities underneath road beds, are found in the literature.

In recent years, a new method of protecting foundations against frost-heave (a process of ground freezing whereby moisture is wicked toward the freezing front where ice-lenses develop) has been developed based on European experience and research in the United States. The technique is generally described in the 1994 HUD publication on frost-protected shallow foundations. This work also involved development of an air-freezing index climatology of the United States and coordination with European methodologies, as documented in the 1995 article by Steurer and Crandell. This work has resulted in the development of the ASCE 32-01 standard for frost-protected shallow foundations, published in 2002, and its subsequent recognition in national model building codes. The story is told by the 2003 Crandell article in *Structure Magazine*. Use of non-frost susceptible soils is also recognized as an accepted practice. In some frozen, saturated soils, the process of thawing can result in thaw-weakening – a loss of soil bearing resistance due to increased soil pressure. On permafrost soils, a similar condition exists when heat loss through building foundations cause the soil profile to thaw and subside or “sink”. All of these moisture effects in soil can cause extensive damage to supported foundations and buildings.

Ground Moisture Effects on Expansive Clay Soils

Selected References

- **Brown, R.W., *Practical Foundation Engineering Handbook*, McGraw-Hill, 1996**
- ***Soils Task Force Report*, Home Builders Association of Metropolitan Denver, November 1, 1996**

Variations in the moisture content of expansive clay soils (sometimes referred to as "shrink-swell" soils) can cause significant structural damage to foundations and buildings. Even though moisture may never enter the building, its effects can be dramatic. Expansive soils have been a widespread and very expensive problem in Denver, in parts of Texas, and in several Atlantic states. As with determining the ground water level on a given site, the potentially expansive nature of a clay soil must be determined based on local experience, geotechnical evaluation, or a combination of both. Depending on the degree of expansion, potential various site and foundation construction practices are considered.

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A.2.4.5 Cold Climate Considerations

Selected References

- **Tobiasson, W.N., and Buska, J.S. “Minimizing the Adverse Effects of Snow and Ice on Roofs,” *International Conference on Building Envelope Systems and Technologies, Ottawa, Canada. 2001***
- **Tobiasson, et al., “Guidelines for Ventilating Attics and Cathedral Ceilings to Avoid Icings at Their Eaves,” *Buildings VIII/Roof Design Practices, December 2001***
- **Crandell, J.H., “Traditional and Improved Practices for Roof Ventilation and Prevention of Ice Dams,” prepared for Institute for Business and Home Safety, Tampa, Florida, January 2004**
- **Rose, W.B., and TenWolde, A. “Venting of Attics and Cathedral Ceilings,” *ASHRAE Journal, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., Atlanta, GA. October 2002***

Wind-driven snow, snow accumulation on roofs, sliding snow, snow melt water, icicles, and ice dams can all have effects on building that result in bulk moisture intrusion and physical damage to gutters, eaves, roof vent stacks, flashings, and walls. Management of these cold-climate concerns through building design and construction practices is covered very well in the literature, including recent technical advancements. In addition, these advancements as well as current building code practices were summarized in the article by Crandell along with recommendations for improved attic ventilation and ice dam protection criteria based on mapped snow load data used in building codes for structural design purposes. While ice dam formation is closely associated with cold climate characteristics such as average daily winter temperature and snow fall amounts, there is little data directly associating these climate data and building roof characteristics to the frequency or probability of ice dam formation of sizes sufficient to cause water intrusion through water-shedding roof systems at eaves. Therefore, the practices associated with protection against water intrusion due to ice dams (e.g., waterproof underlayment along roof eaves) and prevention of ice dam formation (e.g., roof ventilation and attic insulation) have been associated with mapped design snow loads or average January daily temperatures, based on judgment and experience rather than a probabilistic representation of the risks directly associated with ice dams. The literature also recognizes that excessive heat loss into attic spaces due to insufficient attic insulation and “vagrant” heat sources, such as infiltration of air from conditioned spaces and leaks in supply duct runs, can contribute significantly to the potential for chronic ice dam problems in cold climates.

A.2.4.6 Internal Bulk Moisture Sources

Typical bulk moisture problems associated with plumbing systems, appliances, and HVAC systems include

- Clogged or defective condensate drain on air conditioner
- Leaky humidifier basin
- Burst pipes due to freezing (crawl space, exterior walls, power failures, vacant house not winterized)
- Burst washing machine hoses due to pressure fatigue and delayed replacement
- Leaking tub and shower surrounds due to failed/poorly maintained/omitted caulk, flashing or grout
- Leaking water pipe connection due to faulty workmanship or materials
- Leaking water pipe due to corrosive agents; pinhole leaks
- Leaking seals at toilets (tank to bowl, or flange seal) due to delayed replacement or faulty installation
- Fatigued or cracked pipe or stressed joint seal due to improper support
- Nail driven into septic drain during construction later corrodes and causes leak
- Accidental spills or overflows.

Some of these can be catastrophic when they involve rapid release of large amounts of water. Some can be inconsequential when they occur in readily accessible locations and are promptly repaired. The ones that involve slow leaks into concealed spaces are particularly insidious, and can continue for months or even years before the existence of a problem is recognized through secondary symptoms such as stains on interior finishes. There are

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various solutions to the above problems. Many are obvious or similar in nature to those related to preventing bulk moisture problems from external moisture sources:

- Improved material testing/performance criteria and standards
- Improved material selection (e.g., plastic pipe vs. copper)
- Improved quality of installation workmanship
- Improved maintenance and periodic inspection
- Improved protection of plumbing against freezing

Outside of anecdotal sources of information (see Case studies section on Miscellaneous sources) and possibly insurance claims records, there is very little quantitative information on the frequency and magnitude of these types of problems. While there is a wealth of experience to demonstrate that these problems do occur, it is difficult to conclude that they present the magnitude of threat to building durability that is associated with rainwater entry.

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A.2.5 Bulk Moisture Effects by Building Subsystem, Components, and Materials

A.2.5.1 Introduction

This section focuses on literature related to the “resistance” or “response” of building subsystems, components, and materials to the effects of bulk moisture. It addresses research as well as construction practices as they relate to response to various moisture loading conditions, as well as resistance to potential bulk moisture sources and loading conditions.

A.2.5.2 Steep Slope Roof Systems

Introduction

Properly designed roof systems are the first line of defense against bulk water intrusion into a building. It can be said that the role of a roof is to protect the building from water, and the role of the walls is to support the roof. Roof systems may be classified into two basic types based on their method of handling bulk moisture from exterior sources (rainwater and snowmelt): (1) water-shedding and (2) waterproof membranes. Water-shedding roof systems are the most commonly used in residential construction where roofs are usually constructed with relatively steep slopes (e.g., greater than about 2:12). They rely on gravity and the velocity of water draining off the roof to prevent water entry. By far, the most common roofing material used in residential construction is asphalt or asphalt-fiberglass composition roof shingles applied to an underlayment of tarred felt paper. Other common roofing materials include various types of tiles (clay and concrete), wood shingles, and metal roofing (e.g. standing seam roof). All of these systems are water-shedding, steep roof systems.

In general, there is little quantitative research on rainwater penetration of water shedding roof systems. Most research has focused on membrane roofs (mainly commercial applications and issues related to roof ventilation and condensation control). Good practice is relied upon to ensure that materials are properly lapped and flashed to provide water-shedding characteristics. This is similar to the way that water-shedding or rain-screen wall systems have sidings, flashing, and secondary water barriers lapped to provide proper drainage. Practice guidelines are established by approved manufacturer product data, industry guidelines, and in building codes. There is no shortage of guidelines for roofing installation, roof repairs, and other practical roofing issues available from manufacturers, consultants, and trade organizations. For example, see www.rci-online.org and www.rci-mercury.com for numerous articles and guidelines on roofing provided by the Roof Consultants Institute.

Steep Slope Roofing Materials

Selected References

- *Tin Roofers Handbook*, National Association of Master Sheet Metal Workers of the United States, Philadelphia, PA. 1907
- *Tobiasson, "General Considerations for Roofs" in Chapter 16, ASTM, Manual on Moisture Control in Buildings, MNL 18 (1994)*

In general, long-standing experience and logic suggests that steeper roofs tend to have fewer problems with water leakage than flatter roofs. However, it is also clear that steeper roofs are also more difficult to access for construction, maintenance, and replacement. They also create higher lateral wind loads on buildings (as opposed to lower sloped roofs that tend to create higher wind uplift loads). They also tend to have better ventilation capability since it is easier to place vents high and low on the roof system to promote ventilation airflow by the stack effect. For low-slope roofs, special attention is needed in regard to waterproofing, ponding effects that deflect roof members, and ventilation, in addition to ensuring adequate drainage. Tobiasson points out that "a 'dead flat' membrane is a design mistake."

Commonly reported problems with water leakage in water-shedding roof systems result from: improper flashing at roof penetrations or other joints, failed caulking, improper installation of roofing, damaged roofing, aging effects and delayed replacement, special details (e.g., valleys, crickets, step flashing at intersecting walls), misapplication of a water-shedding roof material on a low slope roof, ponding of water caused by debris on the roof or ice dams at the

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eaves, and poorly installed or blocked guttering causing overflow and dampness at the eaves. Most of these issues are related to construction quality, owner maintenance, replacement practices and material durability. Ice dams were addressed under climatic conditions.

Shingle Resistance to High Winds

Selected References

- **ARMA Wind Research Program Report, Asphalt Roofing Manufacturers Association, Rockville, MD, July 1996**
- **Peterka, J. A., “Wind Uplift Model for Asphalt Shingles”, *Journal of Architectural Engineering*, American Society of Civil Engineers, Reston, VA, December 1997**
- **Conference Report, Journal of Research of the National Institute of Standards and Technology, *Fourth International Symposium on Roofing Technology*, Gaithersburg, MD, September 17-19, 1997**

Another topic mentioned above under the topic of extreme climatic loads was the issue of roof shingle resistance to high winds. Shingle damage and blow-off in high winds allows subsequent water intrusion, potentially in large amounts, as is often experienced in moderate to severe hurricanes. These methods have focused on wind resistance of newly installed materials and generally do not address durability or time effects and installation issues that are often major contributors to shingle damage or even complete roofing loss. However, the study and design methodology developed by Peterka does show that for an air-permeable cladding such as composition shingles the actual wind pressure across the shingle may be as little as one-fourth that determined for a non-porous cladding. NIST and other researchers are currently investigating service life and durability issues with asphalt roof shingles and other roofing products, as documented in the 1997 NIST Conference Report.

Roof Overhangs

Selected References

- ***Survey of Building Envelope Failures in the Coastal Climate of British Columbia*, Canada Mortgage and Housing Corporation, Ottawa, Canada, 1996**
- **HUD, *Durability by Design*, 2001, section 4.2.1**
- ***Prevention and Control of Decay in Homes*, 1978**

While the primary feature of a roof is to protect the inside of a building from water, the roof overhang is the primary feature that affords protection against rain water intrusion through exterior building walls and components. Roof overhangs have primarily been determined by aesthetics and experience, but weather protection benefits are understood only in concept. Current U.S. building codes do not specify any requirements for roof overhang amounts in relation to bulk moisture protection of walls. Recent field studies by CMHC including the 1996 report have demonstrated the effect of roof overhangs on limiting water intrusion problems in walls. Recommendations for roof overhang amounts as a function of building configuration, climate, and site exposure are found in relatively few sources and are primarily judgmental in nature. Examples are *Durability by Design* and *Prevention and Control of Decay in Homes*. It is also understood that architectural features such as porch roofs not only provide protection to occupants entering a building, they also provide moisture protection to entry doors and other building components. It appears, however, that decisions about whether or not to use roof overhangs are largely driven by architectural preference and secondly by potential of moisture protection benefits. For example, there is no quantified relationship between the amount of roof overhang provided on a low-rise building and the effects that it might have on durability and water intrusion resistance under actual conditions of use. This type of information would help designers and owners better understand the implications of roof overhangs in the building planning and design process. Aside from aesthetic and cost barriers to the use of substantial roof overhangs, there are some other issues that may tend to thwart the use of roof overhangs. For example, increased impervious area of roofs may be restricted by newer storm water quality regulations, and building tax assessments are sometimes based on roof

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coverage area instead of building size. Wind uplift loads also increase with roof area, and roof overhangs become less effective in protecting against wind-driven rain as building height and wind speed increase.

A.2.5.3 Wall Systems

Introduction

The most common wall systems in U.S. low-rise residential construction are conventional light-frame wood assemblies. Masonry construction is popular in parts of the southeast where moisture loads are particularly high. Other less common residential wall systems include light-gage steel, insulating concrete forms, and structural insulated panels. This section focuses primarily on conventional wood frame walls.

There are several cladding systems used on wood frame homes. The most common type in use today is vinyl siding. Other typical cladding materials include brick, stone, wood, aluminum, fiber-cement board, conventional 3-coat stucco, and synthetic stucco (EIFS). Some of the products have many variations. For example, wood siding methods include panels (e.g., T-111), beveled clapboards, hardboard composite wood siding, board-and-batten siding, and others. Furthermore, installation methods range from direct application to the framing, to systems with a secondary drainage cavity behind the siding (i.e., “rainscreen” cladding approach). Some systems may be designed as a “barrier” or “face-sealed” method (similar to the waterproof membrane approach taken for low slope roofs), whereas others rely on deflection and drainage of rainwater on the surface and behind the surface of the cladding (similar to water-shedding roof systems). The most common types of wall siding, like roofing, rely on some degree of water-shedding capability rather than waterproofing. There have been some notable exceptions (see Case Study section on experience with barrier EIFS). Therefore, experience and most current industry recommendations and building codes favor some variation of a “rainscreen” approach whereby water that penetrates a siding is provided with a means to drain without wetting moisture-sensitive wall components.

- **Damery, D.T., and Fisette, P., "Decision Making in the Purchase of Siding: A Survey of Architects, Contractors, and Homeowners in the U.S. Northeast", *Forest Products Journal*, Forest Products Society, July 2001**

There is almost an endless set of combinations of materials and methods available for wall cladding. However, information on actual installed performance is limited to that gained primarily by experience (see Case Study section). This article reports that most wall cladding systems are selected on the basis of cost, aesthetics, and performance against physical damage, but not necessarily protection from environmental factors. Relatively little quantitative information is available to predict or document actual performance differences between these many options. In many cases, standard test methods may be used to evaluate wall system performance, but usually these methods give little insight into actual in-service conditions with the actual combinations of materials and components in a wall system.

Some of the available information measuring wall cladding system performance with respect to bulk moisture (rainwater intrusion) are presented in this section. A conceptual design philosophy, known as the ‘4-Ds’, is often expressed in the literature regarding wall design against moisture intrusion:

- Deflect* – deflect rain from penetrating past the outermost surface (e.g., siding) of the wall envelope
- Drain* – provide a means for draining water that penetrates the outermost wall surface without harming internal wall components susceptible to water damage
- Dry* – select combinations of materials and configure them in a way to promote wall drying after wetting episodes
- Durable* – use adequately durable materials that are resistant to moisture damage in parts of the wall that are intended to be frequently exposed to moisture.

Wood Frame Walls with Various Claddings

- ***Water Intrusion Evaluation for Caulkless Siding, Window, and Door Systems*, U.S. Department of Housing and Urban and Development, Washington, DC. January 2002**

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This study was done in the interest of evaluating the performance of two siding types (fiber-cement and vinyl) with and without the use of caulking. The work was focused on determining the performance (ability to minimize water intrusion through the siding and various joint details) while minimizing or eliminating the need for caulk. Caulking is considered to be one of the least durable or reliable components of a weather resistant cladding system. It requires frequent maintenance. Therefore, developing practices that do not rely on caulk for adequate cladding system performance was considered to be an important topic for study. It was found that a caulkless approach to fiber-cement siding installation produced volumes of water intrusion similar to that recorded for vinyl cladding. The caulked fiber-cement siding reduced water intrusion, but still was reported to experience a considerable amount of water intrusion under the test conditions. Therefore, whether or not caulk is required in a siding system, the use of a secondary drainage plane was considered as an important feature. The study also demonstrated that these cladding systems with a secondary drainage plane, but without a cavity between the siding and drainage plane, were still able to allow water to drain freely from the wall system. In one case, a ¼" thick drainage cavity was created by using two layers of asphalt shingle strips as furring. Pressure differential across the cladding were not monitored during the tests and the test set-up may have masked the effects of pressure moderation that would otherwise occur in an actual installation. Based on staining of cladding joints, it was surmised that use of caulking created an increased moisture drive into cladding lap joints due to the reduced porosity (pressure equalization effect) of the cladding. The total amount of water draining through the cavity was substantially reduced with the use of caulking at cladding interfaces with trim and window details.

Brick/Masonry Walls and Cladding

Selected References

- **Melander, J.M., and Ghosh, S.K., *Factors Affecting Water Penetration of Masonry Walls*, Masonry Information, Portland Cement Association, Skokie, IL, 1992**
- ***Performance Evaluation of Water Repellents for Above-Grade Masonry*, Technical Series 00-118, Research Highlights, CMHC, Ottawa, Canada, 2000**
- ***Full Scale Tests of Brick Veneer Stud Walls – Strength and Rain Penetration*, Technical Series 97-121, Research Highlights, CMHC, Ottawa, Canada, 1997**

The Melander and Ghosh article reports about index test methods that have been developed and used as standardized or experimental tests for water intrusion resistance of masonry walls and claddings. In these studies, workmanship as well as material characteristics were found to be an important factor in overall masonry wall moisture resistance. The 2000 CMHC report examined a number of spray-applied water repellents for masonry and found 44% to 99% reduction in water penetration relative to a control wall without a repellent. And the 1997 CMHC report gives results of testing brick wall systems attached to steel framed walls for relative structural wind loading and water leakage performance (in combination with rainwater spray). In general this study found that brick claddings cracked at relatively low pressures; however, water leakage was primarily a function of pressure differential applied across the cladding. Weep holes in bricks were found to provide adequate pressure moderation, provided that adequate cavity compartmentalization can be achieved in the field.

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Rainscreen Walls (Cladding Pressure Equalization Effects)

Selected References

- Chown, G.A., Brown, W.C., and Poirier, G.F., "Evolution of Wall Design for Controlling Rain Penetration", Construction Technology Update No. 9, Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada, 1997.
- *Testing of Rainscreen Wall and Window Systems: The Cavity Excitation Method*, Technical Series 96-237, Research Highlights, CMHC, Ottawa, Canada, 1996
- *The Rainscreen Wall: A Commissioning Protocol*, Technical Series 96-238, Research Highlights, CMHC, Ottawa, Canada, 1996
- Garden, G.K., *Rain Penetration and Its Control*, CBD-40, NRC-IRC, April 1963

Several studies have done investigations under the heading of "rain screen" walls. Background information about this type of design appears in the report by Chown et al. However, there are no standardized methods for designing or evaluating the performance of the different variations of a rainscreen wall. Some unique test methods and testing performance criteria have been explored in the two CMHC reports.

The basic functions of a good-performing pressure equalized rainscreen wall are as follows:

- Provide pressure equalization with exterior ambient wind pressure
- Provide horizontal and vertical compartmentalization between positive and negative pressure zones on the building envelope (e.g., at corners) and where large pressure gradients exist (e.g., bottom of the a wall relative to the top near a roof eave), and
- Provide a means to evacuate water from behind the rainscreen (exterior cladding) to prevent water penetration into the wall system (e.g., has a secondary drainage plane with sufficient ability for water to move by gravity to flashings or weeps that allow the water to exit)

The essential components of a basic rainscreen system, as described by Chown et al., include:

- A cladding (rainscreen) of brick, wood siding, vinyl, pre-cast concrete, etc.
- A second line of defense (e.g., a secondary drainage membrane with suitable cavity for water drainage), and
- An air barrier system in the back-up wall (may be an integral component of the wall such as structural sheathing provided it is significantly less porous than the cladding).

The report by Garden describes an "open rainscreen" wall, which is a rainscreen wall that provides complete pressure equalization (perhaps more in theory than in practice in many cases) and which addresses all of the following water transport processes:

- Kinetic energy of raindrops
- Capillarity of cladding and small joints or cracks
- Gravity flow of water on the surface of the cladding
- Air currents through openings in the cladding, and
- Wind pressure differential across the cladding, working alone or in combination with the above factors

In this scenario, the air pressure differential is resisted completely by the supporting wall system (air barrier) behind the cladding. Therefore, the amount of water reaching the air barrier must be limited (e.g., by providing a cavity between the wall and the cladding) or by providing a secondary drainage plane or weather barrier to safely drain this water outside of the wall. As addressed later, the smaller this cavity, the better the pressure equalization effect (due to smaller compressible air volume to respond to fluctuating air pressure on the outside of the cladding). Therefore, the drainage plane/secondary weather barrier approach is often preferred for this and other practical reasons.

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- ***A Study of Rainscreen Concept Applied to Cladding Systems on Wood Frame Walls, Technical Series 96-214, Research Highlights, CMHC, Ottawa, Canada. 1996***

There are presently no standardized design models or calculation methods for the evaluation of the performance of rainscreen walls in terms of predicting water penetration through the cladding (rainscreen) and estimating the pressure equalization based on characteristics of the cladding and wall system under dynamic wind loading. This paper describes a simplified computer model that has been developed and calibrated to some full scale testing results. The application of such a model could also be useful for the purpose of efficiently designing cladding connections to resist realistic, pressure moderated wind loads based on the venting characteristics of the cladding and the wall system. Based on results of a series of pressure water spray tests of wood frame walls with various claddings, it was found that various wood frame walls may inherently exhibit many of the properties of a rainscreen system with respect to pressure equalization. In fact, it was also found that having a smaller cavity behind the cladding (i.e., less volume of air) improved the response in reducing pressure differentials under a simulated dynamic (gust) wind situation. Pressure equalization was also improved by having a relatively flexible cladding and a relative stiff air barrier (or wall system behind the cladding acting as an air barrier). Thus, vinyl siding was particularly effective at reducing differential pressures to a small percentage of the overall wall pressure differential. Brick and stucco claddings also exhibited pressure-moderated rainscreen characteristics.

This article highlights the reality that walls with these features provide a continuum of different levels of performance with respect to each attribute. For example, claddings on some buildings may exhibit greater pressure equalization than others. In turn, pressure equalization effectiveness of the cladding also depends on the degree of airtightness (effectiveness of air barrier) on the wall system behind the cladding so that the structural wall system (which serves as an air barrier behind the cladding) experiences most of the wind load, rather than the cladding sharing a large portion of the wind load with the wall system. The more effective this equalization effect, the less water penetration will occur as a result of liquid water transport due to pressure differentials from the outside to the inside of the cavity. Also, there are different degrees of efficiency in handling and expelling water that penetrates the rainscreen cladding. This efficiency may be related to the amount of drainage space required to allow water to drain freely, and is dependent on the amount of water that penetrates the rainscreen cladding. The amount of ventilation area behind the rainscreen wall cladding also may affect the drying rate of wetted materials following a wetting event.

- ***Laboratory Investigation and Field Monitoring of Pressure-Equalized Rainscreen Walls, Technical Series 96-236, Research Highlights, CMHC, Ottawa, Canada, 1996.***
- **Rousseau, M. Z. "Facts and Fiction of Rain-Screen Walls" http://irc.nrc-cnrc.gc.ca/practice/wal3_E.html**

In general, a rainscreen wall is simply a recognition that all claddings leak and that a mechanism needs to be provided to expel intruded water. The effectiveness of different variations of rainscreen systems depend on detailing and, more importantly, the ability of a particular wall system to moderate pressure differentials across the cladding that can greatly increase leakage rates. However, the 1996 CMHC report shows that if a secondary barrier is provided and the leakage rates do not exceed the ability for water to be transported by gravity and expelled from the wall, then the issue of degree of pressure equalization may not be a major distinction in evaluating rainscreen wall performance. As a matter of jargon, as discussed by Rousseau, the distinction of whether the pressure differential is actually (or intentionally) designed to be moderated or whether it is not intentionally considered in the design of a wall cladding system is often the distinguishing factor in whether it may be called a "rainscreen" wall or just a "cavity" wall (regardless of what pressure equalization is actually achieved in either case).

All of the foregoing studies of wood frame walls with various cladding systems rely on indexing of wall system performance based on a laboratory moisture loading condition. Future work will require better correlation of these relative test methods, loading conditions, and modeling studies to actual in-field performance and moisture loading variation and a wall systems ability to accommodate these conditions with reasonable serviceability over a reasonable service life with reasonable expectations for maintenance and repair. This is not a trivial task and stands as a significant challenge toward drawing practical applications from this type of information. It is likely that use of this type of information cannot be completely separated from judgment and experience. Therefore, better correlation of these test methods and moisture control design tools with actual experience is needed if practical applications are to be made with a reasonable level of confidence.

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Rainscreen Wall Laboratory Test Results

Selected References

- *Measured Pressure-Equalized Performance of a Brick Veneer/Steel Stud Assembly*, Technical Series 00-101, CMHC, Ottawa, Canada (2000)
- *Measured Pressure Equalized Performance of an Exterior Insulated Finish System (EIFS) Specimen*, Technical Series 00-119 and Technical Series 00-02, CMHC, Ottawa, Canada (2000, 2002)
- *Measured Pressure-Equalized Performance of Two Precast Concrete Panels*, Technical Series 00-100, CMHC, Ottawa, Canada (2000)
- *The Influence of Unsteady Pressure Gradients on Compartmentalization Requirements for Pressure-Equalized Rainscreens*, Technical Series 98-117, CMHC, Ottawa, Canada (1998)
- *A Study of Mean Pressure Gradients, Mean Cavity Pressures, and Resulting Residual Mean Pressures Across a Rainscreen for a Representative Building*, Technical Series 96-207, CMHC, Ottawa, Canada (1996)
- *Optimum Vent Locations for Partially-Pressurized Rainscreens*, Technical Series 97-105, CMHC, Ottawa, Canada (1997)

These reports presenting results of several tests on various rainscreen wall systems (including EIFS, brick veneer, wood siding, vinyl siding, and others) have lead to a better qualitative and quantitative understanding of pressure-equalized rainscreens and important design considerations. The general findings demonstrate the following performance characteristics:

1. The degree of applied wind pressure and the degree of pressure equalization across the cladding determine the amount of water penetration experienced in a given cladding system, with or without defects.
2. Having complete pressure equalization will reduce, but not eliminate water intrusion through the rainscreen (cladding) and joints, because of other moisture drivers that exist.
3. Better pressure equalization is achieved by having a relatively flexible rainscreen (cladding) and relatively rigid air-barrier (wall behind cladding).
4. Depending on cladding type, an increase in air-barrier (wall behind cladding) air leakage results in increases in cladding pressure.
5. The vent size in the rainscreen cladding relative to the volume of air behind the cladding served by the vent is important in moderating dynamic wind pressure differentials on the cladding.
6. Air restriction along the flow path to a vent as well as distance from the vent to the farthest portion of the cavity served will tend to decrease pressure equalization.
7. A tight air barrier behind the cladding is more important to static pressure equalization than dynamic pressure equalization.
8. Pressure gradients on a building wall surface are largest at corner and eave regions and, therefore, smaller compartmentization of the air cavity behind the cladding is required in these areas than in more centrally located areas of a wall.
9. All of the tested cladding types have exhibited some degree of pressure moderation, and all leaked water under the fairly stringent test conditions, sometimes also including intentional cladding defects.

Rainscreen Wall Full-Scale Test Results

Selected References

- TenWolde, A., Carll, C.G., and Malinauskas, V., "Air Pressures in Wood Frame Walls", *Thermal Envelopes VII*, Clearwater Beach, FL, December 6-10, 1998
- Carll, C., et al., "Performance of Backprimed and Factor Finished Hardboard Siding", USDA Forest Service, Forest Products Laboratory, Madison, WI, 1998

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Full-scale tests and monitoring of pressure moderating effects across breathable, or air-permeable, or rainscreen wall systems (pick a name) have also been conducted. These reports describe two test houses monitored for cladding pressure where it was determined that the conventionally installed (no air cavity) hardboard siding generally experienced exfiltrative air-pressures which would tend to expel water and the pressures tended to be significantly moderated. The authors conclude that an air space is not necessarily required to provide substantial pressure equalization across the siding. However, the authors recommend that an air space should be considered for its other benefits (better drainage around windows and doors and reduced water load directly on the secondary weather barrier). In any case, there was no sign of moisture entry through the siding when it was removed from the building some two years after being installed. A small amount of moisture staining was found around windows and doors due to failed caulking.

- **Fisette, Paul, "Housewraps, Felt Paper and Weather Penetration Barriers", University of Massachusetts, Amherst, MA. 1999. www.umass.edu/bmatwt/publications/articles**

This article discusses why an air cavity is not necessary in a rainscreen wall, except possibly in extreme exposures such as the Northwest and coastal areas. The reasons are fairly practical and are in reasonable agreement with the data covered above. It is further recognized that the inclusion of an air cavity behind the cladding causes several difficulties and cost increases that are rarely acknowledged in generalized guidance on rainscreen wall construction or what is otherwise known as cavity walls. Some examples of these difficulties include:

- Padding out window and door trim
- Extending flashing around padded out trim and back to the underside of the weather barrier
- Extending door hinges so doors can be fully opened
- Extending roof overhang or trim detailing at gable ends
- Covering the bottom air space with screening
- Difficulty in detecting and correcting leaks without removal of cladding

Moisture in Exterior Wall Systems [MEWS] Project

- **Final Report from Task 8 of the MEWS Project (T8-03) – "Hygrothermal Response of Exterior Wall Systems to Climate Loading: Methodology and Interpretation of Results for Stucco, EIFS, Masonry, and Siding-Clad Wood-Frame Walls," IRC-RR-118, National Research Council Canada, Institute for Research in Construction, Ottawa, Canada, November 2002; www.nrc.ca/irc/pubs**

Initiated in 1998, the main emphasis of the MEWS Project (Moisture in Exterior Wall Systems) was to predict the hygrothermal response of several wall assemblies exposed to North American climate conditions under a range of leakage loads (e.g., rainwater intrusion in the presence or absence of selected defects in the tested envelope systems). The program was initiated in response to rainwater penetration problems that had been experienced in Canada (see the Case Study section above). This ambitious multi-year project investigated many parameters that are important to predicting hygrothermal behavior of wall envelope systems.

Wall systems were selected based on materials and practices found in field studies of building water intrusion problems in Canada as well as those commonly used in the Canadian homebuilding industry. The selected wall systems included Portland cement stucco, brick masonry, vinyl, hardboard (wood-based), and Exterior Insulation Finish Systems (EIFS) claddings. All wall systems used wood frame construction methods and materials. Material properties in relation to moisture were studied to develop basic moisture sorption and desorption relations under a range of ambient temperature and humidity conditions. Climatic conditions in relation to wetting and drying potential of building constructions were investigated and a climate index was developed based on analysis of weather data and comparison of several existing methods (see the discussion of MEWS Task 4 in Climate section above). The climatic studies also identified moisture loading ranges (impinging rain) to be used in subsequent testing and modeling of wall specimens of the various types. However, specific "rules" for associating the climate index with a specific building configuration and exposure were not investigated since the primary role was to provide a plausible set of "bounding" conditions for the purpose of predicting hygrothermal responses.

For the MEWS Task 8 research, wall systems were subjected to various water spray and pressure conditions (wetting episodes) and then allowed to dry under controlled climatic conditions. The moisture entry rates realized during testing were not correlated to entry rates that may actually occur in the field due to various factors, including

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the random occurrence of defects. The results from laboratory tests provided input data and a calibration basis for benchmarking hygrothermal response predictions using a computer simulation model called "hygIRC". The key properties and effects studied parametrically were climate severity, material properties, configurations of wall components, and amount of "accidental" water entry into the wall. For the purpose of evaluating vulnerability to moisture damage and interpreting the hygrothermal modeling results, a damage potential index (e.g., limit state) was developed based on the cumulative time of a particular location in a wall assembly with temperature and humidity above selected thresholds considered to be conducive to wood decay. Less attention was given to effects such as variable indoor humidity levels and air leakage. While different wall systems were studied, the MEWS reports caution that the results are more dependent on the nature of deliberately introduced deficiencies and the construction details employed than to the generic cladding systems themselves. Therefore, the authors caution that results between different cladding systems should not be directly compared. The results should also not be interpreted in an "absolute sense" since the parametric modeling studies involved several simplifying assumptions or educated judgments to overcome a number of obstacles.

Some of the most relevant observations made by the researchers regarding the effectiveness or ineffectiveness of changes to various wall parameters are as follows:

- For conditions when no leakage was considered to occur past the water barrier membrane (if present) into the wall cavity, all of the wall systems performed very well with little to no predicted potential for water damage in all climate severities considered.
- Under the conditions of some amount of water entry into the wall cavity, all wall systems were affected in proportion to the severity of climate and associated water entry load for each cladding type. However, some appeared much less tolerant. For example, walls with exterior insulation tended to experience higher cumulative damage potential. This reason is associated with two factors: (1) the exterior insulation tended to moderate wall cavity temperatures which increased the time spent above a threshold temperature and moisture level considered conducive to the onset of wood decay, and (2) the exterior insulation tended to decrease the drying potential of the wall, further increasing the duration of the condition described in item (1). This observation was noted for all EIFS walls studied as well as brick clad walls when insulation board replaced a more vapor permeable sheathing such as asphalt-impregnated fiber board. A similar response was found when OSB sheathing was replaced with extruded polystyrene (XPS) sheathing for vinyl clad walls. In these cases, moisture accumulation was often reported as "overwhelming", which would indicate propagation of moisture problems to larger areas of walls by other transport mechanisms with high water entry loads due to defects resulting in leaks. This effect is at odds with the benefits of exterior insulation in terms of increasing energy efficiency and reducing condensation potential. It also suggests that higher levels of care in design, construction and maintenance may be required to prevent water leaks when exterior foam board insulation is used. This concern may be moderated by use of a very permeable board insulation material such as expanded polystyrene (EPS).
- Increasing the vapor permeance of interior side of walls in moderately cold to warm climates usually tended to increase drying potential and reduce the duration of potentially damaging moisture conditions in the wall; however, these results depended on assumed interior humidity conditions and are considered to be preliminary and in need of additional study.
- Adding a vented cavity behind the claddings provided a modest reduction in the duration of conditions favorable to moisture damage when leakage amounts were at the smallest levels considered in the study. The benefit of a vented cavity in potentially reducing the water load that may enter a wall cavity through a defect in the secondary or inner water barrier was not investigated in the study.
- Overall the trends in the results were consistent with field observations of and experience with buildings, cladding types, and climate conditions that have resulted in moisture problems due to water penetration in building walls.

In summary, the MEWS studies taken in collection with field experience confirm that water leaks into the wall cavity, in general, should be avoided and corrected promptly. This is entirely consistent with the accepted objective of building envelope design, construction, maintenance, and remediation. However, in wall systems with relatively low drying potential (particularly toward the outside in colder climates) water leakage is more problematic and cannot be tolerated for any substantial length of time. Therefore, these types of wall systems either require meticulous quality control, maintenance and detailing of penetrations, or should be limited to applications in climates with relatively low wetting potential and high drying potential, or should otherwise be protected by roof

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overhangs and wind-shielding to effectively reduce water loading on the wall surface. For some siding systems, drainage planes may provide a suitable level of increased protection against water penetration provided that the drainage plane is subject to the same level of quality control during installation as described above in severe climates. This also shows that systems with low drying potential are intolerant of what may be considered "incidental" leakage in other wall systems of greater drying potential. Sources of incidental leakage may include leakage through window frames, failed or faulty sealant joints, or missing/defective flashing.

A.2.5.4 Windows, Doors and Skylights

Selected References

- www.eifsalliance.com/articles/166.html -- based on CMHC British Columbia study previously cited
- EIFS Review Group report by Wilmington (N.C.) Building Department
- *Water Penetration Resistance of Windows – Study of Codes, Standards, Testing, and Certification, Technical Series 03-125, Research Highlights, Canada Mortgage and Housing Corporation (2003)*

It has been estimated in Canadian building envelope moisture studies that about 40% of windows allow water to leak through multiple leakage paths, either into the building or wall envelope. In separate monitoring of EIFS-clad homes in the United States by the Wilmington, N.C. building department, it was found that about 30% of the houses with leaks around window installations were associated with leaking window frames. The performance of window, door, and skylight systems are generally governed by building codes and related standardized test methods. However, given the implications of these components leaking into the wall, recent interest in Canada has focused on evaluating the effectiveness of these standards in providing products and installations that are more resistant to water intrusion, as discussed in the 2003 CMHC report. Similar concern is evident in the United States. Indeed, many of the water intrusion tests and research addressed in this review have included window and door components in wall system tests. Some of the major concerns with existing window tests are that they do not include or address many of the leakage paths associated with water intrusion in actual field assemblies. In addition, laboratory test specimens are generally fabricated under ideal conditions which are not necessarily representative of actual installation conditions in the field. It should also be noted that, given the number of combinations of wall systems and window systems that are possible in today's market, it is very difficult to fully evaluate all the possible use conditions. However, a wide range of window installation conditions and practices has been recently developed as ASTM standard guide E2112, and a similar document also exists in Canada.

A.2.5.5 Foundations

Selected References

- *Building Foundation Design Handbook*, Oak Ridge National Laboratory, May 1998
- Lstiburek and Carmody, *Moisture Control Handbook*, John Wiley & Sons, 1994.
- *Durability by Design*, U.S. Department of Housing and Urban Development (2001).
- Sacks, A.M., *Residential Water Problems: Prevention and Solutions*, NAHB Home Builder Press, Washington, DC, 1994
- Yost, N. and Lstiburek, J., "Basement Insulation Systems", Building Science Corporation, 2002
- Brown, R.W., *Practical Foundation Engineering Handbook*, McGraw-Hill, 1996

Bulk moisture problems with foundations generally result from surface and subsurface soil water and drainage. Subsurface soil water includes groundwater and water that may move through and accumulate in soil due to recent rain events. Surface drainage deals with drainage or conveyance of surface water (rain or snow melt or irrigation sources) prior to its infiltration into the soil. Controlling surface water drainage is universally recognized as the first line of defense against foundation moisture problems; see, for instance, the Oak Ridge *Building Foundation Design*

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Handbook, or NAHB's *Residential Water Problems: Prevention and Solutions*. While there are other issues associated with surface and subsurface water, the focus of this section is on the potential for bulk water intrusion through or around building foundations (see Moisture Hazard Section). Like the above-ground structure, bulk water intrusion past foundations is often reported in the literature as being a more common concern than other types of moisture problems. However, other moisture transport mechanisms such as capillary flow may be more directly involved with finished basements, and evaporation and air movement can contribute to transferring bulk moisture to other parts of the building.

The foundation types most commonly used in the United States, in rough order of usage, are concrete slab-on-grade, basement, and crawlspace. In special conditions, such as coastal flood plain construction, other types such as elevated pile foundations are more common. Considerable information is available on design and construction practices related to moisture protection strategies for these types of foundations. As is often the case, most of this information is based on accepted practice, experience, and professional judgment.

Foundation moisture protection methods usually include several of the following features, with the combination depending on site conditions or local construction regulations:

- *Site Study* – determine surface and ground water characteristics of the site to aid in initial site selection and construction planning decisions.
- *Site grading (all sites)* – surface water removal
- *Roof Guttering and Drainage* – surface water removal
- *Perimeter Footing Drainage* – incidental surface water and “light” seasonal ground water flows
- *Underfloor Drainage* – wet sites with seasonally high water table
- *Dampproofing* – applied to walls primarily to prevent capillary moisture intrusion resulting in “dampness” on the interior under soil conditions that are not commonly saturated.
- *Waterproofing* – applied to walls on wet sites (commonly saturated soil) for the purpose of giving a higher level of prevention of liquid water entry through minor cracking and by excessive capillary action; does not imply a “flood proof” construction.
- *Floodproofing* – designing foundations to “survive” large hydrostatic pressures, but not necessarily prevent interior water entry during a flood event; gives improved resistance to water intrusion during lesser events.

Design principles, construction practices, and materials used for the above purposes are addressed comprehensively in the *Building Foundation Design Handbook*

Foundation water problems are frequently cited in the literature and building industry surveys as an ongoing problem, as noted in *Durability by Design*. As with other parts of the building, most literature points to essentially two approaches for avoiding or controlling foundation bulk moisture intrusion problems: (1) reduce sources of bulk moisture and (2) implement a variety of bulk moisture protection or management strategies.

The strategies for foundation moisture protection address drainage of roof run-off (guttering), surface grading, foundation drainage systems, and dampproofing and waterproofing of foundation walls. A combination of these strategies is normally recommended or required in all but the driest of site and climate conditions. The practices are based on experience and judgment as to effectiveness and when they may be required. Local knowledge of site conditions and some form of site exploration are normally required or highly recommended. High ground water, however, is particularly difficult to remedy and strategies must start with appropriate knowledge of ground water conditions and selection of foundation type (e.g., avoid basements or crawlspaces with lower interior grade). Flooding is also a significant concern with building foundation selection in order to prevent catastrophic moisture damage or structural failure. Water vapor loads are also significant issues in foundations and are addressed in Section A.3 of this literature review.

Foundation practices in regard to prevention of moisture intrusion are governed by local building codes and experience. Local building codes are usually based on model building code provisions with amendments reflecting local experience, opinion, or risk aversion related to a particular building performance issue. In addition, there are several guides including the *Building Foundation Handbook*, *Durability by Design* and the *Moisture Control Handbook* that provide additional information or enhanced foundation design and construction recommendations. Typical enhanced recommendations include increasing slope of the grade away from the foundation, increasing

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drainage, providing additional capillary breaks between foundation elements, use of porous backfill material, and enhanced coatings or coverings on the exterior of the foundation wall. In one case, a recommendation regarding moisture control for various foundation insulation schemes has been revised due to problems with moisture entrapment behind a more conventional use of vapor barriers on the interior of finished basement foundation walls. This is described in the piece by Yost and Lstiburek (2002). Moisture sources contributing to basement wall problems include vapor diffusion, leakage of water through cracks and joints, capillary action through concrete and masonry, and potential flooding.

Protection of wood products against decay often involve accepted practices and code requirements for use of wood in foundations and other applications on, in, or near to ground. These practices are generally based on use of minimum ground clearances and capillary breaks between wood and cementitious (porous) materials that can wick up ground moisture by capillary action, also known as “rising damp”, as described in *Durability by Design*, the *Moisture Control Handbook*, and other sources. In some cases, increased ground clearances and wood protection requirements have been advocated for enhanced durability and protection against decay in applications subject to wet or damp conditions. In all cases, pressure preservative treated lumber or naturally decay resistant species of wood are required for applications that do not meet the clearance requirements or that are used in direct contact with the ground.

Practices to address ground and surface water generally include:

- Foundation Drainage (ground water and fast recharge surface water)
- Site Grading and Roof Drainage (surface water)
- Foundation Dampproofing and Waterproofing (damp to wet soil conditions)

Just as with building materials, the soils underlying and surrounding a building are also subject to moisture-related problems. These problems can result in structural damage to the building (as with the effect of changing soil moisture in an expansive clay soil, discussed earlier). On a larger scale, high ground water levels can also contribute to landslides, mudslides, subsidence, and liquefaction during earthquakes or excessive ground vibration, with obvious implications for buildings and other structures.

A.2.5.6 Flashing (Cladding-Component Interfaces)

Selected References

- Remmele, "Flashing: The Plain Solution to Leaky Walls", *Building Standards*, International Conference of Building Officials, Whittier, CA. Nov-Dec 1999
- BIA Tech Note 7, "Water Resistance of Brick Masonry - Design and Detailing" (1985, rev. 2001), <http://www.bia.org>
- ASTM E2112-01, *Standard Practice for Installation of Exterior Windows, Doors, and Skylights* (2001)
- *Durability by Design*, U.S. Department of Housing and Urban Development (2001)
- *Asphalt Roofing Manufacturers Association - Flashing Guidelines*

For most rainwater penetration problems it appears that improper flashing and sealants are implicated, or sometimes the sole cause. This primary concern is recognized in the literature, often with recommendations for improvement of building code flashing details and inspections of weather barriers. There is no shortage of information on strategies and details for flashing various types of wall and cladding systems as well as components such as windows and doors. Some important sources are listed above. These guidelines are available through a number of trade associations, manufacturers and other organizations. However, with some justification, it is felt that many of these details are incomplete, or fail to address special situations or combinations of materials found in actual practice. In fact, it is recognized that industry practices may often ignore these details or consider them unnecessary for various reasons. For example, despite manufacturers' recommendations and other sources of flashing details for typical nail-flange window units, these products are generally installed directly to wall sheathing without the presence of flashing or a drainage membrane.

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A.2.5.7 Caulking and Sealants (Cladding-Component Interfaces)

Selected References

- "The Ins and Outs of Caulking", Advanced Housing Research Center, Forest Products Laboratory, Madison, WI, May 2000
- O'Connor, T.F., "The One Percent of Cost That Can Become 90 Percent of Trouble", *Standardization News*, American Society of Testing and Materials, West Conshohocken, PA. June 2003
- Forgues, Y.E., "Properly Sealed Construction Joints", IRC/NRC, http://irc.nrc-cnrc.gc.ca/practice/sea2_E.html

Caulking is often required by manufacturer guidelines as a part of wood and other siding installation. However, there are situations where caulk may be only temporarily beneficial and actually harmful to siding performance if it fails and is not maintained properly. There are other locations where caulk should not be applied and flashing only should be used to promote proper drainage of water. The service lives of caulks are highly dependent on the caulk material as well as installation conditions and care. For these reasons, many believe that caulk should not be relied upon to maintain a weather-resistant barrier. Studies have also been conducted to investigate the performance of caulkless methods of siding installation. For barrier or face-sealed cladding systems that rely on caulk, O'Connor points out that the sealants that may comprise less than one percent of the building cost can become "90% of the problem" if a building develops leaks. For this reason, the author calls for an increased role of standard specifications and guides to reduce this problem. However, others believe strongly that face-sealed cladding systems or other wall systems that rely solely on sealants for prevention of water penetration are unreliable and should be avoided. In addition to the references above, this belief finds support in the case studies cited on EIFS.

Problems with caulks are frequently reported in surveys and information sources on building performance issues. Life-expectancies of caulk and sealants are typically reported to be in the range of 2 to 5 years, whereas other envelope components have much longer life-expectancies ranging from 15 to more than 50 years (see the NAHB statistics referred to in the HUD/PATH 1999 Durability Workshop report). Thus, there is an implied expectation that any siding system that relies on caulking to maintain proper function (e.g., prevent water intrusion) will require periodic maintenance. Considering the variation in performance that may be realized with field installed sealants, the actual life expectancy may typically be less than two years. Guidelines for "optimal" caulk selection and joint design are usually not considered in typical residential construction. However, some practical guidance on caulk selection and application is available, for example in *Durability by Design* and the Forgues piece.

A.2.5.8 Resistance of Wood in Construction to Bulk Moisture

- *TPI/WTCA Interim Guidelines for Use of Alternative Preservative Treatments with Metal Connector Plates*, Wood Truss Council of America, Madison, WI, January 27, 2004

Material properties and design details relating to the protection of wood against the effects of bulk moisture are varied. Recommended practices or building code requirements often rely on a combination of actions. Protection of wood against moisture includes consideration of paints and stains, ground clearances, flashing, joint detailing and end treatment, capillary breaks, preservative treatment, and natural resistance to decay (species dependent). The Wood Handbook and many documents discussed earlier in this literature review (see Section A.2.2.5) address recommended practices or requirements for wood materials in building construction. There are also numerous material standards addressing wood properties and resistance to bulk moisture effects, such as resistance of wood structural panels to edge swelling. Newer wood panel products that exceed minimum edge swelling resistance criteria are also available on the market.

New chemicals replacing chromated copper arsenate (CCA) are being introduced for wood products that are required to be pressure-preservative treated in residential and other non-industrial types of applications. Some of the newer treatment chemicals, in the presence of moisture, have been found to increase the degradation of protective coatings typically used on fasteners for wood. This issue is fairly new and is still under study. Various sources of information on this issue can be found on the world wide web and in industry publications such as the TPI report cited above.

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A.3 Water Vapor-Related Moisture Problems

A.3.1 Introduction

This section summarizes the scope of water vapor-related moisture problems in houses based on a sample of current literature on the topic, including field studies and assessments, technical papers, and research reports. Pertinent building systems and building science dynamics involved in reported water vapor problems are discussed, and current efforts to address these problems are highlighted.

The four comprehensive moisture-related reference works that were summarized in section A.2.1 (*Moisture Control in Buildings*, *Moisture Control Handbook*, *ASHRAE Handbook of Fundamentals* and *Durability by Design*) all address water vapor issues as well as bulk moisture issues. While those works are cited at various points in this section, the descriptions in section A.2.1 should be consulted for more information.

Water Vapor Principles

Before examining specific problems in buildings related to water vapor, it is first useful to discuss the basic principles that govern this form of water. Where does water vapor in buildings come from? How and why does it move from one location to another? This section gives an overview of water vapor in the context of residential buildings, so that the specific problems discussed later in this report can be related to the underlying physical principles that govern both the problems and solutions.

Sources of Water Vapor

Selected References

- Christian, J.E., "Moisture Sources", Chapter 8 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)
- Rousseau, M.X., "Sources of Moisture and Its Migration through the Building Enclosure," *ASTM Standardization News*, November 1984, pp. 35-37.

Water in and around houses can come from a long list of sources – rainwater, cooking, human respiration, lawn sprinkler systems, combustion appliances, etc... Therefore it is helpful to categorize water sources into three categories: (a) external, (b) interior or occupant-generated, or (c) “built-in”.

External sources of water include rain, snow, ground moisture, and airborne humidity. In terms of water vapor, ground moisture and airborne humidity offer tremendous sources of moisture that can make its way into buildings. For example, Rousseau reports that a crawlspace foundation without ground cover can release as much as 40-50 liters per day of moisture into conditioned space. Christian indicates that high outdoor absolute humidity levels may contribute from 30 to 120 liters per day to a building. Moisture from outdoor air is especially critical in cooling climates, where it may represent the major source of internal moisture.

Interior or occupant-generated moisture comes from a wide range of sources including occupant respiration, combustion from appliances such as natural gas stoves, bathing and showering, cooking, humidifiers, plants, and even pets and fish tanks. All of these sources can release water vapor into the indoor air of a house. Based on various references cited by Christian, internal moisture loads for single-family houses can range from roughly 4 to 23 liters per day. The upper end of this range can be significantly exceeded by venting clothes dryers indoors, using kerosene-fueled heaters or unvented heaters extensively, and storing large quantities of firewood inside. Interior moisture sources are more important to the overall water vapor balance in colder climates.

Built-in moisture is water that is present in building materials as a house is constructed, either as a result of the installation/fabrication process (e.g. water in concrete) or exposure to wetness during construction (e.g. wetted framing lumber). Major sources of built-in moisture include fresh concrete, lumber, and wet-applied insulation. For example, Christian reports that over the first two years of a building’s life, each cubic yard of concrete releases 90 liters of water, meaning that an “average” foundation would release roughly 2300 liters of water in the form of water vapor. For newly constructed houses, the moisture loading from built-in sources may average 10 liters per day

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during the first winter and roughly ½ this rate during the second year, before falling off to no loading at all. Most (though probably not all) of this water would be released into the indoor air.

Water Vapor Movement

Selected References

- Kumaran, M.K. et al, "Fundamentals of Transport and Storage of Moisture in Building Materials and Components", Chapter 1 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)
- David T. Harrje, "Effect of Air Infiltration and Ventilation", Chapter 9 of *Moisture Control in Buildings*. ASTM MNL 18, 1994
- Lstiburek and Carmody, *Moisture Control Handbook*, Chapter 1 (1994)
- ASHRAE Handbook 2001 *Fundamentals*, "Moisture Migration" p.23.14 (2001)

Water can move from place to place in both liquid form and as water vapor by a number of mechanisms. Where houses and residential buildings are concerned, the most important movement mechanisms and driving forces are:

- Liquid flow driven by gravity or air pressure differentials
- Liquid flow driven by capillary suction through porous building materials
- Water vapor diffusion driven by vapor pressure differences
- Water vapor movement via air flow, which is driven by air pressure differentials

Since the moisture problems discussed in this section focus on water vapor-related issues, a brief discussion of water vapor diffusion and water vapor movement via air flow follows. For each movement mechanism, the physical process is described along with the implications for moisture problems in houses. In examining *any* moisture movement dynamic, it is helpful to recognize that for water to move it must have 1) a source (discussed above), 2) a pathway to travel, and 3) a driving force to push it along its pathway.

Vapor diffusion is the movement of moisture as a vapor through a material. The pathways for diffusion are the pores within a material, and the driving force is the vapor pressure differential acting across the material. Since a water source, a pathway, and a driving force are all necessary for water to move, for vapor diffusion to occur across a wall, for instance, the wall must be permeable to vapor migration and there must be a difference between the indoor and outdoor vapor pressures. *Controlling* vapor diffusion therefore requires controlling either the moisture source (indoor, outdoor, or built-in moisture), the pathways (pores in building materials), or the driving force (vapor pressure differentials).

The resistance of a material to vapor diffusion flow is characterized by its permeance, expressed in "perms" (grains/hr * ft² * in. Hg). The "permeability" (perm * in.) of a material is the water vapor flux per unit thickness of that material. Building materials that have a strong resistance to vapor flow (e.g. a low permeability) are called vapor diffusion retarders. Vapor diffusion retarders act to slow the flow of vapor through them. Common examples of vapor diffusion retarder materials include polyethylene sheets, vinyl wall coverings, aluminum foils, low permeability paints, asphalt impregnated facings, and impermeable rigid insulations.

The effectiveness of a vapor diffusion retarder in blocking diffusion is a function of its permeance, installation, and operating conditions. In heating climates, the vapor pressure is typically higher inside the building compared to outside, so vapor diffusion acts to move moisture outward through the building shell. In cooling climates, the outdoor environment often has the higher vapor pressure, and vapor diffusion acts to move vapor from the outside towards the interior of a house.

Depending on the climate and building materials used, vapor diffusion retarders may be employed in the building shell to minimize the transfer of moisture into building assemblies. In heating climates, for example, a vapor diffusion retarder is commonly installed behind the drywall on exterior walls to reduce the wintertime diffusion on interior water vapor outward into the building envelope (where it could contact cold surfaces and condense). The

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effectiveness of a vapor diffusion barrier is directly related to its coverage of the surface across which diffusion is to be blocked. Thus a vapor diffusion retarder that covers 75% of a building envelope is 75% effective.

Water vapor problems can result from either the omission of a vapor diffusion retarder where it is needed or the installation of a vapor diffusion retarder in a locations where it blocks vapor diffusion and causes condensation to form within a building assembly. Examples of such problems are discussed later in this report.

The **movement of water vapor via air flow** is a powerful mechanism in which air containing moisture (e.g. humidity) flows from one location to another, bringing with it the moisture that it carries. The pathways for water vapor movement via air flow are openings in a building envelope through which air can travel (e.g. cracks around an attic hatch). The driving force is an air pressure difference between two adjacent areas.

Since a water source, a pathway, and a driving force are all necessary for water to move, in order for water vapor to migrate into a house via air flow there must be moisture in the outside air, the building envelope must have cracks or holes to act as pathways, and there must be an air pressure difference between the building interior and outdoors. Similarly, *controlling* the movement of moisture by air flow requires controlling either the moisture source (indoor, outdoor, or built-in moisture), the pathways (cracks and holes in the envelope), or the driving force (air pressure differentials created by stack effect, wind, or mechanical systems).

The movement of water vapor by air flow is far more powerful than vapor diffusion effects in houses, as even fairly small air leaks can move large amounts of water vapor compared to vapor diffusion. Harrje estimates that the ratio of moisture transported by air flow compared to vapor diffusion is 10 to 1 or even higher. ASHRAE 2001 *Fundamentals* recognizes that effectively controlling moisture in a building requires an effective *air barrier* or *air infiltration barrier*, and states that “without effective control of airflow, vapor retarders are completely ineffective.” Air barriers - or "airflow retarders" as they will be referred to in this paper - are designed to reduce airflow through the building envelope and in doing so help to control the transport of water vapor into and through building assemblies.

Whereas the continuity of a vapor diffusion retarder is not crucial since its effectiveness is determined by the extent of coverage, continuity is critical for airflow retarders. Small gaps in airflow retarders can concentrate both air leakage and the deposition of moisture as condensation in localized areas, causing significant moisture damage.

Significant water vapor problems can result from the leakage of moisture-laden air into building assemblies, where surface temperatures below the dew point of the flowing air will cause condensation to form. Conversely, the flow of air through building assemblies can also have a positive effect and aid in the drying of wetted areas. Finally, efforts to control water vapor movement by air flow by eliminating pathways (e.g. air sealing of the building envelope) can also lead to moisture problems. Examples of this range of issues are discussed in the following section of the report.

A.3.2 Water Vapor Problems and Causes - General Approach

This part of the report provides an integrated discussion of reported moisture problems related to water vapor in houses and the building systems and building science involved in each issue. The water vapor issues discussed in the following sections have been drawn from a sample of current industry technical papers and research reports, and focus primarily on conclusions that have been drawn from recent field-based assessments. The cited references were identified and used to provide a cross-section of water vapor-related problems, issues, and research needs; however, the reference collection list should by no means be considered exhaustive. Finally, it should be noted that all of the references are anecdotal in nature when considered in the context of the U.S. housing stock. Therefore the water vapor-related issues discussed are not ranked by severity or frequency and can be used only qualitatively to characterize water vapor issues in the overall housing stock.

The moisture issues are organized first by building system (e.g. attic, walls, foundation) and secondly by the specific issue. In those cases where an issue overlaps into multiple areas it is noted. Further, while the water vapor problems described below are discussed as stand-alone issues, it is very important to realize that real moisture problems in houses are typically the result of a combination of factors. For example, a house with a relatively tight building envelope but no other vulnerabilities might not experience any significant moisture issues. However, when

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this same house also has significant built-in moisture from wet construction materials, heavy internal moisture loads from cooking and occupants, inadequate exhaust capacity at point sources of moisture, and an air-conditioning system that is improperly sized and unable to address the latent load, these factors can easily combine to create moisture problems in the home. This paper discusses these issues independently for the purpose of clarity, but in reality it is combinations of issues working in concert that create moisture problems in houses.

A.3.3 Water Vapor Issues in Exterior Walls

Water vapor issues in exterior walls – as well as all other types of moisture issues - can be broken down into the core components of moisture transport:

- Moisture source (exterior, interior/occupant-generated, or built-in),
- Pathway (diffusion – porous materials; air flow – cracks and leakage points), and
- Driving force (diffusion – vapor pressure differential; air flow – air pressure differential).

For each of the issues described below, one (or more) of these components of water vapor movement is functioning in a way that causes moisture damage in homes.

- **Interior Vapor Diffusion Retarders in Hot/Humid Climates**

Selected References

- **Lstiburek and Carmody, *Moisture Control Handbook*, Chapter 6, "Moisture Control Practices for Cooling Climates" (1994)**
- **ASHRAE Handbook 2001 *Fundamentals*, "Water Vapor Retarders and Airflow Retarders " p.23.15 (2001)**
- **Texas Association of Builders, "Recommendations for the Prevention of Water Intrusion and Mold Infestation in Residential Construction", December 2002.**

For houses in cooling-dominated climates, the outdoor environment usually has a higher vapor pressure than indoors. Air-conditioning removes moisture from the indoor environment, which further reduces indoor vapor pressure and increases the outdoor-indoor vapor pressure differential. This differential is the driving force for vapor diffusion, which acts to move water vapor from the outdoor air into the building envelope under these conditions.

As discussed in the *Moisture Control Handbook*, moisture problems arise when houses in cooling climates are built with interior (e.g. behind the drywall or an interior wall covering) vapor diffusion retarders. Low permeance interior wall coverings (e.g. vinyl wallpaper, vapor impermeable interior paints) and polyethylene vapor retarders located behind drywall can create moisture problems when hot, humid outdoor air comes in contact with these surfaces. These surfaces are highly resistant to vapor transport so they block the vapor diffusing inwards from outdoors, plus they are cooled by the indoor air-conditioning. As a result, the vapor diffusion from the outdoor environment is halted, the air/vapor mixture contacts the cool vapor retarder surface, and condensation in the wall cavity or gypsum results if this surface is below the dew point of the air/vapor mixture.

The components of this problem are:

- Source – airborne moisture in the outdoor air,
- Pathway – the issue is actually the lack of a pathway. The vapor diffusion is blocked by the interior vapor diffusion retarder, and due to the location of the retarder condensation forms in the wall cavity, and
- Driving force – vapor pressure differential between indoors and outside.

Current efforts to address this issue include:

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- education on the difference between airflow retarders and vapor diffusion retarders,
- increased recognition of the permeance implications of interior wall finishes like vinyl wallpaper, and
- recommendations for interior vapor retarders that allow some inward vapor diffusion.

The approach of using a single building material as both the vapor diffusion retarder and the airflow retarder has been used with success in the homebuilding industry and remains a viable design approach in some climates. Using a single membrane to control both vapor diffusion and airflow requires that this material be installed continuously to control airflow. However, if a low vapor permeability material is used as an airflow retarder (e.g. polyethylene sheet), it should not be located where it can create and accumulate condensation.

With respect to vapor diffusion retarder recommendations, the Texas Association of Builders has recently made strong recommendations against the use of polyethelene film as a vapor retarder in Texas houses:

“in [Texas] counties required by the IRC [*International Residential Code*] to have a moisture vapor retarder installed on the warm-in-winter side of the insulation, neither polyethelene film nor any other impermeable materials shall be permitted as a vapor retarder in this application. Kraft backed batts are instead recommended as true vapor retarders, since this materials slows – but does not halt – vapor diffusion.”

The potential moisture damage from using interior vapor retarders in hot, humid climates is even greater if compounding factors like HVAC-induced pressure imbalances are present. This issue is discussed in the HVAC Issues section below.

- **Vapor Diffusion from Absorbent Exterior Claddings**

Selected References

- **Lstiburek, "Solar Driven Moisture in Brick Veneer",**
http://www.buildingscience.com/resources/walls/solar_driven_moisture_brick.htm (no date)
- **Straube, J. "Moisture in Buildings", *ASHRAE Journal*, January 2002**

Buildings with exterior claddings that can absorb water (e.g. brick, wood) from exterior sources like rain can experience intermittent vapor diffusion that acts to diffuse water vapor into wall cavities. Rain is absorbed into the cladding materials during wet periods, followed by periods of solar radiation which heat the wall cladding. As the water-soaked cladding materials are heated, a high vapor pressure develops at the wall cladding, which can drive vapor diffusion through permeable wall sheathing materials into the wall cavity. In heating climates, where typical wall profiles include an interior vapor diffusion retarder (e.g. polyethylene or kraft-faced batts) combined with more permeable wall sheathing materials that facilitate drying to the outside, this vapor may diffuse into the wall cavity and condense on cooler wall surfaces during periods where air conditioning is in use. Depending on the frequency and duration of these conditions and the permeability of the wall materials, moisture accumulation and damage in the wall cavity may result.

The components of this problem are:

- Source – exterior rain water absorbed into cladding, which is subsequently changed to water vapor by solar heating,
- Pathway – porous wall sheathing materials which allow the diffusion of vapor from the exterior cladding through the sheathing and into the wall cavity, and
- Driving force – vapor pressure differential between indoors and environment at the wall cladding.

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Indirect efforts to address this issue include addressing the initial wetting of the wall cladding and may involve improved wall overhangs and less absorbent cladding materials. Direct efforts to address this issue include recommendations to apply a vapor diffusion retarder behind absorbent claddings in heating climate houses.

- **Control of Vapor Diffusion in Mixed Climates**

Selected References

- *Durability by Design*, section 4.2.3, U.S. Department of Housing and Urban Development (2001)
- CMHC, *The Envelope Drying Rates Study*, Technical Series 01-139, see http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/01-139_e.html (2001)
- Kuenzel, H.M. "More moisture load tolerance of construction assemblies through the application of a smart vapor retarder." In ASHRAE, *Thermal Performance of the Exterior Envelopes of Buildings VII*, pp.129-132 (1998)
- Lstiburek and Carmody, *Moisture Control Handbook*, Chapter 5, "Moisture Control Practices for Mixed Climates" (1994)
- Mei, H.T., "Moisture Migration in the Warm Humid Region of Texas – Final Report," Mechanical Engineering Department, Lamar University, Beaumont, TX, 1992

Designing buildings to handle vapor diffusion in mixed climates is not as straightforward as in more heating- or cooling-dominated climates, because in a mixed climate the side of the wall with the higher vapor pressure will shift from inside to outside depending on the season. Vapor diffusion may act from inside to outside for several months during the winter and in the opposite direction for another 3 or 4 months during the summer. This creates a dilemma of where to locate a vapor diffusion retarder(s) and how permeable it (they) should be.

If an interior vapor diffusion retarder like polyethylene sheet is used, summertime vapor diffusion from outdoors into the wall will occur (assuming vapor permeable sheathing and cladding materials are on the outside of the wall). When the water vapor reaches the polyethylene sheet it will not be able to diffuse through this material and will condense if the sheet's surface temperature is below the dew point. This is essentially the same effect described above in "Interior Vapor Diffusion Retarders in Hot/Humid Climates."

The opposite problem may occur in the winter if a low permeance exterior sheathing is applied in combination with vapor permeable materials towards the inside of the wall (e.g. no polyethylene sheet, un-faced batts). Moisture from the indoor environment may diffuse into the wall and eventually condense within the wall cavity at the exterior vapor diffusion retarder. In this scenario the source is indoor humidity, the pathway is a porous wall system until the vapor reaches the exterior retarder, and the driving force is the vapor pressure differential between moist indoor air and dry outdoor air.

Given this situation, a natural question might be: why not use materials with some vapor diffusion retarder properties at both the interior *and* exterior of the wall system? This could potentially limit vapor diffusion from outdoors during humid summer conditions and retard diffusion from indoors during the winter. This practice has been applied with success subject to the requirement that a minimum ratio of the permeabilities of the interior and exterior retarders be maintained and that a double-vapor barrier wall profile is not created (e.g. avoid combinations of interior and exterior materials that both are 1 perm or less). Maintaining this ratio – such as an exterior to interior perm ratio of no less than 5 to 1 in cold climates - promotes the ability for a wall to dry to the outside (in this example) given the right environmental conditions, as discussed in section 4.2.3 of *Durability by Design*. During periods when vapor diffusion results in condensation that cannot escape because of a low permeance layer on one side and a negative vapor pressure differential on the other (e.g. a humid summer day in a heating-dominated climate), wooden walls have the ability to absorb and temporarily store moisture until conditions permit drying.

The hazard with establishing vapor diffusion retarders at both the interior and exterior surfaces of a wall is that water could find its way into the wall cavity via mechanisms other than diffusion (e.g. leaks or the flow of moist air),

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accumulate, and not be able to dry by vapor diffusion in either direction. This set of circumstances could cause substantial moisture damage. For this reason strong recommendations against “double vapor barriers” designs exist.

This raises a key point – that vapor diffusion is an important consideration because if handled improperly it can cause condensation within walls *as well as* because it can facilitate drying of wall components that are wetted by some other mechanism like bulk water leakage. Given that the current mindset that views most construction as imperfect and anticipates some water intrusion into assemblies, designing walls that prevent vapor condensation issues at the same time they facilitate drying of wetted materials is critical.

In fact, a large body of work has been performed to study the drying behavior of walls for this reason. The CMHC Envelope Drying Rates Study evaluated the drying potential of walls sections to the exterior during cool, humid conditions typical of the Vancouver B.C. winter (41°F, 70% RH). It should be noted that the face of the test walls that would normally dry to the building interior was completely sealed in these evaluations and that no air leakage through the wall panels occurred, so the results reflected only drying to the exterior by vapor diffusion. The study results included findings on the re-distribution of moisture within the wall assembly and drying rates as a function of the exterior rainscreen material (e.g. building paper, housewrap). While this work produced wall panel drying performance data to the exterior in a cool, damp environment, the researchers recognized the need for further research on:

- Wall panels with additional cladding systems like vinyl siding
- Drying performance of wall panels to the interior
- Drying performance in varying climate conditions
- Air leakage through wall panels and its impact on drying performance
- Innovative systems and materials designed to enhance wall permeance

Given the likelihood of wall wetting from bulk water leakage, changes in building materials and building characteristics (e.g. tightness), and the challenge of accounting for vapor diffusion and drying in mixed climates, additional research into the drying performance of wall systems is certainly justified. Work in this area should attempt to incorporate as many relevant factors as possible, including new construction materials, the impacts of air flow through walls, moisture storage effects, and “typical” indoor moisture levels.

Research efforts in these areas will help address questions regarding wall drying potential and approaches to vapor diffusion in mixed climates. One area of particular interest is the development and application of “smart” vapor diffusion retarders. “Smart vapor barriers,” as they are often called, have properties that allow them to become more or less permeable under different circumstances (e.g. varying humidity levels). When applied correctly, these dynamic properties can help address vapor diffusion under changing conditions – like one finds in a mixed climate. This ability to change has made such products the topic of increased interest and research in recent years. For example, the Kuenzel paper describes one such material – a nylon film – that has been found to have a perm rating of 1 when RH levels are less than 50% and a rating as high as 36 perms at 90% RH. Materials with such dynamic properties, and their effectiveness in mixed climate wall assemblies, should also be included in future research on wall drying performance.

Current efforts to address vapor diffusion in mixed climate wall assemblies include design guidance on where to locate vapor diffusion retarders in the assembly, permeability levels, and the selection of appropriate materials. Examples include Durability by Design, the Moisture Control Handbook and the report by Mei. Such design guidance is usually combined with related recommendations that address other issues affecting vapor diffusion such as internal moisture control. This reinforces the concept that few of the moisture issues discussed here will develop in isolation, but instead are more likely to combine to create a moisture problem.

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- **Air Leakage into Wall Cavities**

Reference

- **Karagiozis, A.N. and H.M. Salonvaara. *Hygrothermal performance of EIFS-clad walls: Effect of vapor diffusion and air leakage on the drying of construction moisture*. ASTM STP 1352, pp 32-51 (1999)**

While the three previous sections have dealt with vapor diffusion issues in exterior wall systems, air leakage into wall cavities involves the transport of water vapor by air flow, not diffusion. For the sake of discussion this issue is broken out separately, but in terms of building performance it is very closely tied to “Interior Moisture Loads” and “Duct Leakage, Pressure Imbalances and Induced Infiltration”, which are both discussed in later sections.

The flow of indoor or outdoor air through wall assemblies carries with it the water vapor it holds. If this air flows past wall surfaces that are cooler than the dew point of the air-vapor mixture, condensation will form on the surface. This is the primary concern with air leakage into wall cavities. If the air infiltration barrier, which in many cases is the interior drywall finish combined with caulking and sealing, has even minor gaps and openings, then air leakage and condensation can be concentrated at these points. This obviously undermines the moisture control strategy of the building.

Common air leakage problem points in walls are:

- Bathtubs located on exterior walls
- Electrical boxes for switches or outlets
- Plumbing penetrations
- Telephone and TV wiring penetrations
- Dropped ceilings and cabinet bulkheads
- Cantilevered floors

Air leakage at these points forms the pathway for moisture to move into a wall assembly. The other two components of moisture movement – a source and a driving force – will be discussed in other sections.

The primary conclusion of this section is that air leakage is a primary component of some exterior wall moisture problems, and that addressing these leakage points is a commonly recommended technique to reduce excessive infiltration and control the flow of moisture into building assemblies.

It is worth noting that air flow can sometimes help to *dry* building assemblies instead of wetting them. In circumstances where building assemblies have been wetted by some other mechanism like construction moisture, research has found that air flow can aid in drying wet components. See, for example, the 1999 paper by Karagiozis et al.

- **Built-In Wall Moisture**

Selected References

- **Christian, J.E., "Moisture Sources", Chapter 8 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)**
- **USG, "Sheetrock Brand Gypsum Liner Panels - Enhanced", <http://literature.usg.com/pdf/WB2313.pdf>**
- **Cellulose Insulation Manufacturers Association, Technical Bulletin # 3, "Standard Practice for the Installation of Sprayed Cellulosic Fiber Wall Insulation" (no date), http://www.cellulose.org/pdf/cellulose_bulletins/tech_bulletin3.pdf**
- **APA - The Engineered Wood Association, "Storage and Handling of APA Trademarked Panels", <http://www.apawood.org/pdfs/managed/U450.pdf> (2002)**

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Moisture problems in wall assemblies may also develop as a result of built-in wall moisture. And although this issue is not necessarily connected to water vapor, it is certainly prominent enough to include in this review of moisture problems. In this scenario the moisture pathway and driving force are essentially bypassed, because the wall assembly is wet before the building is completed. This can occur in two ways:

- Wall materials have high moisture content due to unintended wetting during the construction process.
- Wall materials are installed with relatively high moisture content by design (e.g. wet applied insulation, green lumber).

Unintended, on-site wetting can affect framing lumber, which is often shielded from falling rain on job sites but not protected from ground moisture below. This moisture can then condense on the underside of rain-sheeting and subsequently wet framing lumber.

Framing is also subject to rain once it is erected but before a building is under cover. Delays in construction schedules can prolong the amount of time that materials and framing are left exposed on-site and increase wood moisture levels. In other cases, building systems like shaft wall assemblies in townhouses include materials like gypsum (used because of its fire rating) that should not experience significant wetting. However, due to their location in the structure of the building these materials necessarily must be installed relatively early in the construction cycle, which exposes the materials to potential wetting by rain. This “shaft wall issue” has become prominent enough that gypsum manufacturers have developed new products for this application that are intended to be more resistant to moisture damage. See for example the USG fact sheet on a mold and mildew resistant gypsum liner panel.

Finally, building materials may show up at the site wet to begin with due to storage conditions at the supplier.

As far as wall materials that are installed with higher moisture levels intentionally, these assemblies can be integrated into wall systems where they can dry once the building is completed (depending on the season and the permeability characteristics of the wall) or they can be allowed to dry out before “closing-in” the wall. The Cellulose Insulation Manufacturers Association notes this issue in its standard practice for installation of spray-applied wall insulation.

Current efforts to address built-in wall moisture include:

- education and guidance from APA and other sources on proper on-site storage of construction materials
- builder protocols to check moisture levels before close-in
- development of more moisture-resistant materials for shaft wall applications
- guidance on setting up builder-supplier relationships that address moisture and mold on materials
- extensive marketing of treatment products for lumber that will make framing less prone to mold growth if it becomes wetted

The potential research needs in this area should focus on evaluating the overall performance of new or alternative materials that are proposed because they appear to be more resilient in the face of on-site moisture. Such assessments should consider moisture, structural, fire, and thermal performance as well as other important considerations like cost, installation issues, and integration with other building materials.

Treatments for framing lumber that claim to prevent the growth of mold were not researched systematically as part of this project. However, based on the public’s awareness of mold issues such products are being heavily marketed and gaining some interest. While treatment products should certainly be assessed for their effectiveness and safety implications, they should also be viewed with some caution because they are not a substitute for the proper management of moisture during the construction and operation of a building.

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A.3.4 Water Vapor Issues in Attics and Cathedral Ceilings

The condensation of water vapor in attics and cathedral ceilings in houses can create chronic moisture problems that affect structural members, degrade insulation, and promote mold growth. Major issues found in current literature are discussed below.

- **Air Leakage from Indoors to Attics and Cathedral Ceilings**

Selected References

- **David T. Harrje, "Effect of Air Infiltration and Ventilation," Chapter 9 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)**
- **Rose, W. and TenWolde, A., "Venting of Attics and Cathedral Ceilings" *ASHRAE Journal*, October 2002**
- **Lstiburek and Carmody, *Moisture Control Handbook*, Chapter 3, "Wetting and Drying of Building Assemblies" (1994)**
- **Buchan, Lawton, Parent Ltd. 1991. *Survey of Moisture Levels in Attics*. Canada Mortgage and Housing Corporation, Research Division (1991)**
- **Rose, W. "Measured values of temperature and sheathing moisture content in residential attic assemblies." *Thermal Performance of the Exterior Envelopes of Buildings V*, pp. 379-390 (1992)**

The transfer of moisture from the indoor environment into attic spaces by air transport has been documented as a major contributor to attic condensation problems; see the articles by Harrje, and by Rose and Tenwold. Interior moisture – which may come from an external source, be built-in, or be generated by occupant activities – can create indoor air with enough moisture content to cause condensation if it comes into contact with cold attic surfaces. Air flow between the house interior and the attic space – which may be driven by the buoyancy of heated indoor air or the “stack effect” – often occurs at leakage points like recessed lights, ceiling fixtures, attic access hatches, and framing details. It may even occur by design if bath fans are vented into the attic, although this practice is universally criticized. Whatever the source, as this moisture-laden indoor air flows into the attic space it contacts cold surfaces and under proper conditions will condense, often on the underside of the roof deck, as mentioned in the *Moisture Control Handbook*. In sub-freezing weather, the condensation may also freeze, and then melt later on when outdoor temperatures rise. This delay in the appearance of liquid water can sometimes mask the core problem: condensation as the result of the leakage of moist indoor air upward into the attic space.

Approaches to dealing with this scenario include:

- relying on attic ventilation with outdoor air to dry condensation that forms
- reducing leakage points between the house and the attic (the pathway)
- reducing and controlling indoor moisture levels (the source)

Numerous studies have documented the close link between high interior moisture and high attic moisture levels. See the 1991 report by Buchan, Lawton, Parent for an example. Based on this finding the current consensus, as summarized in Rose and TenWolde, is that controlling indoor moisture should be the primary means to controlling attic condensation. This approach can also help address other problems that result from high indoor moisture such as air leakage into walls. It is recognized that attic ventilation strategies can provide some condensation control benefits in certain climates and that sealing air leakage pathways into the attic is beneficial. However, Rose and TenWolde view these measures as complementary to controlling indoor moisture levels.

Efforts to address indoor moisture sources are discussed in the Interior Moisture Loads section and in some of the HVAC-related topics that follow. Attic ventilation practices are discussed in the following sections.

Indoor air leakage into cathedral ceilings can occur in ventilated ceiling cavities when ridge vents are used without soffit vents. This arrangement draws moist indoor air upward into the ventilated cathedral ceiling cavity through

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available openings, and can result in condensation forming in the ceiling area. More information appears in the 1992 article by Rose.

- **Attic Ventilation in Cool, Damp Climates and in Hot, Humid Climates**

Selected References

- **Rose, W. and TenWolde, A., "Venting of Attics and Cathedral Ceilings", *ASHRAE Journal*, October 2002**
- **Forest, T.W. and I.S. Walker, *Attic Ventilation and Moisture, Final Report, Canada Mortgage and Housing Corporation (1993)***

In cool and wet climates like the Pacific Northwest the moisture in the outside air that is introduced to the attic space as ventilation is a major source of moisture in the attic. In fact, the report by Forest and Walker determined that in wet coastal climates in Canada, higher attic ventilation rates actually resulted in higher sheathing moisture contents than did lower ventilation rates.

This finding, combined with the conclusion from the previous section that indoor moisture control is the most effective mechanism for addressing attic condensation, lead Rose and TenWolde to the conclusion that unvented attics could be a better approach in wet, cold climates assuming that the indoor humidity is controlled.

A similar situation exists in hot and humid climates. The outdoor air in these climates is often too humid to effectively reduce attic moisture and can instead serve to increase it. According to Rose and TenWolde, "If attic ventilation is recommended for houses in hot, humid climates, it must be based on other considerations besides moisture control."

Current efforts to address attic ventilation issues in both of these climates appear to revolve around unvented attic designs and indoor moisture control. Research on unvented attic performance is ongoing as part of the DOE Building America project, yet the concept is still unfamiliar to most in the industry and often resisted by the building code and inspection community at the local level. Additional research data demonstrating the performance of this approach and documenting its application in varying climates would help to advance and perhaps improve the unvented attic design.

A.3.5 Water Vapor Issues in Building Foundations

Water vapor and condensation problems in building foundations can result from multiple combinations of moisture sources (ground moisture, ambient humidity) and movement mechanisms. While wet foundations issues are most often due to bulk water leakage, a number of issues tied to condensation of water vapor are discussed within current industry literature. Condensation problems in foundations can cause the long list of moisture degradation effects discussed in the introduction to this paper, and can also go unnoticed in some situations because they often occur in unseen locations.

- **Crawlspace Ventilation in Hot, Humid Climates**

Selected References

- ***Crawlspace Myths*. Craig DeWitt, Ph.D., P.E., *ASHRAE Journal*, November 2003**
- ***Field Test Homes and Experiment Setup*. Advanced Energy Website, 2002 www.advancedenergy.org**
- ***Crawlspace Ventilation: Reality versus the Code*, Bruce Davis, Advanced Energy**

One of the most widely discussed foundation moisture issues is proper ventilation design for crawlspaces, especially crawlspaces in hot and humid climates. The concern is that ventilated crawlspace foundations intentionally introduce warm, humid outdoor air into the cooler foundation area, which creates the potential for water vapor condensation on surfaces like floor framing and foundation walls. This wetness can develop over extended periods

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of time when outdoor conditions are warm and humid, and lead to mold growth, water accumulation, and insulation wetting. In some cases builders may actually mis-diagnose the problem and introduce *more* outdoor ventilation air into a wet crawlspace during a humid period of the year, which just exacerbates the problem instead of facilitating drying.

Recent research as reported by Craig DeWitt has investigated the historical basis for current building code requirements for crawlspace ventilation, and found that traditional recommendations developed over time from the *Property Standards and Minimum Construction Guidelines* (1942), the Housing and Home Finance Agency (1949), and the FHA *Minimum Property Standards* (1958). However, DeWitt concluded that crawlspace ventilation requirements – even those in modern codes like the 2000 *International Residential Code* (IRC) – are not adequately supported by a body of research.

This same report also points out that traditional crawlspace ventilation practices are now being applied to new houses that are fundamentally different in ways that will affect crawlspace condensation. Such differences include:

- the tendency to utilize wetter sites for building new homes
- foundations that are built deeper into the ground
- reduced (or eliminated) roof overhangs
- less reliable foundation drainage
- the widespread use of air-conditioning – which is the most significant difference.

Deeper foundations and indoor air-conditioning can both create cool surfaces in a crawlspace where condensation can form. The other factors listed above can also introduce more water leakage into crawlspaces, which can increase humidity both in the crawlspace and the house itself.

Current efforts to address this issue include manually closing crawlspace vents during humid periods, and running dehumidifiers during humid periods to reduce condensation potential. Also, an area of great interest is the design and performance of unvented, or sealed, crawlspace foundations. Sealed crawlspace designs are currently being evaluated for their ability to control crawlspace humidity and limit condensation potential, as well as related factors like their thermal performance and resistance to insect infestation.

Research into sealed crawlspace designs in the southeast U.S. during the summer of 2002 indicated that sealed crawlspaces stayed drier and maintained lower humidity levels than crawlspaces with traditional wall vents. Humidity in the vented crawlspaces closely followed outdoor relative humidity levels, whereas relative humidity in the unvented crawlspaces was lower and much less connected to outdoor moisture levels. Information on the test homes is available on the Advanced Energy website.

Research needs in this area include additional work to validate the moisture performance of proposed sealed crawlspace designs and to assess related factors such as the impacts of workmanship and energy performance. The article by Bruce Davis identifies the energy performance of sealed crawlspaces as a current research gap that, once addressed, could help progress the adoption of this technology into building codes.

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- **Ground Moisture Condensation in Crawlspaces**

Selected References

- Rose, W.B., "Case Study: Moisture Damage to Homes in Champaign Country, IL," *Proceedings, Building Thermal Envelope Coordinating Council Symposium on Air Infiltration, Ventilation, and Moisture Transfer*, Dallas, TX (1986)
- Rousseau, M.X., "Sources of Moisture and Its Migration through the Building Enclosure," *ASTM Standardization News*, November 1984, pp. 35-37
- Christian, J.E., "Moisture Sources", Chapter 8 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)
- Tsongas, G.A., "The Spokane Wall Insulation Project: A Field Study of Moisture Damage in Walls Insulated Without A Vapor Barrier," US DOE/Bonneville Power Administration DOE/BP-541, September 1985

While the previous section dealt with condensation in crawlspaces due to water vapor in outdoor ventilation air, another concern with crawlspaces is ground moisture issues caused by water released from the ground beneath a building. Stored liquid water deep below the ground surface offers an immense source of water, and the soil beneath a building can also be influenced by surface drainage around the site. These sources make water vapor evaporated from the ground into crawlspace areas a major problem if not addressed correctly.

In fact, the *Moisture Control Handbook* states that "leaky basements and the evaporation of moisture from exposed ground into crawl spaces without a polyethylene ground cover continue to remain among the largest contributing factors to moisture-related building problems." The 1986 case study by Rose looked at 670 Illinois houses and arrived at a similar finding, concluding that a clear correlation existed between moisture damage and the presence of evaporative sources of moisture such as exposed soil in a crawl space.

Ground moisture evaporated into the crawlspace environment increases the humidity level and the potential for condensation on surfaces like joists. The increased humidity level can also influence *indoor* humidity when air leakage between the crawlspace and indoor environment occurs. The article by Rousseau states that a crawlspace without ground cover may release as much as 40-50 liters/day of moisture into conditioned space. Christian reports that crawlspaces can draw large quantities of water from uncovered ground surfaces when the water table is within 18 feet of the crawlspace base and the ground soil is something other than porous sand or rock.

The key ingredient in this problem is the lack of a ground cover to inhibit the evaporation of ground moisture. While a polyethylene ground cover is very common in newly constructed houses, older, existing houses may have exposed ground in crawlspaces. For example, the Tsongas article describes a study of 96 houses in Spokane, Washington, conducted in the 1980's, which found that over 43% of the houses with crawlspaces did not have ground cover.

Efforts to deal with this issue primarily consist of applying ground cover to crawlspace floors in new construction and when possible, in existing houses.

- **Built-In Basement Moisture**

Selected References

- Straube, J. "Moisture in Buildings", *ASHRAE Journal*, January 2002
- Christian, J.E., "Moisture Sources", Chapter 8 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)

Basement foundations constructed with concrete have a significant amount of built-in moisture. Based on the amount of water released by concrete and the average size basement, estimates reported by Straube and Christian place the quantity of water vapor released by concrete foundations at several thousand liters over the first two years.

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A.3.6 Water Vapor Issues in the Indoor Environment

The two issues discussed in this section, Interior Moisture Loads and Reduced Infiltration in Tight Buildings, are closely related to each other and to several other issues discussed in this paper. Again, they are broken out into separate issues for the purpose of organizing and discussing water vapor behavior in houses, but in practice interior moisture loads and building tightness work hand-in-hand to influence interior moisture levels and the overall moisture performance of a home.

- **Interior Moisture Loads**

Selected References

- **Lstiburek, "Relative Humidity", Indoor Air Conference, Austin, TX (2002)**
- **International Energy Agency, *Annex XIV: Condensation and Energy, Volume 2: Guidelines and Practice*, August 1990**
- **Trechsel, H.R. and Achenback, P.R., "Field Studies of Moisture Problems in Exterior Walls of Family Housing Units at Naval Air Station, Pensacola, FL," contract report to Naval Civil Engineering Laboratory, Port Hueneme, FL, 1984**
- **Prestemon, D.R., "Perceived Moisture Problems in Iowa Homes," Technical Note, *Forest Products Journal*, Vol. 41, No. 6, June 1991, pp. 47-48**
- *Wall Moisture Problems in Alberta Dwellings*, CMHC

Interior moisture loads (or sources) in a house are a concern because they can strongly affect indoor humidity levels. Indoor humidity levels, along with surface temperatures, determine whether condensation, wetness, and mold will occur on interior materials like windows and drywall. Or in cases where indoor air flows into building assemblies such as attics or exterior walls (both discussed above), the indoor humidity level is a major factor in determining if condensation will form in these areas.

Elevated relative humidity levels *at a surface*, like the drywall corner where two exterior walls meet, can cause condensation, mold growth, and other related moisture problems. The 2002 article by Lstiburek cites a relative humidity level of 70% as the upper limit for RH at a surface before moisture problems will occur, while the IEA report states that a mean monthly RH of 80% or greater next to the surface is necessary for mold growth. While both of these values may seem quite high given that typical indoor RH levels will range from roughly 20 to 60 percent, it is important to understand that relative humidity values in the air adjacent to a surface are strongly affected by air circulation within the space and the temperature of the adjacent surface. The report by Treschel and Achenback shows living areas with satisfactory RH levels at the center of the space could still experience mold growth in cold corners, due to high surface RH levels created by poor air circulation and/or inadequate insulation in exterior walls. This may be a common issue in old houses lacking wall insulation and located in cold climates, especially if warm air is not distributed at perimeter walls.

The combination of moderate to high indoor humidity levels, poor air circulation, and thermal bridges at corners, windows, and points of missing insulation often leads to condensation forming on the interior of the building shell. Window condensation is the most common example of this set of conditions. For example, Prestemon reports on a 1988 survey of over 300 Iowa houses where window condensation was the most frequently observed moisture issue. Obviously older single-pane windows are most susceptible to this effect.

In extremely cold climates even modest indoor RH levels towards the low end of the "typical" range can result in problematic surface relative humidity levels because of the effect of the cold building envelope. The Lstiburek paper states that in severe cold climates, limiting indoor RH levels to 25% results in RH levels at the surface of exterior walls below 70%, assuming walls are insulated to code-minimum R-values. Similarly, the CMHC report, based on for 41 houses and 9 multi-unit buildings located near Calgary and Edmonton, showed that attempts by occupants to maintain indoor RH above 30% during the winter contributed to 14% of all moisture problems in the buildings.

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Indoor humidity levels are directly affected by a multitude of interior moisture loads; information on these sources appears in Chapter 8 of *Moisture Control in Buildings*. The following discussion covers three categories of internal moisture sources that are prominent in current literature on indoor humidity and condensation control: unvented combustion heaters and fireplaces, clothes dryer exhaust, and bathroom humidity.

Unvented Combustion Space Heaters and Fireplaces

Selected References

- ***Recommendations for the Prevention of Water Intrusion and Mold Infestation in Residential Construction*. Texas Association of Builders, Building Standards Initiatives, December 2002.**
- **Tsongas, "Case Studies of Moisture Problems in Residences", Chapter 14 of *Moisture Control in Buildings*, ASTM MNL 18, 1994**
- **"Assessment of the Potential Impacts of Vent-Free Gas Products on Indoor Relative Humidity", Vent Free Gas Products Alliance, December 2002**

Unvented combustion space heaters and, more recently, unvented fireplace units, are used in indoor environments in some houses. When these units operate the products of their combustion, of which water vapor is a major component, are released into the indoor environment. Depending on factors including the frequency and duration of use, unit size or capacity, and the size of the room in which a unit is used, the water vapor released in the combustion products may significantly increase indoor relative humidity levels.

Current industry literature reflects concern that indoor relative humidity levels could be significantly increased by the use of these systems, which could lead to condensation on cool indoor surfaces or the migration of moist indoor air into assemblies like attics. For example, the Texas Association of Builders recently recommended against using gas-operated ventless fireplace units, and Tsongas has noted that "homes with unvented space heaters often have very major indoor moisture problems." The *Moisture Control Handbook* also makes reference to health concerns associated with the release of combustion products into an indoor environment, stating that "it is unwise to use unvented combustion devices in any climate zone due to moisture and other health-related concerns."

Like many other issues in this paper, it is difficult to isolate the impact of this specific issue in real houses and assess its relative significance on interior RH levels. A recent modeling study of vent-free appliances found that the key factors in determining their impact on indoor RH were room volume, size of connected space, number of room walls with external contact to outdoors, number of people in the room, outside temperature, and air exchange rate. The "worst-case" indoor RH scenarios occurred when ventless gas appliances were operated in isolated rooms.

Clothes Dryer Exhaust

Selected References

- **Tsongas, G.A., "The Spokane Wall Insulation Project: A Field Study of Moisture Damage in Walls Insulated Without A Vapor Barrier," US DOE/Bonneville Power Administration DOE/BP-541, September 1985**
- ***Recommendations for the Prevention of Water Intrusion and Mold Infestation in Residential Construction*. Texas Association of Builders, Building Standards Initiatives, December 2002**
- **"Assessment of the Potential Impacts of Vent-Free Gas Products on Indoor Relative Humidity", Vent Free Gas Products Alliance, December 2002**

The exhaust from clothes dryers is heavily laden with water vapor and, according to Chapter 8 of *Moisture Control in Buildings*, can add 2 to 3 liters of moisture per load to the indoor environment if exhausted inside the house. This issue is similar to ground cover in crawlspaces, in that new houses generally have dryer exhausts routed to the outside, but some homes may have dryers exhausted indoors due to the original installation or the desire of

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occupants to add humidity to the indoor air. For instance, in the 1985 Tsongas study of moisture damage in Spokane houses, it was observed that over one-quarter of the 96 houses had the clothes dryer vented indoors.

In new construction, emphasis is being placed not only on venting clothes dryers outdoors, but also on the *design* of dryer exhaust ducts. The Texas Association of Builders now offers specific recommendations on the allowable length of dryer exhaust ducts and calls for a professional engineer to design any exhaust systems that go beyond this limit.

Bathroom Humidity

Selected References

- **Brennan, Cummings and Lstiburek, "Unplanned Airflows and Moisture Problems", *ASHRAE Journal*, November 2002**
- ***Recommendations for the Prevention of Water Intrusion and Mold Infestation in Residential Construction*. Texas Association of Builders, Building Standards Initiatives, December 2002**
- **Tsongas, "Case Studies of Moisture Problems in Residences", Chapter 14 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)**

The moisture generated by showering and bathing and its effect on building materials in bathrooms has recently received increased attention in the building industry. The issue revolves more around the *materials* in the humid environment than the moisture source itself. Due to the high humidity in bathroom areas and the likelihood of wetting from splashes, condensation and leaks, recommendations have been made to substitute alternative products in place of the gypsum-based "green board" that is often used for bathroom walls. Brennan et al. have determined that paper-covered gypsum is very sensitive to moisture, whereas materials like gypsum covered with fiberglass fabric, foam insulating sheets, and fiber-cement boards are more resistant to moisture damage and mold growth. Similarly, the Texas Association of Builders now recommends the use of cement board, fiber cement, or composite products as substrates for bathtub and shower enclosures finished with tile or plastic finished wall panels. They also recommend disallowing the use of paper faced gypsum products (including green board) in these applications.

Efforts to address interior moisture loads and moisture control may be viewed in two categories: existing houses and new houses. Tsongas offers a bleak assessment of existing homes: "simply stated, indoor moisture control in all types of *existing* homes is a myth. If it happens, it usually occurs by happenstance rather than by proper design." Where newer homes are concerned, interior moisture loads are being viewed far more cautiously (as evidenced by the TAB recommendations), with certain products or systems being deemed as too likely to contribute to a moisture problem.

Research needs in the area of interior moisture loads are challenging. Efforts to collect objective data on the moisture implications of specific products or systems would be informative, but in the end these products are just one piece of a much larger moisture management puzzle. Research on emerging building products designed to be more moisture resistant will be needed as new products are developed or product needs are identified.

Also needed is research that can establish target humidity levels for the indoor environment based on consensus surface RH levels that will prevent condensation and mold growth. This would involve building materials research in the context of biological growth to establish surface RH limits, coupled with thermal analysis and airflow/moisture modeling within buildings to determine the corresponding interior conditions.

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- **Reduced Infiltration in Tight Buildings**

Selected References

- **Sherman, Max and Nance Matson, *Air Tightness of New U.S. Houses: A Preliminary Report*, Lawrence Berkeley National Laboratory, March 2002**
- **Tsongas, "Case Studies of Moisture Problems in Residences", Chapter 14 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)**
- ***Moldy Houses: Why They Are and Why We Care & Additional Analysis of Wallaceburg Data: the Wallaceburg Health and Housing Studies*, Canada Mortgage and Housing Corporation**
- **ASHRAE Standard 62.2-2003, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. American Society of Heating, Refrigeration and Air-Conditioning Engineers, Atlanta, GA (2003)**

One of the most frequently cited changes in modern residential construction that affects moisture performance is the trend toward “tighter” building envelopes which allow less natural air infiltration to occur. “Infiltration” in this discussion is the natural flow of air between indoors and outside, whereas “ventilation” is considered to be directly driven by mechanical means (fans) and will generally be referred to as “mechanical ventilation”. The tightness of the building envelope is a major factor in the amount of natural infiltration that will occur into and out of a house, and is determined by the number, size, and distribution of cracks, holes, and other leakage points in the building envelope.

Numerous studies have examined building envelope tightness levels through field assessments like fan pressurization (blower door) testing and tracer gas testing. Some of the most noteworthy findings on building tightness levels emerge out of an ongoing effort by Lawrence Berkeley National Laboratory (LBNL) to collect and analyze the tens of thousands of test measurements that have been made on U.S. dwellings. LBNL currently has over 80,000 individual building tightness test entries in its database, with about one-fourth of these properly vetted for use in analyses.

In a recent analysis of air tightness of new US houses, Sherman and Matson of LBNL arrived at the following conclusions:

- New construction in the US is significantly tighter than the overall housing stock
- The air tightness of new construction is no longer becoming tighter. It appears that there was a trend toward tighter construction that continued until about 1997, at which time air tightness levels for new houses stopped changing and stabilized.

The moisture implications of reduced air infiltration in newer homes are significant but not necessarily straightforward. Sealing building envelopes and reducing infiltration can have the effect of *increasing* indoor moisture levels, especially in heating climates where interior moisture sources tend to dominate. In these regions the exchange of drier outdoor air for more humid indoor air can help to mitigate indoor humidity by essentially diluting the indoor moisture. Tsongas reports that assessments of weatherization programs which air-seal building envelopes and other field studies have concluded that reducing infiltration can cause higher indoor moisture levels, especially in cold climates with significant indoor moisture sources.

However, this tight building/cold climate/high indoor humidity scenario is a function of several factors, including building tightness, infiltration driving forces, interior moisture sources, building size, and building operation (e.g. use of exhaust fans or other mechanical ventilation). And in fact, some research sponsored by CMHC has arrived at a contrary result, finding that tighter houses with lower air exchange rates did *not* have higher indoor RH levels or higher condensation levels. This same study recognized that moisture issues in homes are a function of multiple factors, and that while infiltration and ventilation can certainly help to dilute indoor moisture, outdoor air alone is not the solution to moisture problems. Controlling and limiting the *sources* of moisture is also essential.

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CMHC's conclusion is a good summary of current efforts to address the issue of reduced infiltration in tight buildings: source control and ventilation. Building envelopes continue to be constructed to be more airtight than homes in the past, with emphasis placed on air sealing of building envelope penetrations. To account for the reduction in natural infiltration, efforts are being made to increase moisture source control measures (e.g. exhaust fans), educate homeowners on controlling indoor moisture, and integrate mechanical ventilation in new houses. ASHRAE's Standard 62.2, as approved in July 2003, requires mechanical ventilation in virtually all new houses and reflects the position that ventilation and tight building envelopes are complementary measures.

A.3.7 HVAC-Related Water Vapor Issues

Water vapor exists in an air-vapor mixture in houses. HVAC systems are especially important in the behavior of water vapor in a house because they exert a strong influence on how air moves inside houses and through building envelopes. HVAC systems also play a direct role in the control of water vapor through dehumidification, which removes water vapor from the air, and ventilation. Several water vapor issues that are tied to HVAC systems are discussed below.

- **Duct Leakage, Internal Pressure Imbalances and Induced Infiltration**

The use of forced-air heating and cooling systems in houses has steadily grown over the past several decades to the point where most new construction today utilizes a central blower(s) in combination with ductwork that supplies air to and returns air from living spaces. When supply and return airflows are not balanced in the system because of duct leakage or pressure imbalances due to system design, spaces within a house (or the entire house) become pressurized or depressurized. Since air pressure differentials are the driving force for air flow, these dynamics can cause air, and whatever moisture it contains, to move in unintended and unforeseen ways. Water vapor and condensation problems may result, as further described below.

Duct Leakage

Air leakage from supply ducts in unconditioned spaces can lead to a depressurized house interior when the air handler is operating. While supply air is being lost to unconditioned space like attics or crawlspaces by leaky ducts, the return duct system is pulling in as much air as the air handler is supplying (before duct leakage occurs). Thus more air is being pulled *from* the house by the return system than is being supplied *to* the house by the supply ducts. The result is negative pressurization of the house interior, which causes humid outdoor air to flow in through exterior walls and other building assemblies.

A common example of this scenario is a house in a hot, humid climate like Florida with leaky supply air ducts in the attic. When the HVAC system runs the house is at a negative pressure relative to outdoors, and increased infiltration of outdoor air occurs. During the cooling season when the house is air-conditioned, this dynamic can cause humid outdoor air to be drawn into exterior wall cavities, where it condenses on cool surfaces like the back side of the gypsum wall covering. The problem is exacerbated if there is a vapor diffusion retarder like vinyl wallpaper on the inside face of the wall, because moisture will accumulate at this surface and not be able to dry to the inside. This scenario is discussed in a case study in Chapter 7 of the *Moisture Control Handbook*.

Internal Pressure Imbalances

Selected References

- Brennan, Cummings and Lstiburek, "Unplanned Airflows and Moisture Problems", *ASHRAE Journal*, November 2002
- Lstiburek 1993; Tooley and Moyer, 1988 – from Lstiburek, "Residential Ventilation and Latent Loads", *ASHRAE Journal*, April 2002
- Keeler, "Heating and Cooling Equipment", Chapter 10 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)

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Internal pressure imbalances are pressure differentials that can develop within a house due to the design and operation of forced-air HVAC systems. When spaces within a house become pressurized or depressurized as a result of HVAC operation, unintended airflows carrying moisture will be driven by the differences in pressure.

Central returns are a common example of an HVAC design feature that can create pressure imbalances within a house during system operation. While supply air is ducted to individual rooms, spaces such as bedrooms rely upon a central return grille located in a hallway to draw air back to the system air handler. When bedroom doors are closed air is still supplied to the bedrooms, but the return air pathway is constricted, causing the parts of the building not receiving supply air but still losing return air (like the hallway) to become depressurized. This is described in the article by Brennan et al. Lstiburek et al. report that in these circumstances bedrooms reach positive pressures of 10-20 Pascals with continued supply air but reduced return air flow because the closed door blocks the pathway to the central return. Keeler notes that return air flow from bedrooms is especially important during winter nights, especially if night setback is used, in order to prevent the buildup of humidity (from respiration) and the cool surface temperatures that could result in condensation.

Leaky return air systems constructed from building cavities like joist bays and wall cavities are another example of HVAC design features that can cause internal pressure imbalances. Other features in a house that may also cause internal pressure imbalances include high capacity exhaust fans like commercial-grade range hoods, fireplaces that draw combustion air from indoors, and other combustion appliances that draw indoor air. Even low-capacity exhaust fans in baths and kitchens will create pressure differentials.

Induced Infiltration

Selected References

- **Cummings and Tooley reference from Lstiburek, "Residential Ventilation and Latent Loads", *ASHRAE Journal*, April 2002**
- **Ask, "Ventilation and Air Leakage", *ASHRAE Journal*, November 2003**

HVAC features that create pressurized and depressurized areas in a house are important because they cause increased, or induced, infiltration whenever the HVAC system operates. For example, research done by Cummings and Tooley in the late 1980's and 1990's showed that for homes in hot, humid climates, air exchange rates ranged from 0.5 – 1.0 ACH while the HVAC system was operating. Without HVAC operation, the air changes rates were just 0.1 to 0.2 ACH. And because air flow is a powerful means of moisture transfer, induced infiltration can move large quantities of moisture and lead to condensation and related moisture problems in building assemblies. The energy implications of induced infiltration are also significant, but are beyond the scope of this paper.

To return to the example of a Florida house with leaky supply ducts in the attic, if this house experiences a 5-fold increase in infiltration due to this duct leakage when the air-conditioning system operates *and* it has vinyl wallpaper as an interior wall finish, large quantities of humid outdoor air will be drawn into wall assemblies and may create condensation on the back-side of the vinyl wallpaper. During prolonged periods of hot weather when the A/C operates frequently this problem will grow continually worse. While this scenario involves multiple issues, it illustrates the impact of duct leakage and induced infiltration.

Current efforts to address moisture problems related to duct leakage, pressure imbalances, and induced infiltration include construction practice recommendations revolving around sealing ducts and employing techniques to facilitate return air pathways (e.g. transfer ducts). This work is applicable to new homes and to a lesser extent, existing houses. There is also interest in using building pressurization to control air flow patterns and thus moisture migration. For instance, the article by Ask recommends that buildings in hot, humid weather should maintain positive pressures with respect to the outside, while buildings in cold climates can be slightly negative. It remains to be seen if more sophisticated approaches like this can be integrated into mainstream residential construction.

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• Indoor Air Dehumidification

Dehumidification usually involves cooling air, thereby reducing its ability to hold as much moisture and causing moisture to condense out of the air. As many of the issues above have illustrated, high indoor humidity issues can contribute to moisture problems in houses. In residential buildings, air-conditioning systems serve to dehumidify indoor air when they operate. In addition to removing moisture content from the air (latent load), residential A/C systems also reduce the air temperature, which addresses the sensible cooling load.

While air-conditioning systems in homes can help to dehumidify indoor air and thus help control water vapor levels, issues related to A/C system performance and design can compromise the effectiveness of this equipment to control indoor humidity. Two such issues identified in current literature are discussed below.

Partial-Load Periods with High Humidity

Selected References

- Keeler, "Heating and Cooling Equipment", Chapter 10 of *Moisture Control in Buildings*, ASTM MNL 18 (1994)

Air-conditioning cooling systems can remove moisture from indoor air when they operate, but the design of A/C systems limit their utility under part-load (mild), humid conditions. Conventional A/C controls operate the equipment based on the dry bulb temperature of the air, not humidity levels. Thus, during mild and humid conditions (which often characterize shoulder seasons in hot, humid climates) the sensible load on a house will be low and the thermostat will not engage the A/C system to operate. As a result, no dehumidification of the indoor air occurs. Even if an A/C system would run under such conditions, residential A/C systems cool the air as they dehumidify it and have no re-heat capabilities, which would cool the indoor environment past the typical comfort range. Therefore, as reported by Keeler, indoor humidity is often difficult to control during shoulder seasons and other periods with part-load temperature conditions and high outdoor humidity.

Air-Conditioning Sensible Heat Ratio and Oversizing Problems

Selected References

- Gatley 1993 reference from Lstiburek, "Residential Ventilation and Latent Loads", *ASHRAE Journal*, April 2002
- Keeler, "Heating and Cooling Equipment", Chapter 10 of *Moisture Control in Buildings*. ASTM MNL 18 (1994)
- Lstiburek, "Residential Ventilation and Latent Loads", *ASHRAE Journal*, April 2002

The Sensible Heat Ratio (SHR) of an air-conditioning system indicates its ability to address sensible cooling loads. Cooling loads are comprised of sensible and latent (moisture) components. Typical SHR values for residential A/C systems are around 0.70, which indicates that the unit is designed for cooling loads that are roughly 70% sensible (temperature) and 30% latent (moisture removal).

When building cooling loads vary from these proportions in the direction of higher latent loads, residential A/C systems lose their ability to control indoor humidity. Gatley found that houses in hot, humid climates typically experience latent cooling ratios in the 40 – 50% range. Similarly, Keeler states that when buildings have high latent loads and relatively lower sensible heat ratios (< 0.65), cooling systems controlled by typical thermostats will not be effective in controlling indoor humidity.

When HVAC systems are “oversized”, meaning the installed system has a cooling capacity significantly greater than the loads which the house will experience, a similar problem develops. The cooling system is *too* responsive in meeting sensible cooling loads because of its oversized capacity, and as a result satisfies the thermostat too quickly. The A/C system does not run long enough to address the latent load in the house, inadequate moisture removal takes place during the short A/C run cycles, and indoor humidity levels in the house can become elevated.

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When oversized A/C systems are *combined* with partial-load conditions, these factors work in tandem and indoor humidity control becomes very difficult. The article by Lstiburek concluded that when A/C systems are oversized by just 20%, latent heat removal capacity during part-load conditions is reduced to just 15% of the total cooling load. (Recall that latent cooling load ratios in humid climates can range from 40 - 50 %.) Further, this same article states that residential A/C systems are typically oversized on the order of 150% or more of the total cooling load. Thus, the combination of A/C oversizing and the difficulty of addressing latent cooling loads during part-load conditions highlights problems with indoor humidity control in homes.

Efforts to address these issues include developing and applying improved tools for HVAC design, builder education on the moisture implications of oversizing, and investigating the performance and cost-effectiveness of options for supplemental dehumidification equipment. Supplemental dehumidification could soon become an important consideration for new houses in hot, humid climates once mechanical ventilation requirements for new houses start to take hold, because the mechanical introduction of outdoor air will add even more latent load to the indoor environment. Research into the moisture and energy performance of supplemental dehumidification equipment, as well as methods for improving the latent cooling capacity of residential A/C systems, would therefore be valuable.

• HVAC-Related Sources of Water Vapor

HVAC systems in homes can also act to gather and distribute water vapor in buildings, in both intended and unintended ways. This section discusses a few such issues cited in current industry references.

Humidifiers

Central humidifiers are sometimes integrated with the forced-air system of a house to add moisture and increase indoor humidity during dry seasons of the year. Occupants want to maintain humidity at reasonable levels for comfort and respiratory reasons, and for maintaining wood products in a house like flooring and furniture. Central humidifiers have controls that adjust when they operate and add moisture to the air flow of the duct system.

However, humidifiers are subject to adding too much moisture to the indoor environment due to occupants setting the controls too high, inaccurate controls, or equipment failure. In addition, humidifiers can also experience biological growth and leak liquid water around the unit. One inspector claimed to have inspected dozens of humidifiers and found only one to be operating. See May, "Moisture Problems: From Case Studies and Home Inspections" in NIBS, *Bugs, Mold and Rot I* (1991).

HVAC Condensate

As discussed in the previous section on dehumidification, residential A/C systems remove water vapor from indoor air and collect it as condensed water. A/C units are designed to collect and drain away this condensate as it accumulates at the coiling coil.

Moisture problems can occur when:

- The condensate does not drain due to design or maintenance issues
- The air handler fan runs continuously, even immediately following A/C run cycles
- The condensate is drained to an improper location

For the first point above, the *Moisture Control Handbook* states that "the improper draining of condensate from AC systems, which allows for the re-evaporation of moisture and subsequent migration back into conditioned spaces, has proven to be a major contributing factor to moisture-related health and building problems."

The Florida Solar Energy Center reports on a related issue that can occur when the air handler fan runs continuously. This can have the effect of allowing moisture that has been condensed out of the air stream to re-evaporate off the wet cooling coil immediately following a cooling cycle. As a result, moisture that was just removed from the indoor air by the A/C system is immediately re-evaporated, raising indoor humidity. See their report "Another Aspect of Duty Cycling, Effect on Indoor Humidity" (1987).

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Lastly, when A/C condensate is drained away from the coiling coil, common sense dictates that it should not drain to places like a crawlspace or underneath a slab, where it could accumulate and create other moisture problems in a house.

HVAC Cold Spots

Selected References

- **Lstiburek, "Relative Humidity", Indoor Air Conference, Austin, TX 2002**
- **Keeler, "Heating and Cooling Equipment", Chapter 10 of *Moisture Control in Buildings*. ASTM MNL 18 (1994)**

Another issue involving air-conditioning in houses is the creation of “cold spots” on building surfaces from a steady flow of cooled air directly upon a surface. Cold air leaving an A/C system will be in the 55 – 60 °F range. This can lower the interior or exterior surface of a wall below the local dew point, causing condensation to form.

It is hard to judge the significance of this issue in isolation, but Lstiburek reports that when it is coupled with other factors like high outdoor humidity, excessive infiltration of outdoor air into wall assemblies, and impermeable wall coverings like vinyl wallpaper, it can contribute to condensation problems. Keeler also advises that the location of supply air registers, the direction of air flow, and the mixing of supply air with room air must all be considered.

• **Mechanical Ventilation Design and Performance Issues**

Selected References

- **Canada Mortgage and Housing Corporation, *Field Tests of Ventilation Systems Installed to Meet the 1993 OBC and 1995 NBC***
- **Tsongas, G.A., “The Northwest Wall Moisture Study: A Field Study of Excess Moisture in Walls and Moisture Problems and Damage in New Northwest Homes,” US DOE/Bonneville Power Administration, DOE/BP-91489-1, June 1990**
- **Tsongas, G.A., “A Field Study of Moisture Problems and Damage Inside New Pacific Northwest Homes,” *Proceedings, ASHRAE/DOE/BTECC conference on the Thermal Performance of the Exterior Envelopes of Buildings V*, Clearwater, FL, December 1992**
- ***Field Investigation of Mechanical Ventilation Strategies in Residential Construction*. Prepared for U.S. EPA by NAHB Research Center (2001)**
- **Lstiburek, "Residential Ventilation and Latent Loads." *ASHRAE Journal*, April 2002**

Mechanical ventilation systems in houses, now generally required by ASHRAE Standard 62.2, are increasingly viewed as a technology that will complement tighter building envelopes and address the need for additional indoor moisture control. While the “track record” of mechanical ventilation systems in mainstream U.S. residential construction is fairly limited, some telling research has been performed in both the U.S. and Canada. Much of this work has shown that while mechanical ventilation systems can potentially be effective in providing controlled air exchange and helping to control moisture, these systems require proper selection, design, installation, and operation to be effective.

For instance, a CMHC-sponsored field study of 49 houses in Canada found that none of the ventilation systems inspected met all of the requirements established for systems in new houses. Most of the shortcomings were due to insufficient duct sizing, which caused inadequate air flows. The study concluded that there were problems in the design, installation, commissioning, and approval of ventilation systems in new Canadian houses.

Also, as documented in the two reports by Tsongas, inspections of 86 new homes in the Pacific Northwest found that the majority of the ventilation systems, which included both spot exhaust fans and air-to-air heat exchanger

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units, were either were not working as well as expected or were not even being operated. In newer houses, central mechanical ventilation systems have sometimes not achieved adequate moisture control because they do not operate often enough, they are installed incorrectly, or they are improperly designed. In fact, measured flow rates of installed ventilation systems are often just one-half that of the rated fan flow capacity.

Other recent research performed by NAHB Research Center for the U.S. EPA documented the performance and cost implications (first cost and operating cost) of various mechanical ventilation systems installed in new U.S. houses. The performance monitoring did not focus extensively on moisture control, but results did show that the measured whole-house air exchange rates were markedly increased by the use of mechanical ventilation and were close to the design flow rates. This work also noted that careful system design and post-installation flow measurements and adjustments were required to achieve satisfactory air exchange performance.

Climate-specific moisture issues associated with mechanical ventilation system performance have also been noted. In hot and humid climates, for example, the addition of outdoor air via a ventilation system will significantly increase the latent (moisture) load in the building – especially during partial-load times when the A/C does not operate frequently. For this reason, the 2002 Lstiburek article in *ASHRAE Journal* has recommended the use of supplemental dehumidification through stand-alone dehumidifiers, enhanced A/C systems with variable speed blowers and compressors, or ventilating dehumidifiers.

The studies and issues identified above illustrate that mechanical ventilation systems can be used in houses to provide controlled air exchange with outdoors. If an appropriate system is selected for a given house and climate, and if it is properly designed, installed, maintained, and operated, then a mechanical ventilation system can provide both air exchange and moisture control benefits. There are clearly several steps in this process however, and as building codes adopt requirements for mechanical ventilation based on ASHRAE 62.2, a large number of contractors unfamiliar with this technology will become involved. The ultimate results are unclear.

Therefore several research needs in this area emerge, including:

- Easy-to-use design tools for residential mechanical ventilation systems, possibly integrated with HVAC load sizing software (which would help address latent load impacts)
- Programs to address what appear to be widespread shortcomings between system design and as-built performance
- Programs to investigate mechanical ventilation retrofits for existing houses with moisture issues that could be addressed by ventilation

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A.4 Moisture Modeling, Design and Analysis Tools

The frontiers of moisture analysis for buildings involve the development and deployment of computer software tools and underlying analysis methods capable of modeling all types of moisture flows throughout entire buildings. There are many facets to the moisture issue, and many approaches to modeling the underlying phenomena. Transport by diffusion, capillary action, convective flow and gravity all involve different equations and methods of analysis. Water can appear as liquid, vapor or even ice and changes form readily. Building material properties can vary with basic parameters such as moisture content and temperature. Complexities abound in any attempt to develop a model of reasonable accuracy, even one designed for application in a limited domain.

The earliest modeling approaches were simple enough to be performed manually. They focused on vapor pressure-driven diffusion through materials of specified permeances under boundary conditions representing indoor and outdoor design temperatures. The results depict steady-state performance. The goal was to determine whether a particular assembly was susceptible to interstitial condensation as moisture diffused from the inside to the outside (or vice versa). While this problem is computationally tractable, it has also been recognized as one of the least important parts of the overall moisture picture since it is limited to diffusion. More recent models have worked to encompass a variety of other transport modes and effects while lifting the constraints of one-dimensional steady-state analysis. The impact of convective flows, for example, is of great interest because they occur in the same assemblies yet can carry far more moisture than diffusion. The phenomena of moisture storage and drying potential can also be modeled, since water vapor (or liquid) will also be absorbed by or released from different building materials in amounts that depend on their specific properties and local environments. Phase change through the evaporation of liquid water and condensation of water vapor represents also involves the release or storage of latent heat, which affects local temperatures. Since thermal and hygric behavior are interdependent, the recent trend has been for models to address heat flows and thermal storage at the same time as they track the movement and accumulation of water vapor. This class of approaches is referred to as "hygrothermal" analysis and the most comprehensive models incorporating them are referred to as "HAM" ("Heat, Air and Moisture") models. At the same time, simple one-dimensional, steady-state models of vapor diffusion and heat flow have evolved into two- and even three-dimensional forms that are suitable for capturing transient effects and spatial performance variations within particular building assemblies. This growing complexity increases data requirements and can make results harder for the non-specialist to interpret. There is also a need for validating, calibrating or benchmarking performance before the results can be considered reliable, which is difficult when the models are evolving so rapidly.

From a practical standpoint, the applications of modeling tend to revolve around specific limit states of interest, such as whether a given construction will allow vapor to condense as it migrates through a building cavity (potentially causing damage), or whether moisture content in framing members will reach levels that promote rot, or the likelihood that relative humidity at a particular surface will exceed 70 percent for a sustained period of time and thereby support mold growth. There is also interest in using these modeling methods to derive new criteria for incorporation into codes and standards, since existing rules are often based on the older methods.

For this discussion, another way to assess software tools is whether they are primarily accessible to researchers (i.e., they call for input data that is not readily available, special knowledge or programming ability, non-standard computing platforms, the use of a cumbersome or unintuitive user interface, or interpretation of complex output formats), or if they are approaching or have reached the point of practical utility as tools for architects and building designers. Clearly the potential of these tools will not be realized until they can provide meaningful evaluations of building designs with minimal effort for users in the latter category. Furthermore, they should be able to draw as much data as possible from files used for other design applications if they are to be convenient to use, rather than having their own data input requirements. Ideally, for example, they would be able to analyze a building representation stored in an AutoCad file for a specified geographic location and orientation, and report back on the degree to which different parts of the design are vulnerable to moisture damage through bulk water or interstitial condensation. Designs could then be improved in an iterative way, rather than by relying on extensive sets of standard details that may not be necessary for a particular location or specific building. While this vision of speed and simplicity has yet to be achieved, it should not be forgotten in future work.

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A.4.1 Manual Design Tools

Selected References

- TenWolde, "Design Tools," *Moisture Control in Buildings*, ASTM MNL 18 Chapter 11 (1994).
- ASHRAE, *2001 ASHRAE Handbook of Fundamentals*, Chapter 23
- TenWolde, "Manual Analysis Tools" in *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM MNL 40 Chapter 7 (2001).

The 1994 TenWolde paper describes manual tools used to design building envelopes for moisture control. These include the Dew Point Method, the Glaser Diagram and the Kieper Diagram. Detailed examples of each method and the differences among them are presented. There is a discussion of limitations of manual design tools including their focus on condensation rather than moisture damage, their failure to address phenomena such as mold or paint failure that are not necessarily related to surface condensation, their ignoring of air leakage through the assemblies being modeled, their failure to address capillary transport or other transport mechanisms besides diffusion, their inability to model transient conditions, their failure to model latent heat, and their one-dimensional nature which rules out detailed analysis of thermal bridges, corners, holes, cracks, etc. It is recommended they be used only in relatively airtight structures, with monthly average (not design) temperature data (to avoid overly stringent conclusions), and that follow-up evaluation of any condensation indicated in the calculations be performed to assess whether it is potentially hazardous or benign. The chapter ends with a brief discussion of numerical analysis methods that represent extensions of the manual design methods but lack the scope of HAM models. None of the numerical methods identified in this paper appear to have been further developed.

The 2001 ASHRAE *Handbook of Fundamentals* gives brief descriptions of steady-state design tools as part of Chapter 23, "Thermal and Moisture Control in Insulated Assemblies - Fundamentals." As in the 1994 TenWolde paper, the steady-state tools include the dew point method, the Glaser diagram and the Kieper diagram. Much of the text on steady-state tools closely follows TenWolde (1994). All three methods compare vapor pressures at different points (based on vapor diffusion equations) with the saturation vapor pressures. This requires profiling temperature through the assembly (based on assumed indoor and outdoor conditions as well as the thermal resistances of different components) and comparing it to the local vapor pressure to determine whether condensation will occur. If conditions at any point indicate vapor condensation, failure is indicated. Once condensation occurs, subsequent steps along the flow path are not accurately modeled. A simplified method of incorporating airflow through the assembly is also described. Limitations in the methods, including limitation to vapor diffusion and failure to account for water absorption by materials or drying potential, are described. While these tools are simple enough to be used for design, and have been widely used for that purpose, the text cautions that "[r]esults obtained with any of these methods should therefore be considered as approximations and be used with extreme care." It also states that "they should only be used to estimate seasonal mean conditions." Graphs and tables illustrating use of these methods are included.

The 2001 paper by TenWolde is essentially a reprint of the "Manual Analysis" chapter in ASTM MNL 18 (described above), with a few corrections or clarifications. One substantive change is elimination of one of the "Recommendations for Use" in the earlier paper, which had suggested that under some conditions a construction might be acceptable for use even though one of the manual methods had identified the potential for condensation. That point does not appear in this version of the paper.

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A.4.2 Dynamic Modeling - General

Selected References

- Ojanen, Kohonen and Kumaran, "Modeling Heat, Air, and Moisture Transport through Building Materials and Components," *Moisture Control in Buildings*, ASTM MNL 18 Chapter 2 (1994)
- ASHRAE, *2001 ASHRAE Handbook of Fundamentals*, Chapter 23
- Straube and Burnett, "Overview of Hygrothermal (HAM) Analysis Methods" in *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM MNL 40, Chapter 5 (2001).
- Straube and Schumacher, "The Role of Hygrothermal Modeling in Practical Building Design - Case Studies" Presented at eSim 2002, Montreal Canada, September 2002.
<http://www.esim.ca/2002/documents/Proceedings/Session%203b-6.pdf>.

The Ojanen chapter in ASTM MNL 18 reviews the state-of-the-art in comprehensive HAM modeling as of 1994. It begins with a summary of the results of an International Energy Agency review of the subject that identified 28 relevant models. These models varied greatly in complexity. Half of the models were one-dimensional heat and moisture transport models. The others were more sophisticated, all the way up to two models classified as "three-dimensional heat, air and moisture transport models." It is worth noting that the only one of these models remaining in use, at least under the same name, is MOIST (discussed further below).

Ojanen goes on to describe a Finnish model, "TCCC2D" ("Transient Coupled Convection and Conduction in 2-Dimensions" that was rated in the IEA study as one of the most sophisticated available. The model is designed to focus on residential building walls of lightweight construction. Results of three selected applications of TCCC2D are presented. These applications include (1) moisture accumulation due to air convection over a period of 31 days, (2) exfiltration of indoor air through different points of a wall over a period of 100 hours, and (3) air exfiltration and moisture accumulation in residential wall cavities over a 52-week period, in nine Canadian and three Finnish locations. The results show how TCCC2D calculates for moisture content of insulation or sheathing, temperatures, and relative humidities under the varying conditions examined. Sensitivity of the results to rate of exfiltration, indoor relative humidity and point airflow vs. uniformly distributed airflow is documented. The concluding remarks emphasize the progress made in this field between 1984 and 1994, but caution that users must fully understand the assumptions and limitations, embedded in these modeling approaches. Like many other sources, they also argue that while absolute results of the model may not be correct, the primary value of the modeling is in assessing the relative performance of different constructions.

Chapter 23 of the 2001 *Handbook of Fundamentals* includes a short section on mathematical models for moisture analysis. The focus is on transient models that solve for conditions on an hourly basis rather than steady-state models. This part of the text is written in general terms and specific models are not described. It emphasizes that transient models are essential for capturing short-term processes including driving rain absorption, condensation under rapidly varying summer conditions, and phase changes. A comprehensive list of "features of a complete moisture analysis model" is also presented. These features include various material properties and their dependence on humidity and temperature; detailed weather data including wind and rainfall; and many others. The text cautions that "[t]wo-dimensional and three-dimensional hygrothermal models are extremely complex and mostly require the direct expertise of the authors,." and emphasizes that while transient models are more realistic than steady-state models, they are also difficult to use and the results are hard to interpret.

The Straube and Burnett paper presents a conceptual discussion of a whole range of issues common to the implementation and use of HAM modeling tools. It begins with a discussion of the relationship between the purpose of the analysis and the appropriate tool to use, distinguishing between applications for design of new buildings and assessments of existing buildings or research. This is followed by a review of the different types of information required for analysis (enclosure geometry, boundary conditions, material properties, physical modeling and performance thresholds) and the performance dimensions that distinguish sophisticated from simple HAM software.

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The final section of Straube and Burnett organizes the available analysis tools into three categories: heat flow models, simplified HAM models and detailed computer models. The heat flow models do not address moisture directly. The simplified HAM models include the Glaser diagram (for diffusion) and simple extensions of that model such as EMPTIED and SHAM. Brief descriptions with references are also offered for the following detailed computer models: WALLDRY, TRATMO, MATCH, MOIST, TCCD2, FSEC, WUFI, WUFIZ, and LATENITE.

The eSim paper by Straube and Schumacher presents two case studies to demonstrate how HAM tools can be used to improve specific aspects of building design. The modeling tools used are THERM, HEAT2D and WUFI (note that of these three, only WUFI attempts to model moisture flows). Introductory sections present a general description of the modeling process and identify required choices faced by the model user. The first case study involves choosing a specific wall design for a multi-story apartment building in the Pacific Northwest. It involves evaluating the potential need for the walls to include (1) polyethylene sheathing as a vapor retarder and (2) insulating sheathing. THERM 2.1 was first used to calculate temperature profiles for the various wall configurations, then WUFI 3.2 Professional was used to simulate moisture performance of each wall over a 20-month period. The key concern was the effect of driving rain and rainwater absorption on moisture levels in the wall. The model calculated RH at the polyethylene and exterior sheathing layers, and showed which configurations had high levels of RH that might promote mold growth or corrosion. The second case study involved heat loss through insulated and uninsulated basement floor slabs with embedded radiant heat pipes, but did not involve moisture analysis.

A.4.3 Specific Modeling Tools

MOIST

- **Burch and Chi, "MOIST: A PC Program for Predicting Heat and Moisture Transfer in Building Envelopes," Version 3.0, NIST SP 917, National Institute of Standards and Technology (1997)**
<http://www.bfrl.nist.gov/863/moist.html>

MOIST is a microcomputer program that performs one-dimensional analysis of heat and moisture flows to model moisture accumulation in walls, low-slope roofs and cathedral ceilings. Although the software is freely available for download at the NIST web site, technical support is no longer offered. The computational requirements for Version 3 (the latest) are extremely modest (486DX CPU, 500 kB RAM and Windows 3.1 or above). MOIST is coded in Visual Basic. Weather data allows modeling to be performed for a total of 46 U.S. and 5 Canadian locations. The software encompasses moisture transport through multi-layer assemblies by vapor diffusion and capillary flow, but is not able to model transport of moisture by air movement or temperature-dependent effects. MOIST has been used to model the need for and optimum placement of a vapor retarder in a specific building assembly and climate, as well as the surface relative humidity at different construction layers (which can indicate the potential for mold growth).

- **Doug Burch and George Tsongas, "MOIST: A Numerical Method for Design", Chapter 8 in *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM MNL 40 (2001)**

This paper gives comprehensive background information about release 3.0 of the MOIST software, which has been publicly available since January 1998. The software models heat and moisture transfer as one-dimensional phenomena. The moisture focus is on transport by diffusion and capillary action; convective transport is not modeled. A brief summary of the model theory and a summary of program limitations are followed by a description of the program, including installation; editing material properties; selecting weather data (ASHRAE WYEC hourly data is used), analysis period and time step; running the simulation; and plotting the results. Special program capabilities are highlighted, such as flexibility in specifying indoor temperature and relative humidity, the ability to incorporate paint and wallpaper as modeling elements, the ability to model heat and vapor flow through interstitial air spaces, and different choices for modeling heat and moisture storage in insulation layers. A series of hypothetical applications is described for illustrative purposes. The mathematical basis of the software is described in an Appendix.

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EMPTIED

- **Canada Mortgage and Housing Corporation, "Research Highlights: Envelope Moisture Performance Through Infiltration, Exfiltration And Diffusion - EMPTIED," Technical Series 99-23, <http://www.cmhc-schl.gc.ca/publications/en/rh-pr/tech/1999-123e.html>**

This web page describes the "EMPTIED" software for Microsoft Windows systems, and explains how to obtain it for free from the Canadian Mortgage and Housing Corporation. EMPTIED is a tool to predict condensation amounts from heat, air and moisture flows based on one-dimensional analysis and monthly temperature and humidity bin data. The user can specify monthly indoor temperature and humidity conditions, and must input the equivalent leakage area for the structure as well as the details of wall construction. Capillary absorption, moisture storage and rainwater are not modeled or addressed. The software is described as very fast, and generally suitable for differential, but not absolute, analysis. It is also characterized as making enough simplifying assumptions to be practical for designers to use in order to compare the relative effects of different climates, indoor conditions, wall materials and airtightness on wall performance. A quicker way to obtain EMPTIED and the program documentation is via links on http://www.cdnarchitect.com/asf/enclosure_design_tools/digital_tools/digital_tools.htm.

WUFI ORNL/IBD and MOISTURE-EXPERT

- **Kuenzel, Karagiozis and Holm, "A Hygrothermal Design Tool for Architects and Engineers (WUFI ORNL/IBP)" in *Moisture Analysis and Condensation Control in Building Envelopes*, ASTM MNL 40, Chapter 9 (2001)**

This paper presents information about development and features of the WUFI-ORNL/IBP software, developed in spring 2000 through a collaboration between Oak Ridge National Laboratory and the Fraunhofer Institute of Building Physics (Germany). The section on Physical Background reviews physical principles of moisture storage, moisture transport and liquid transport, and presents the equations governing each process. A database of necessary material properties for common building materials is included with the program. The relevant properties include density, porosity, heat capacity, heat conductivity, diffusion resistance factor, sorption/suction isotherms and liquid diffusivity. Details of the treatment of heat and moisture exchange between building surfaces and the indoor and outdoor environments are discussed. The software comes bundled with ASHRAE hourly weather data files for 60 North American locations. Possible sources of errors in the results are identified; these include programming errors, input data errors, uncertainty in specification of some required parameters, limitations of the mathematical model (such as one-dimensionality), and numerical problems (unstable convergence). The model is reported to be "most likely the most validated and benchmarked model for hygrothermal applications", and three experimental investigations on which this statement is based are described. Finally, the model features, software architecture and user interface are presented.

The WUFI-ORNL/IBP software is described as having been developed exclusively for university-trained architects and building envelope designers. Results can be displayed in an animated form that shows changes over time. Hygrothermal performance outputs can be used as inputs to "peripheral post-processing modules" for further analysis of specialized issues including energy consumption and potential for mold growth. Additional modules are reported to be under development. Although the model is described as user-friendly software for Windows 95 and later systems, background information about the program on the ORNL web site cautions that proper application of WUFI-ORNL/IBP requires experience in the field of hygrothermics and some basic knowledge in the use of numerical calculation methods. See http://web.ornl.gov/sci/btc/apps/moisture/ibpe_sof1.html. Non-commercial users can download the latest version for free at http://www.ornl.gov/sci/btc/apps/moisture/ibpe_sof161.htm.

- **Karagiozis, "Advanced Hygrothermal Models and Design Models" Presented at eSim 2001, Ottawa, Ontario Canada <http://www.esim.ca/2001/documents/proceedings/Session3-4.pdf> (2001)**

This paper contains a detailed discussion of two models developed, in whole or in part, at Oak Ridge National Laboratory (ORNL). Both models are described as representing the state-of-the-art in their respective domains. The simpler model, "WUFI-ORNL/IBP", is characterized as a design tool and described as "a moisture engineering assessment model that predicts the transient transport of heat and moisture." The program runs on a PC under Windows. It is a one-dimensional model that does not address airflow. Outputs include temperatures and relative humidities at user-selected monitoring positions, as well as the mean moisture contents of specific materials. Transient profiles of temperature, relative humidity and moisture content as output by the model can be displayed in

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graphical form. WUFI is unusual in its ability to model moisture intrusion through wind-driven rain. The original WUFI software was released in Europe in 1994. A professional version, "WUFI-pro V3.0 with advanced features and options" is also available. The standard, public-domain version of the program is available for download from ORNL at <http://www.ornl.gov/btc/moisture>.

The second model described in the paper, "MOISTURE-EXPERT", is characterized as a research tool that extends the capabilities of WUFI-ORNL/IBP to address two-dimensional heat, air and moisture transport. It is also designed to address durability processes by incorporating aging characteristics (e.g., how the properties of a weather barrier change based on weather exposure and elapsed time). Variability in material properties (e.g. permeance or sorption), with temperature or humidity, can also be addressed with suitable input data.

The paper moves on to list differences between advanced hygrothermal models and advanced design models as well as assumptions required by all these models. Finally, it presents results of example simulations of different weather barrier configurations on a stucco-clad building wall using each model. The comparisons based on the WUFI/ORNL model indicated that more than two layers of sheathing paper did nothing to improve wall performance, while MOISTURE-EXPERT results showed the effects of water penetration on moisture content and spatial relative humidity in a leaky wall.

APPENDIX B

ONGOING RESEARCH

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B.1 Introduction

This Appendix includes short descriptions of a wide range of ongoing non-proprietary research projects that directly or indirectly involve moisture problems in houses. Most of the work is sponsored and performed by a variety of governmental or quasi-public agencies. Information was compiled from published sources and interviews with researchers or program managers at numerous U.S. and Canadian facilities. Contact information is presented where available. The listings are organized alphabetically by sponsor name. This information has been compiled to provide an up-to-date context for developing recommendations on future moisture research projects.

B.2 Project Descriptions

ASHRAE - Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls - Research Project No. 1091.

Contact: Eric F.P. Burnett, Pennsylvania State University Housing Research/Resource Center, 814-865-2341.

This study, which began in September 2000 and is scheduled for completion by September 2004, is designed to generate experimental data on the performance of sheathing membranes and air cavity ventilation strategies on overall thermal and moisture performance of wall systems, and to use modeling to develop guidelines on the use of sheathing and cavity ventilation as a function of climate and cladding properties. Results will be used to develop materials for the 2005 ASHRAE Handbook of Fundamentals. Work is being performed by Penn State University, Oak Ridge National Laboratory and John Straube of the University of Waterloo. An abstract of the project is included at the following URL: <http://www.ashrae.org/template/AssetDetail/assetid/26625>.

Building Research Council, University of Illinois at Urbana-Champaign - Mitigating Mold and Moisture Damage at the Wall/Ceiling Junction in Residential Construction.

Contact: Bill Rose, UIUC Building Research Council, 217-333-1801.

This two-year study is intended to identify practical, effective retrofit solutions to the problem of condensation and development of mold at the juncture of exterior walls and ceilings. Such locations are particularly vulnerable to moisture problems, especially in older homes located in cold climates, due to low surface temperatures resulting from inadequate wall insulation, lack of ceiling insulation over the wall top plate, and localized thermal bridging effects. The study is comparing the costs and thermal performance of three potential retrofit approaches including an insulated crown molding and two other insulation approaches. It is being performed in conjunction with the Turtle Mountain Housing Authority in North Dakota.

Building Research Council, University of Illinois at Urbana-Champaign - Field Evaluation of the Moisture Balance Technique to Characterize Indoor Wetness.

Contact: Bill Rose, UIUC Building Research Council, 217-333-1801.

This project, performed as part of the HUD Healthy Homes Initiative, is an investigation of using the "moisture balance approach" to characterize wetness in buildings. The lack of a generally accepted, objective method for assessing the wetness or dryness of building interiors relative to the outdoors is regarded as an impediment to scientific study of moisture problems. One approach to assessment uses the moisture balance (MB), which is defined as the difference between indoor and outdoor water vapor pressure. This difference, which will generally vary over time, can be calculated from indoor and outdoor temperature and relative humidity data. In the absence of dehumidification, a positive MB provides an indication of interior moisture generation, although the magnitude of the MB also depends on the ventilation rate. For this study, MB values were tracked over a 5-month winter period for 31 dwelling units in a total of 15 buildings located in Providence, Rhode Island. Data analysis is complete and results have been submitted for publication.

Canada Mortgage and Housing Corporation (CMHC) - Water Penetration Testing on Wall Systems.

Contact: Silvio Plescia, CMHC, 613-748-2000.

This project responds to increasing calls for rainscreen or cavity wall construction to improve moisture protection, given the current lack of good qualitative data comparing the drainage characteristics of different claddings, drainage cavity configurations and building materials used in wall assemblies. Under this project, a variety of different wall drainage cavity configurations and media will be tested in a laboratory setting to determine their ability to drain water or retain it within the wall cavity. Project completion is expected in spring 2005.

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CMHC - Wind-Rain Relationships in Southwestern British Columbia.

Contact: Silvio Plescia, CMHC, 613-748-2000.

Wind-driven rain is considered one of the largest contributors to the overall moisture load on building envelopes, especially in Canada's coastal regions. This is a pilot project to analyze climate data at weather stations in southwestern British Columbia to develop a better understanding of the relationships between wind and rain, including how wind speed and direction relate to coincident periods of rain, and how the relationships vary by season. Information on rainfall will be related to the potential impact on the building enclosure in the form of rain intensity. Completion is expected by fall 2004.

CMHC - Development of Driving Rain Maps and Loads for Canada.

Contact: Silvio Plescia, CMHC, 613-748-2000.

The objective of this project is to develop maps of Canada and nomographs that quantify the driving rain load for different types of buildings located across Canada. Tasks include (1) documenting and extending current driving rain prediction methodologies, (2) collecting, analyzing and interpreting hourly driving rain information as it relates to building enclosure performance, (3) creation of climate maps and tables relating to driving rain that are as useful for building enclosure design as current structural load maps and tables are for the design of structural members, and (4) generating a range of statistics and correlations that improve understanding of driving rain loads and how they vary with climate. The project is expected to be completed by the end of 2004.

CMHC - Comparative Study of Hygrothermal Modeling and Field Monitoring of Building Envelopes.

Contact: Silvio Plescia, CMHC, 613-748-2000.

This project is to compare predictions generated by hygrothermal computer simulation models against actual field-monitored conditions in exterior wall assemblies. It is meant to improve the benchmarking and validation processes for the simulation models, which have generally been limited to comparisons in laboratory settings under controlled conditions. The goal is to improve the integrity and reliability of building moisture management prediction tools suitable for use in building analysis at the design stage. The project has recently been put on hold.

CMHC - Modify and Upgrade WALLDRY Computer Program.

Contact: Silvio Plescia, CMHC, 613-748-2000.

This project is to enhance the CMHC-developed WALLDRY computer program for HAM analysis of wall assemblies under specified external climatic loads and interior conditions. Completion is expected by summer 2004.

CMHC - Hygrothermal Models for Building Envelope Retrofit Analysis.

Contact: Duncan Hill, CMHC, 613-748-2000.

This project is to assess commercially available hygrothermal models for applicability to building envelope retrofits. The assessment criteria include model availability and cost, availability of technical support, ability to model selected wall assemblies and retrofit strategies, transparency of the algorithms, and ease of use. One or two models will be recommended for use in a subsequent project to evaluate the impact of insulation retrofit scenarios on a variety of different wall systems. The expected completion date is not available.

CMHC - Ice Damming Research.

Contact: Don Fugler, CMHC, 613-748-2000.

Two related projects are underway relating to ice damming. The first is to photograph roofs in two Canadian locations during periods of heavy frost or light snow and identify specific "hot spots" where melting takes place, then to determine whether those houses experienced ice damming in the preferential melting locations. As of late 2003, weather conditions had not allowed the final steps of the project to be completed. The second project involves potential solutions for existing ice dam conditions, specifically by making changes to roofs and attics designed to lower attic temperatures. Efficacy of the solutions will be assessed based on actual occurrence of ice dams (relative to adjacent control buildings). If weather conditions do not lead to ice damming, then temperature monitoring will be used instead. Results were planned to be available by mid-2004.

CMHC - Relationship between Moisture Content and Mechanical Properties of Gypsum Sheathing.

Contact: Silvio Plescia, CMHC, 613-748-2000.

This study is focused on the relationship between moisture content and mechanical properties of gypsum sheathing products, including standard gypsum wall board, exterior-grade gypsum, and glass-fiber faced gypsum. Mechanical properties of interest include adhesion or delamination of the facer material, ability to resist fastener pull-out, and

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flexural strength. The study will also determine whether handheld electric resistance-type moisture meters can measure moisture content accurately in these products, or if some new apparatus or protocol is required. Project completion is expected in the fall of 2004.

Florida Solar Energy Center - Crawlspace Moisture Problems in Manufactured Housing.

Contact: David Beal, FSEC, 321-638-1000.

This project, performed under the DOE Building America program, involves performing experiments in the crawlspaces of three single-wide manufactured houses located side-by-side. The houses use different approaches to crawlspace moisture protection in the form of ground cover and ventilation. They are being monitored to determine the impact of these systems on crawlspace humidity and temperature. The project will run through the summer of 2005.

Florida Solar Energy Center - Manufactured Housing Laboratory.

Contact: Neil Moyer, FSEC, 321-638-1000.

This project, performed under the DOE Building America program, uses a 1600 square foot 3-bedroom 2-bath manufactured house modified to serve as a research house and test laboratory. Equipment in the research house allows controlling sensible and latent cooling loads, and sensors inside the walls allow profiling temperature and humidity through the wall section. Six different types of ventilation systems are under study, using a two-week testing cycle, in order to learn about the impact of different whole-house ventilation rates and strategies on indoor moisture levels and energy use. The impact of different interior wall finishes on moisture levels (e.g., vinyl wallpaper vs. painted drywall) is also being investigated. The project is planned to continue through March 2005. More information about this research house is available at <http://www.fsec.ucf.edu/bldg/baihp/data/mhlab/index.htm>

IRC-NRCC - Development of Performance Guidelines for Basement Envelope Systems and Materials.

Contact: Not available.

This project, which began around 2000 and was scheduled to last for three years, involves development of guidelines for design and evaluation of basement envelope systems and materials. It focuses on what the systems must do, and what materials in the system must do, to achieve long-term control of heat loss, air leakage, soil gas entry, exterior and interior moisture, rain water and ground water. A Steering Committee with 14 funding agencies as members (including CMHC, the Canadian Home Builders Association and numerous other associations and material interests) is providing guidance and review. In addition to developing guidelines the project includes a component directed at revising relevant codes and standards. As of mid-2002 the background work constituting Phase I was complete, while Phases II and III remained to be done.

IRC-NRCC - Evaluating the Effectiveness of Wall-Window Interface Construction Details to Manage Rainwater (Wall-Window).

Contact: Dr. Michael Lacasse, IRC-NRCC, 613-993-2607.

This project, sponsored by IRC in partnership with CMHC, calls for development of a consortium of North American organizations to fund testing that will determine the ability of particular construction details at the window-wall interface to manage rainwater entry into the wall assembly. Approximately 40 percent of total funding requirements will be raised from consortium members over a three-year period. The balance will be funded by IRC and CMHC. Testing will be designed to simulate wind-driven rain conditions, and will be performed using IRC's Dynamic Wall Test Facility. The test program will be tailored based on the interests of consortium members. While distribution of results will initially be restricted to consortium participants, CMHC also intends to use them in developing a "Best Practice Guide for Window Installation."

IRC-NRCC - Hygrothermal Properties of Building Materials.

Contact: Dr. Phalguni Mukhopadhyaya, IRC-NRCC, 613-993-2607.

This project involves characterizing various properties of over 100 building materials such as bricks, mortars, stucco, cladding products, building membranes, wood and wood-based materials, concrete and insulation. The properties of interest, which are used in hygrothermal modeling, include heat capacity, thermal conductivity as a function of temperature, vapor permeance as a function of relative humidity, equilibrium moisture content as a function of relative humidity, water absorption coefficient, liquid water diffusivity and its dependence on water concentration, and air permeance as a function of pressure differentials. This level of detail will support several refinements to existing modeling software. Results for 39 materials appear in an ASHRAE research report, results for another 40 materials are in the MEWS Task 3 report, and results for another 22 materials are to be published in a

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report in spring 2004. IRC also sells a database containing properties of selected materials suitable for use in HAM models, as well as a one-dimensional version of "hygIRC", described as a "state-of-the-art hygrothermal model."

IRC-NRCC, CMHC and MEWS Consortium Partners - Guidelines for Moisture Management in Exterior Wall Systems.

Contacts: Dr. Michael Lacasse, IRC-NRCC, 613-993-2607, and Silvio Plescia, CMHC, 613-748-2000.

This project is an outgrowth of the multi-year MEWS (Moisture in Exterior Wall Systems) project, carried out since 1998 under management of the Institute for Research in Construction of the National Research Council Canada with funding and technical support from CMHC and over a dozen MEWS consortium partners. Based on results of the MEWS technical research program (some of which are discussed earlier in this Background Paper), the goal of this work is to develop guidelines presenting moisture management strategies designed to ensure long-term performance and durability of wall systems for the entire range of North American climates. The ongoing guidelines development project started in 2003 with presentations of "Building Science Insights" seminars based on findings from the MEWS work. Completion date is unknown.

Manufactured Housing Research Alliance - Solutions to Moisture Problems in Hot, Humid Climates.

Contact: Emmanuel Levy, MHRA, 212-496-0900.

The Manufactured Housing Research Alliance has an ongoing PATH-funded research project to investigate a variety of potential solutions to the moisture problems that affect some manufactured homes (as well as other types of homes) located in the hot, humid parts of the southeastern U.S. The current project builds on a series of three earlier MHRA studies that (1) developed general guidelines for preventing moisture problems, (2) reported results of diagnostic tests in 70 southeastern manufactured homes with identified moisture problems, and (3) performed experiments in two manufactured homes to quantify the contributions of numerous construction and operating variables to indoor-outdoor pressure differences that can introduce humid air into building cavities and interior spaces. The earlier studies identified the importance of controlling pressure differentials and operating homes at a slight positive pressure over outdoor conditions in order to avoid moisture problems in these climates. The current study is aimed at developing more detailed design guidelines for industry covering the use of ventilation, HVAC balancing and air barriers to maintain desired pressure relationships and minimize summer moisture problems.

National Institute of Standards and Technology - Moisture Detection using Radio Waves.

Contact: Bill Healy, NIST, 301-975-5900.

This project aims to investigate methods for using radio waves to detect moisture inside wall assemblies, and is being done in collaboration with Intelligent Automation, Inc. Ultra-wideband radio waves are directed into the wall, and particular frequencies are reflected back by moisture pockets. The elapsed time to receipt of the reflected waves at different locations in front of the wall is analyzed by computer to generate a 3-D wall image showing the wet areas. The method has been used on a simple prototype wall constructed with gypsum, fiberglass insulation and OSB, and is being studied with real walls that include studs, wires, pipes and windows that may complicate the readings. Funding is provided by the HUD Healthy Homes office and NIST. More information is available at http://www.nist.gov/public_affairs/taglance/current.htm#radio. Note that a similar project underway at the Georgia Tech Research Institute is aimed at using radar and possibly other types of radiation to detect mold behind gypsum wallboard; see http://www.innovations-report.com/html/reports/process_engineering/report-28659.html.

Oak Ridge National Laboratory - Moisture-Related Materials Property Research.

Contact: Andre Desjarlais, ORNL, 865-574-0022.

This project is an ongoing DOE-funded effort to develop new and improved information about moisture-related properties of building materials, including moisture capacity, water vapor permeability, moisture diffusivity, air permeability, liquid diffusivity and others. The dependence of these properties on relative humidity and temperature are also measured. Results are used to expand a database of material properties that is used by hygrothermal modeling tools. Testing is performed in a facility operated by Oak Ridge, with about a dozen materials added to the database each year. Information is available at <http://www.ornl.gov/sci/roofs+walls/research/hygrothermal.htm>

Oak Ridge National Laboratory - Hygrothermal Modeling.

Contact: Andre Desjarlais, ORNL, 865-574-0022.

Oak Ridge currently is funded by DOE to support two hygrothermal modeling tools: WUFI/ORNL and MOISTURE-EXPERT. Both are dynamic models. WUFI/ORNL is a one-dimensional tool intended for use by practicing architects and designers. It does not model air leakage but is relatively easy to use. MOISTURE-

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EXPERT is a 2-D HAM tool for the research community (both tools are described in greater detail in the modeling section of this report). Ongoing work in support of WUFI/ORNL includes provision of four 2-day training classes per year, as well as annual revisions to improve the user interface, expand material properties and otherwise enhance the model. Oak Ridge has also done work to determine the most appropriate weather data to use with the tool, and distributes a software weather analyzer that processes NOAA weather data into files suitable for use with the modeling tool. There are two ongoing parametric modeling studies with MOISTURE-EXPERT. The first is to determine how ventilation of crawl spaces in humid southeastern U.S. climates affects the moisture content of crawl space materials. The second is to determine how does the presence of a ventilated cavity behind wall cladding (e.g. the air space behind a brick veneer) affects moisture levels in different parts of the wall assembly.

Oak Ridge National Laboratory - Wall Tests.

Contact: Andre Desjarlais, ORNL, 865-574-0022.

Oak Ridge is performing ongoing studies of the moisture performance of different wall structures. This DOE-funded work is being performed in cooperation with APA, the EIFS Industry Manufacturers Association and Weyerhaeuser as additional sponsors. The program involves two test houses; one in Seattle WA (in operation since early 2003) and the other in Charleston SC (currently under construction). The test houses are long, slender one-story structures oriented such that the long sides face the prevailing direction of incoming weather. Multiple wall panels each about 5 feet wide can be tested in parallel. Current testing involves the performance of OSB sheathing and different vapor retarder systems.

Pacific Northwest National Laboratory - Moisture-Related Model Building Code Amendments.

Contact: Craig Conner, PNNL, 509-375-2121.

On behalf of the U.S. Department of Energy, the Pacific Northwest National Laboratory developed thermal and moisture-related amendments to requirements in the *International Residential Code* and the *International Energy Conservation Code*. These revisions were approved by ICC in May, 2004, and will be part of the 2004 Supplement to the I-codes and (subject to any revisions in the next code change cycle) in the 2006 editions of the relevant codes. The proponent's reason states that this proposal is designed to incorporate aspects of the latest building science regarding energy efficiency and its effects on moisture control and durability. The following are key moisture-related features of the proposal as approved:

- Climate zones in the IRC and IECC are being reduced to 8 and revised to reflect multiple climate variables rather than just heating degree days. New moisture-related climate classifications for moist, dry and marine (Pacific) climate regions are included, as well as a line delineating warm-humid (southeastern) climates from the remainder of the U.S.
- The proposed vapor retarder requirements in IRC section R318.1 do not apply in proposed climate zones 1-4, which extends to about 5,400 HDD65. The existing code requires vapor retarders in all locations above 3,500 HDD65.
- The conditions under which unvented crawl spaces are permitted were clarified in IRC section R408.3 and rewritten to allow this type of construction so long as the walls are insulated, the ground is covered, and the crawl space is conditioned or provided with adequate continuous mechanical exhaust ventilation.
- A new section R806.4 is added to allow unvented conditioned attics if the roof deck insulation and vapor retarder treatment meet certain climate-specific conditions.

USDA Forest Products Laboratory - Research Demonstration House.

Contact: Mike Ritter, USDA-FPL, 608-231-9200.

The Advanced Housing Research Center at the USDA Forest Products Laboratory in Madison, Wisconsin, in conjunction with APA, the Southern Pine Council and numerous other sponsors and contributors, funded construction of a 2,200 square foot research demonstration house that features a variety of technologies including moisture-resistant building practices. The two-story house on a permanent wood foundation was completed in the fall of 2001. The OSB wall sheathing is instrumented to monitor temperature and moisture content, and indoor relative humidity is being maintained at 40 percent through cold weather to determine the impact of relatively high interior moisture loads on moisture content of the OSB. More information about this research house is available at http://www.buildabetterhome.org/bbh_level_b.cfm?content=app_bbh_watchlearn.

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USDA Forest Products Laboratory - Development of portable instrumentation to detect, identify and quantify mold in homes.

Contact: Carol Clausen, USDA-FPL, 608-231-9200.

This project, funded by the HUD Healthy Homes office and being performed in conjunction with a private firm, involves developing antibodies to the surface proteins on mold spores and using them in a field test for rapid detection of mold in residential environments. A field test could offer many advantages compared to conventional air sampling followed by microscopic analysis in the laboratory. The project began in 2002 and the first phase was completed in March 2004.

USDA Forest Products Laboratory - Immunodiagnostics for detection of incipient fungal decay in wood products in-service.

Contact: Carol Clausen, USDA-FPL, 608-231-9200.

When moisture intrusion in building assemblies is discovered, one of the first questions is whether the wood has suffered structural compromise. This project, which has been ongoing since 1994, is developing a new way to test for evidence of decay. The test uses monoclonal antibodies that react with an enzyme produced by common decay fungi as they propagate through wood. The test is essentially non-destructive, and is sensitive enough to detect fungal decay prior to weight loss or strength loss in the wood member. The underlying patent has recently been licensed to a private-sector firm that plans to commercialize a test kit for use by home inspectors or in forensic studies.

USDA Forest Products Laboratory - Designing nontoxic mildewcides for indoor protection of cellulose-based building products from mold establishment.

Contact: Carol Clausen, USDA-FPL, 608-231-9200.

This project, which began early in 2002 and is ongoing, is looking at several types of chemicals that could enhance the resistance of building interiors to attack by mold. The chemicals of interest include azo-borates and quaternary ammonium compounds. In principle they could be applied to lumber, OSB or the paper facing of gypsum board.

Washington State University Energy Program - Improving the Hygrothermal Performance of Building Envelopes.

Contact: Chuck Murray, WSU Energy Program, 360-956-2000.

This project, which began around the year 2000, is intended to develop and implement a systems engineering approach to designing wood-frame building assemblies that are energy efficient and moisture tolerant in the Pacific Northwest climate. It was motivated by concern about the possibility that requirements in modern energy codes for insulation, ventilation and air tightness were contributing to high rates of moisture problems in newly-constructed Seattle-area buildings. Funding is from the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy, as well as Weyerhaeuser, APA - The Engineered Wood Association, Fortifiber Corporation, and CertainTeed Corporation. Supporting technical work has been performed by Oak Ridge National Laboratory.

Phase I of the project involved modeling the performance of 35 different wall assemblies exposed to Seattle climate conditions. Results are described in an April 2002 report from Oak Ridge (Karagiozis, *Building Enclosure Hygrothermal Performance Study Phase I*, ORNL/TM-2002/89). Phase 2 of the project (2003-2005) concentrates on obtaining additional data on the performance of walls through laboratory testing of building material hygrothermal properties and field testing of full-scale walls. Data gathered during the test phase will then be used to further calibrate the advanced hygrothermal modeling systems at Oak Ridge National Laboratory. In 2003 WSU established a Natural Exposure Test Facility that is currently gathering data on the heat and moisture transfer performance of 12 full-scale wall sections. This project is funded through 2005. Nonproprietary results are to be released following conclusion of the project. More information about the project is available on the web at <http://www.energy.wsu.edu/projects/building/moisture.cfm>.

APPENDIX C

COORDINATION OF FUTURE RESEARCH

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C.1 Introduction

HUD has sponsored development of a research agenda on moisture and durability problems in housing, based on an extensive review of the literature, an identification of ongoing work, and input from a panel of experts. The scope of the agenda includes demonstration, education and outreach in addition to conventional research. The resulting research agenda identifies dozens of candidate projects, some of them potentially quite costly, while funds available for moisture-related work are very limited and scattered among a large number of agencies and organizations. This situation highlights the importance of improving coordination to achieve greater efficiency in pursuing the shared overall goal of reducing the burden created by uncontrolled exposure to moisture in residential environments. This paper summarizes ideas about how to achieve improved coordination.

Section C.2 identifies public- and private-sector organizations that are actively involved in funding or performing moisture research. The focus has been on funding sources rather than organizations performing work with outside funding. Section C.3 describes opportunities for creating an informal research coordinating process, with suggestions about how HUD and other federal agencies can make this happen.

C.2 Organizations Involved in Moisture Research

C.2.1 Federal Agencies

Department of Energy. The U.S. Department of Energy is the largest public-sector sponsor of moisture-related R&D. Much of the DOE-funded work focused specifically on moisture is performed by Oak Ridge National Laboratory under its Building Envelopes program; see <http://www.ornl.gov/sci/roofs+walls/research/index.html>. Several other National Labs work on related issues including Pacific Northwest National Laboratory (energy codes and standards) and Lawrence Berkeley National Laboratory (HVAC and indoor air quality); the buildings research programs at various National Labs are described at <http://www.eere.energy.gov/buildings/tech/labs.html>. The Department also sponsors five private-sector teams working with home builders to achieve high levels of energy efficiency, primarily in new house construction, under the "Building America" program. See http://www.eere.energy.gov/buildings/building_america/research_teams.html. While the focus is invariably on energy efficiency, the teams typically work to include improved indoor moisture management through design and ventilation as part of an overall energy efficiency approach in Building America homes. In addition, DOE has provided substantial funding for operation of the Building Environment and Thermal Envelope Council, which is discussed further below. Finally, DOE provides large amounts of grant funding to state energy offices for code-related work, which often involves development of requirements and educational programs focused on tight construction, ventilation and moisture management.

Department of Housing and Urban Development. HUD sponsors moisture-related research through two avenues: the PATH program and the Healthy Homes program. PATH work has been focused on introducing new technologies and proper use of existing technologies. Moisture-related work has generally come under the topic of durability. For example, PATH has sponsored conferences dealing with moisture titled "Durability and Disaster Mitigation in Wood-Frame Housing" as well as development and publication of *Durability by Design*, a guidebook for builders and contractors covering numerous aspects of moisture control in design and construction. For more information see http://www.pathnet.org/sp.asp?mc=issues_durability. The HUD Healthy Homes program administers grants, some of which relate to moisture, primarily as it relates to mold. Healthy Homes is also a sponsor of RMMN, discussed further below. More information is at <http://www.hud.gov/offices/lead/hhi/index.cfm>.

USDA - Forest Products Laboratory. The Forest Products Laboratory uses internal and external funding to support programs of basic and applied research into protecting wood products and wood-frame structures from moisture-related deterioration. Since 1999, much of the relevant FPL work has been carried out under the Advanced Housing Research Center; see <http://www.fpl.fs.fed.us/ahrc/welcome.htm>. During 2002 FPL, in cooperation with APA - The Engineered Wood Association, organized the "Residential Moisture Management Network" (RMMN), a network of government agencies and private industry groups. The RMMN website lists over 20 organizations as members, most of them trade associations for product manufacturers or service providers. The goals of RMMN are to coordinate programs; enhance efforts; share information; and disseminate research, technical findings, and best practices that specifically help manage moisture in residential buildings. See <http://www.rmmn.org>.

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Environmental Protection Agency. EPA has been involved with building moisture under the general heading of indoor air quality, because moisture sources including leaks, flooding and condensation contribute to the development of mold and other biological contaminants. Various EPA guides address moisture control, often under a framework where water vapor represents one of a number of contaminants. The extent to which EPA funds moisture-related research is unknown.

Other Federal Agencies. The Department of Defense has an interest in moisture control in housing owned by the military, and the General Services Administration, which serves as landlord to federal agency tenants around the country, has a clear interest in moisture control in those office-type occupancies, especially public buildings. The extent to which either agency funds moisture-related research, particularly research with residential applications, is unknown.

Canadian Government Agencies. Most moisture problems do not respect national boundaries. Two government agencies in Canada that fund research into building moisture performance are the Canada Mortgage and Housing Corporation, at <http://www.cmhc-schl.gc.ca/en/index.cfm>, and the Institute for Research in Construction of the National Research Council - Canada, at <http://irc.nrc-cnrc.gc.ca/research.html>

C.2.2 Nonprofits, Associations and Universities

American Society of Heating, Refrigeration and Air-Conditioning Engineers. ASHRAE is a trade association for engineers involved in the HVAC industry. It develops and publishes standards, maintains engineering handbooks for practitioners, and sponsors research on new or emerging issues in the HVAC field. The ASHRAE *Handbook of Fundamentals* is one of the authoritative sources on control of condensation in building envelopes, indoor humidity control and indoor air quality. ASHRAE also sponsors development of standards such as the ASHRAE 62 series on indoor air quality, which includes ventilation requirements for moisture control. Technical support for much of the moisture-related work done by ASHRAE, including standards development and maintenance of the Handbooks comes through the volunteer efforts of its membership, supplemented by occasional relatively small research projects sponsored by ASHRAE Technical Committees (TC's). Several of the TC's are directly relevant to the issue; for example, TC 1.12, "Moisture Management in Buildings." Ongoing ASHRAE research projects are listed at <http://www.ashrae.org/template/AssetDetail/assetid/26625>. The total ASHRAE research budget is reportedly around \$3 million per year, but the primary focus is on issues relating to large, complex, commercial and industrial HVAC systems and only a small part is relevant to moisture problems in low-rise residential buildings.

National Institute of Building Sciences. NIBS operates the Building Environment and Thermal Envelope Council (BETEC), which sponsors Research Coordinating Committees and Operating Committees on multiple topics, including moisture and mold. BETEC has a long history of work in this field, including a series of "Bugs, Mold and Rot" symposia and recent conferences on membranes in building envelopes and building mold. See <http://www.nibs.org/betecnews.html>. BETEC is further discussed below.

American Society for Testing and Materials. ASTM sponsors the development of standards for building materials, products, systems, installation and related matters. Voluntary industry participation in the standards development process is extensive, and a whole array of ASTM standards deal with building moisture control and protection, most of them under Committee E06 on Performance of Building Constructions. While ASTM generally does not fund research projects, they do publish two definitive manuals on moisture control: ASTM MNL 18, *Moisture Control in Buildings* (Treschel, ed., 1994), and ASTM MNL 40, *Moisture Analysis and Condensation Control in Building Envelopes* (Treschel, ed., 2001).

APA - The Engineered Wood Association. APA produces technical information on moisture protection of wood panel sheathing, plywood siding and other wood products, as well as on mold. It is a co-sponsor of RMMN, which is discussed further below.

National Association of Home Builders. NAHB has sponsored research projects at irregular intervals to document moisture problems and solutions (e.g., wet basements and EIFS remediation), as well as work designed to help builders shift liability for moisture problems to suppliers, subcontractors or customers.

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Institute for Building and Home Safety. IBHS has a clear interest in mitigating residential moisture problems. They have investigated data from member companies on moisture-related property insurance claims, but since the results of this research are for use in setting insurance rates, they are considered proprietary.

Universities and University Affiliates. Many university engineering or architecture departments in the U.S. and Canada have programs relating to moisture control in housing. Most probably benefit from some internal university funding, but they typically supplement this with research grants from third parties. Some of the more active programs are listed below.

- Building Research Council - University of Illinois: <http://brc.arch.uiuc.edu/>
- Florida Solar Energy Center (University of Central Florida): <http://www.fsec.ucf.edu/>
- Pennsylvania State University - Housing Research Center: <http://www.engr.psu.edu/phrc/>
- Washington State University Energy Extension: <http://www.energy.wsu.edu/projects/building/>

C.2.3 Private Sector Companies

Private U.S. companies known to have been active in moisture research include DuPont (Tyvek), CertainTeed (MemBrain) Owens-Corning (Tuff-N-Dry, elastomeric roof membranes), and USG. Large wood and paper companies such as LP and Georgia-Pacific undoubtedly also fund research on moisture control, and there are certainly others involved. This work is extraordinarily difficult to document because it is usually confidential and proprietary, with the principal evidence of its existence in the form of new products that reach the market. The opportunities for these firms to share information about their work and to collaborate in research are not only constrained by competitive issues, but also by antitrust concerns.

C.3 Research Coordination Process

C.3.1 Existing Venues for Coordination

There are at present at least two groups mentioned above that are situated to serve a coordinating role for moisture research: They are:

- BETEC, operated by the National Institute of Building Sciences, and
- RMMN, jointly operated by the Forest Products Laboratory and APA - The Engineered Wood Association.

Of the two BETEC is better established, having been in existence for over 20 years. BETEC funding comes primarily from the U.S. Department of Energy, supplemented by membership fees and publication sales. The group is probably best known for hosting several thematic conferences and symposia each year, where research results on particular building envelope topics of interest are presented. While BETEC's mission includes moisture control, it is clearly much larger, also encompassing energy efficiency, indoor air quality and environmental sustainability, and most recently acoustic performance, building envelope security and mold. BETEC has clearly identified the need to coordinate research on these topics; multiple BETEC "Research Coordinating Committees" have been formed, including committees on Moisture and Mold, but to the degree they are active, their work apparently is focused primarily on developing content for BETEC conferences.

The second existing group that could potentially play a role in coordinating moisture research is RMMN, which was created in 2002 with funding from the two sponsors (FPL and APA) and a grant from the HUD Office of Healthy Homes and Lead Hazard Control. RMMN reportedly suspended operations during 2003 when its funding was cut, and resumed activity in mid-2004. Like BETEC, the mission of RMMN includes coordination of research among multiple participating organizations. However, unlike BETEC, the principal focus of RMMN is clearly on preventing moisture problems in housing. Thus far RMMN has not sponsored conferences, does not charge for membership, and does not serve as a professional association the way BETEC is viewed by some.

Although either of these organizations might theoretically serve a role of coordinating moisture-related research, there are reasons for doubting this will succeed. Factors that would help include their relatively low operating cost and the broad involvement they enjoy among potentially interested parties. Indeed, BETEC and RMMN are becoming positioned as competitors for leadership in this area. But BETEC already has many other issues on its agenda, and RMMN has yet to achieve real traction. Perhaps most importantly, neither group is led or openly controlled by the groups who fund research, and there is no evidence that meaningful coordination has resulted.

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Until the research sponsors are directly involved and fully vested in operation of the group, the goals of increasing collaboration and leveraging research funding are likely to remain out of reach.

C.3.2 A Potential Federal Approach

Rather than attempting to use BETEC or RMMN as a vehicle for coordination of moisture research, an alternative approach is recommended. The underlying model is the "Federal Roofing Committee" (FRC), a relatively informal group of federal agencies with a common interest in improving the longevity and performance of roofs in buildings they own or occupy. The FRC originated some 25 years ago as the "Tri-Service Roofing Committee" which included representatives of laboratories performing roofing research for the Army, Navy and Air Force. Participation has varied over the years, but agencies currently involved include the U.S. Army, the Department of State, NIST and the U.S. EPA. The FRC meets annually to discuss roofing research, methodologies and technological developments. Outside associations with a direct interest in roofing technology and research are not members of the committee, but they are allowed to attend and participate in committee meetings. While the FRC does not fund research, its members do provide funding. Its meetings also provide a venue for sharing research results, plans and ideas, and an opportunity to create informal alliances or divide tasks across multiple agencies to avoid duplication and overlap.⁸

Organize a Federal Moisture Research Committee. The first step in implementing a broad-based approach to research coordination is to organize a "Federal Moisture Research Committee". The group should be kept informal and un-bureaucratic to the maximum extent possible. Membership would be open to any federal agency that funds moisture-related research; the possibility of including the Canada Mortgage and Housing Corporation and the Institute for Research in Construction at the National Research Council - Canada, both of whom fund research into moisture problems, should be seriously considered as well. The designated agency representatives should have direct responsibility for making funding decisions about (or at least managing) research related to moisture in housing. The Committee would be charged with maintaining a research agenda based on input from all the participants. It would meet at least once a year, probably for a day or even 1-1/2 days, with a standing agenda that could include:

- reports from all members on work completed since the last meeting
- presentations on work in progress and newly started projects
- exchange of information about planned work, and
- revisions or updates to the research agenda.

This is described as a governmental committee given the fact that virtually all the non-proprietary research into moisture problems is government-funded. However, it is certain that representatives of outside organizations would strongly desire to be involved. Representatives of selected groups should be invited to attend meetings as observers and participate in discussions as appropriate. There would also be an opportunity for those organizations to comment on federally-funded activities, provide information about their own work, and solicit federal participation or cost-sharing in activities they are performing or planning.

Informational function. The Committee function would be primarily informational in nature. Information presented to or developed by the Committee, including the research agenda and details about ongoing projects, should be posted on the internet with links to any documentation available from the sponsors. Comments from website visitors might be solicited and circulated to the appropriate agencies. A newsletter containing similar information, perhaps with highlights of recent results, could be prepared and distributed electronically or in hard copy. The target audiences would go beyond Committee members to include domestic and international research organizations, subject matter experts, university engineering departments and anybody else with an interest in the topic. If resources permitted each issue could include in-depth coverage of a selected theme; there are many to choose from.

Outreach by the Committee. A final element of this approach would be active outreach to other groups, inviting their input on research needs and advising them of research opportunities. The best approach would be in-person

⁸ A similar organization with a much broader scope that includes coordination of R&D on housing is the "Federal Agency Housing Partnership", which is the successor to the PATH "Federal Agency Working Group" See <http://www.fpl.fs.fed.us/ahrc/fahp.htm>.

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presentations to groups such as EEBA, BETEC, ASHRAE and ASTM where researchers and other interested parties are likely to be found. If formal solicitations are underway or anticipated, this information could be communicated, and if contracting requirements permit, information could be presented about how the agencies represented on the Committee would respond to unsolicited proposals.

Costs and Support. The cost of agency participation in this kind of effort would be modest if meetings were infrequent and conveniently located. But some supporting services would be necessary, probably from an outside contractor rather than delegated to agency participants in order to ensure follow-through and demonstrable progress between meetings.. In addition to organizing and facilitating meetings, the contractor could create and maintain the website, keep the research agenda up to date, prepare the newsletter, and perform outreach or identify outreach opportunities appropriate for representatives of member agencies. Although this is not a trivial level of effort, it is clearly much less than a full-time job. Obviously some way of sharing this cost among the agency participants would need to be devised.

While there is no assurance this type of effort will be successful, periodic open sharing of information about what is happening, what is planned and what remains to be done will make all the participants aware of the degree to which their interests are shared, their programs are overlapping, and their research efforts could benefit from closer interaction or collaboration. Bringing outside groups into the discussion in a structured way could further enhance this process. In other words, they will all have the chance to coordinate implicitly by dividing up responsibilities, or explicitly by co-funding projects of mutual interest.