MOISTURE ANALYSIS *and* CONDENSATION CONTROL *in* BUILDING ENVELOPES

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Editor

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Moisture Analysis and Condensation Control in Building Envelopes

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Foreword

THIS PUBLICATION, *Moisture Analysis and Condensation Control in Building Envelopes*, was sponsored by Committee C16 on Thermal Insulation and Committee E06 on Performance of Buildings. The editor was Heinz R. Trechsel. This is Manual 40 in ASTM's manual series.

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Preface

by Heinz R. Trechsel[1]

PURPOSE OF THE MANUAL

In ASTM Manual MNL 18, *Moisture Control in Buildings,*[2] Mark Bomberg and Cliff Shirtliffe, in their chapter "A Conceptual System of Moisture Performance Analysis," make the case for a rigorous design approach that "should involve computer-based analysis of moisture flow, air leakage, and temperature distribution in building elements and systems." In the Preface to the same manual, I state that one objective of Manual 18 is to help establish moisture control in buildings as a separate and essential part of building technology.

In 1996, the Building Environment and Thermal Envelope Council (BETEC)[3] conducted a Symposium on Moisture Engineering. The symposium presented an overview of the current state-of-the-art of moisture analysis and had a wide participation of building design practitioners. The consensus of the participants was that moisture analysis was now practical as a design tool, and that it should be given preference over the simple application of the prescriptive rules. However, it was also the consensus that the architect/engineer community was not ready to fully embrace the analytical approach. Thus, both the building research and the broader building design community recognized the need for moisture analysis and for a better understanding of currently available moisture analysis methods.

The concerns for moisture control in buildings have increased significantly since the early 1980s. One sign of the increased concern is the number of research papers on moisture control presented at the DOE/ASHRAE/BETEC conferences on "Thermal Performance of Exterior Envelopes of Buildings" from 8 in 1982 to 17 in 1992 and to 27 directly related to moisture in 1998. Another measure is that the Building Environment and Thermal Envelope Council held four conferences/symposia from 1991 through 1999, and only two between 1982 and 1990.

In response to these developments ASTM Committees C16 on Thermal Insulation and E06 on Performance of Buildings have agreed to co-sponsor the preparation and publication of this new manual to expand and elaborate on the relevant chapters of MNL 18: Chapter 2, "Modeling Heat, Air, and Moisture Transport through Building Materials and Components," and Chapter 11, "Design Tools." The objective of this manual, then, is to familiarize the wider building design community with typical moisture analysis methods and models and to provide essential technical background for understanding and applying moisture analysis.

THE CURRENT PRESCRIPTIVE RULES TO PREVENT MOISTURE PROBLEMS IN BUILDING ENVELOPES

In 1948, the U.S. Housing and Home Finance Agency (a forerunner of the current Federal Housing Administration) held a meeting attended by representatives of build-

[1] H. R. Trechsel Associates, Arlington, VA; Trechsel is also an architect for Engineering Field Activity Chesapeake, Naval Facilities Engineering Command, Washington, DC. The opinions expressed herein are those of the author and do not necessarily reflect those of any Government agency.

[2] *Manual on Moisture Control in Buildings, ASTM MNL 18,* Heinz R. Trechsel, Editor, Philadelphia, 1994.

[3] The Building Environment and Thermal Envelope Council is a Council of the National Institute of Building Sciences, Washington, DC.

ing research organizations, home builders, trade associations, and mortgage finance experts on the issue of condensation control in dwelling construction.[4] The focus of the meeting was on vapor diffusion in one- and two-family frame dwellings in cold weather climates. The consensus and result of that meeting was the Prescriptive Rule to place a vapor barrier (now called a vapor retarder) on the warm side of the thermal insulation in cold climates. The meeting also established that a vapor barrier (retarder) means a membrane or coating with a water vapor permeance of one Perm or less. One Perm is 1 $g/h{\cdot}ft^2{\cdot}in.Hg$ (57 $ng/s{\cdot}m^2{\cdot}Pa$). The rule was promulgated through the FHA Minimum Property Standards.[5] It still is referenced unchanged in some construction documents.

The 1948 rule was based on the assumption that diffusion through envelope materials and systems is the governing mechanism of moisture transport leading to condensation in and eventual degradation of the building envelope. Since 1948, and particularly since about 1975, research conducted in this country and abroad has brought recognition that infiltration of humid air into building wall cavities and the leakage of rainwater are significant, in many cases governing mechanisms of moisture transport. Accordingly, the original simple rule with a limited scope has been expanded to include air infiltration and rainwater leakage, and to cover other climates and building and construction types. The current, expanded prescriptive rules can be summarized as follows:

- install a vapor retarder on the inside of the insulation in cold climates,
- install a vapor retarder on the outside of the insulation in warm climates,
- prevent or reduce air infiltration,
- prevent or reduce rainwater leakage, and
- pressurize or depressurize the building so as to prevent warm, moist air from entering the building envelope.

The current expanded rules have greatly increased the validity and usefulness of the prescriptive rules. However, the rules still do not fully recognize the complexities of the movement of moisture and heat in building envelopes. For example:

- The emphasis on either including or deleting a separate vapor retarder is misplaced, and the contribution of the hygrothermal properties of other envelope materials on the moisture flow are not considered. In fact, incorrectly placed vapor retarders may increase, rather than decrease, the potential for moisture distress in building envelopes.
- Climate as the only determining factor is inadequate to establish whether a vapor retarder should or should not be installed. Indoor relative humidity and the moisture-related properties of all envelope layers must also be considered.
- The two climate categories "cold" and "warm" have never been adequately or consistently defined, and large areas of the contiguous United States do not fall under either cold or warm climates, however defined. For example, ASHRAE,[6] in 1993, used condensation zones based on design temperatures. For cold weather, Lstiburek[7] suggests 4000 Heating Degree Days or more, and the U.S. Department of Agriculture[8] uses an average January temperature of 35°F or less. For warm climates, ASHRAE[9] established criteria based on the number of hours that the wet bulb temperature exceeds certain levels, Odom[10] suggests average monthly latent load greater than

[4] Conference on Condensation Control in Dwelling Construction, Housing and Home Finance Agency, May 17 and 18, 1948.

[5] HUD Minimum Property Standards for One- and Two-Family Dwellings, 4900.1, 1980 (latest edition).

[6] ASHRAE, *Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 1993.

[7] Lstiburek, J. and Carmody, J., "Moisture Control for New Residential Buildings," *Moisture Control in Buildings, MNL 18*, H. R. Trechsel, Ed., American Society for Testing and Materials, Philadelphia, 1994.

[8] Anderson, L. O. and Sherwood, G. E., "Condensation Problems in Your House: Prevention and Solutions," Agriculture Information Bulletin No. 373, U.S. Department of Agriculture, Forest Service, Madison, 1974.

[9] ASHRAE, *Handbook of Fundamentals*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, 1997.

[10] Odom, J. D. and DuBose, G., "Preventing Indoor Air Quality Problems in Hot, Humid Climates: Design and Construction Guidelines," CH2M HILL and Disney Development Corporation, Orlando, 1996.

average monthly sensible load for any month during the cooling season, and Lstiburek[11] suggests defining warm climate as one receiving more than 20 in. (500 mm) of annual precipitation and having the monthly average outdoor temperature remaining above 45°F (7°C).

Over the last 20 years or so, building researchers have tried to refine the definitions of cold and warm climates. Except for the efforts of Odom and Lstiburek (for which the jury is still out), not much progress has been made. In the meantime, much progress has been made in the development of analytical methods to predict surface relative humidities, moisture content, and even the durability performance of building envelope materials.

The above suggests that the prescriptive rules alone will not assure that building envelopes are free of moisture problems. Accordingly, and consistent with the consensus of the 1996 BETEC Symposium participants, we must look to job specific moisture analysis methods and models for the solution to reduce or eliminate moisture problems in building envelopes. This does not mean that the traditional prescriptive rules should be ignored or that they should be violated without cause. They should, however, be used as starting points, as first approximations, to be refined and verified by moisture analysis. This, then, is analogous to the practice in structural design, where, for example, depth-to-span ratios are used as first approximations, to be refined by analysis. Which is, very much simplified, what Bomberg and Shirtliffe advocate in Manual 18.

ANALYTICAL METHODS AND MODELS AND THEIR LIMITATIONS

The progress made in the development of computer-based analysis methods, or models since the publication of MNL 18 in 1994, has been spectacular. At last count, there exist now well over 30 models that analyze the performance of building envelopes based on historical weather data, and new and improved models are being developed as this manual goes to press. The models vary from simplified models useable by building practitioners on personal computers to sophisticated models that require specially trained experts and that run only on mainframe computers.

The simpler models may or may not include the effect of moisture intrusion due to air and water infiltration. The more sophisticated models are excellent tools for building researchers and, as a rule, include the effects of rainwater leakage and air infiltration. As mentioned above, air infiltration and water leakage are significant causes of moisture distress in building envelopes. This would seem to imply that only models that include these two factors are useful to the designer. However, this is not necessarily so for the following reasons:

- The input data for air infiltration and water leakage are unreliable. Infiltration and leakage performance data for various joint configurations and for entire systems are generally unknown. Also, much of the performance of joints depends on field workmanship and quality control over which the designer seldom has significant control.
- Air infiltration and rainwater leakage, unlike diffusion, occur at distinct leakage sites. These are seldom evenly distributed over the entire building envelope. Accordingly, the effect of air and water leaks are bound to be localized with the locations unknown at the design stage.
- Both air and water leaks are transitional in nature, with durations measured in hours, days, or weeks. Rainwater leakage depends on wind direction, and rainfalls one day may not fall again during the next day or week. Air infiltration depends on wind direction. Moist air moves into the envelope one day; the next day dry air may enter the envelope and wetting turns to drying. In contrast, diffusion mechanisms operate generally on a longer time horizon, frequently for weeks, months, or over an entire season.

Although models that include air infiltration and rainwater leakage are excellent research tools, models that do not include these transport mechanisms are still most

[11] Lstiburek, J., "Builder's Guide for Hot-Humid Climates," Westford, 2000.

useful for the designer/practitioner provided that their limitations are recognized and proper precautions are taken to reduce or eliminate air infiltration and water leakage.

The use of moisture analysis alone does not guarantee moisture-resistant buildings. Careful detailing of joints and the use and proper application of sealants and other materials are necessary. The issues of field installation and field quality control, mentioned above, must be addressed adequately by the designer and specification writer. For example, for more complex and innovative systems, specifying quality control specialists for inspecting and monitoring the installation of envelope systems in Section 01450 and specifying that application only be performed by installers trained and approved or licensed by the manufacturer will go a long way towards reducing moisture problems in service. Also important are operation and maintenance, both for the envelope and for the mechanical equipment. Face-sealed joints need to be inspected and repaired at regular intervals. If pressurization or depressurization are part of the strategy to reduce the potential for moisture distress, documentation of proper fan settings is critical. However, these concerns are outside the scope of this manual and will not be discussed further.

Moisture analysis is still an evolving art and science. While great advances have been made in the development of reliable and easy-to-use models and methods, some input data needed for all the models are still limited:

Weather Data

Appropriately formatted data are available only for a restricted number of cities. However, it is generally possible to conduct the analysis for several cities surrounding the building location and to determine the correctness of the assumptions with great confidence. Also, the data currently available were developed for determining heating and cooling load calculations; their appropriateness for moisture calculations has been questioned. Chapter 2 of this manual provides new weather data specifically developed for moisture calculations.

Material Data

Data on the hygrothermal properties of materials are available only for a limited number of generic materials. A major effort is currently under way by ASHRAE and by the International Energy Agency to develop the necessary extensive material database. Some of the most recent material data are included in Chapter 3 of this manual.

Failure Criteria

Reliable failure criteria data are available only for wood and wood products, and even for these the significant parameter of length of exposure has not been studied to the desirable degree. Chapter 4 of this manual discusses these criteria.

Despite these concerns about the application of moisture models, designs based on rigorous analysis are bound to be far more moisture resistant than designs based on the application of prescriptive rules alone. The authors of this manual hope that it will encourage building practitioners and students to conduct moisture analysis as an integral part of the design process. The more widespread use of moisture analysis to develop building envelope designs will then in turn provide an added incentive for model developers to improve their models, for producers to develop the necessary data for their materials, and for researchers to establish new databases on weather data better suited for moisture calculations.

CONCLUSIONS

One objective of this manual is to provide the necessary technical background for the practitioner to understand and apply moisture analysis. In addition, two models are discussed in detail to familiarize the practitioner with the conduct of typical computer-based analysis. The selection of the two models is based on ready availability and on ease of operation. The two models are included on a CD ROM disk enclosed in the pocket at the end of the manual. Also included on the disk are two programs to convert various properties of air. Based on the information provided, the reader should be able to start his or her own hands-on training in moisture analysis.

Heinz R. Trechsel
Editor

Acknowledgments

THIS MANUAL IS NOT THE WORK of a single person. It is the result of cooperation between the authors of individual chapters, a small army of reviewers, staff support people, and the editor, all working together.

Thus, my utmost thanks to the authors who prepared their chapters. Each one is a leading expert in his field, and the chapters are at the forefront of the current state-of-the-art in moisture analysis. Next, I want to thank the reviewers, who generously gave of their time and whose comments and suggestions improved the individual chapters and the utility of the manual. The names of the reviewers are listed below. My appreciation also goes to the executive committees of the two sponsoring ASTM Committees, C16 on Thermal Insulation and E06 on Performance of Buildings.

Aside from the technical inputs mentioned above, the manual would not have been born without the untiring support of ASTM's staff: Kathleen Dernoga and Monica Siperko, who shepherded the preparation of the Manual through all its phases and provided much needed administrative support; and David Jones, who capably edited the final drafts of the individual chapters. To all of them my most sincere thanks and appreciation.

Our special thanks also to Mr. Rob Davidson of the Trane Company and to Dr. Carsten Rode of the Technical University of Denmark for their permissions to reproduce the conversion programs. Also to Dr. James E. Hill, Deputy Director of the Building and Fire Research Laboratory at the National Institute of Standards and Technology in Gaithersburg, Maryland, to Prof. Dr. -Ing. habil. Dr. h.c. mult. Dr. E.h. mult. Karl Gertis, of the Fraunhofer Institute für Bauphysik in Holzkirchen, Germany, and to Dr. Andre Desjarlais of Oak Ridge National Laboratory at Oak Ridge, Tennessee, for their permission to reproduce the two moisture analysis programs. I'm also much indebted to Mr. Christopher Meyers of the Engineering Field Activity Chesapeake, Naval Facilities Engineering Command for coordinating the four programs and preparing a user friendly interface for the CD-ROM.

Finally, but by no means least, I was encourged by two good friends to prepare this manual long before the first word was ever written. Ev Shuman of Pennsylvania State University and Reese P. Achenbach, formerly Chief of the Building Environment Division at the National Institute of Standards and Technology, assisted me in formulating the initial plan for the manual. Both are no longer among us. However, their suggestions have, to a large degree, shaped the manual you hold in your hands. My thanks to them.

Heinz R. Trechsel
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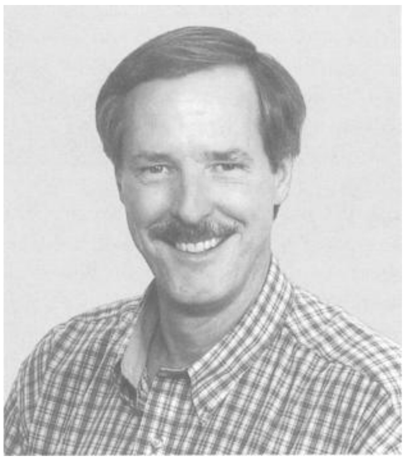


Mark A. Albers is the principal scientist and manager of the Thermal Technology Laboratories at the Johns Manville Technical Center near Denver, CO. He has two B.S. in Engineering degrees, an M.S. in Physics, and the coursework for a Ph.D. in Physics from the Colorado School of Mines. His interests have involved theoretical modeling and experimental research in thermal insulations and systems from cryogenic to refractory temperatures. More recently his research concerns building physics and hygrothermal modeling. He has published in the areas of vacuum and cryogenic thermal testing as well as thermal radiation modeling in insulations. Mark is chairman of ASTM C16.94 on Thermal Insulation Terminology and is active in ASTM C16.30 on Thermal Measurements. He is on the editorial board of the *Journal of Thermal Envelope & Building Science* and is a member of the American Physical Society. His patents are in the areas of cryogenic insulations and radiative enhancement of glass fibers.

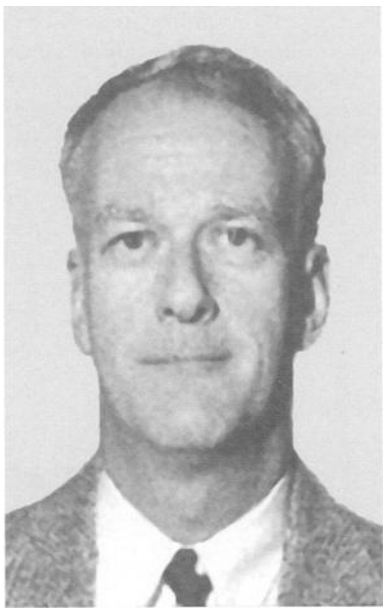
Doug Burch

Doug Burch currently is an engineering consultant with his company, Heat & Moisture Analysis, Inc. He is currently developing a public-domain, two-dimensional, heat and moisture transfer model. Mr. Burch worked previously at the National Institute of Standards and Technology (NIST) for 28 years. While at NIST, he served as project leader on a wide range of research projects including: (1) measuring and predicting the effect of thermal mass on the space heating and cooling loads of buildings; (2) measuring the steady-state and dynamic heat transfer in walls in a calibrated hot box; (3) conducting infrared thermographic surveys of buildings to locate thermal anomalies and quantify heat loss; (4) measuring the heat and moisture properties of building materials; (5) measuring space heating and cooling loads for buildings; and (6) conducting full-scale experiments to measure the heat and moisture transfer in attics and walls. Before retiring from NIST, Mr. Burch developed the public-domain, one-dimensional, heat and moisture transfer model called MOIST (Release 3.0). Mr. Burch has published 100 papers and reports in the technical literature. He received a B.S. in Electrical Engineering from the Virginia Polytechnic Institute and State University in 1965. Additionally, Mr. Burch received a M.S. in Mechanical Engineering from the University of Maryland in 1970.

Eric F. P. Burnett

Eric F. P. Burnett is a structural engineer with specialist competence in the broad areas of building science and technology, building performance, and structural con crete. He has extensive experience of the building industry, having been involved in the design and construction of buildings on three continents. He has worked with and consulted a number of R and D agencies in the United States, Canada, and elsewhere. Dr. Burnett is currently the Bernard and Henrietta Hankin Chair at the Pennsylvania State University. He is cross-appointed to the Departments of Civil and Environmental Engineering and Architectural Engineering. He is also the Director of the Pennsylvania Housing Research Center. Both as an educator and a researcher, Dr. Burnett was associated with the University of Waterloo for more than 25 years. He was Director of the Building Engineering Group, as well as a Professor of Civil Engineering. As senior Consultant and Technical Director for Building Science and Rehabilitation Group, he was involved with Trow Consulting Engineers Ltd. For more than ten years. Dr. Burnett's current research interests are directed at the performance of building enclosures, i.e., wall systems, roofs, etc., and the integration of structural and control (heat, air, moisture) functions. Recent projects have involved reinforced polymer modified bitumen membranes, FRP and PVC structural elements, masonry (brick veneer/steel stud, tie systems, durability, etc.). A number of projects have been directed at the wetting and drying mechanisms in wall systems using a full-scale test facility. He has been involved in the development of a number of building systems in particular housing.

Donald G. Colliver

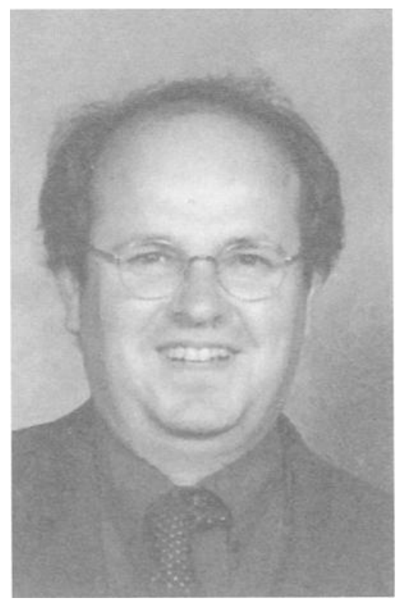


Donald G. Colliver is an Associate Professor in the Biosystems and Agricultural Engineering Department at the University of Kentucky in Lexington, Ky. He has conducted extensive research in energy usage in residences, air infiltration and ventilation, and the analysis of climatological data for determination of design weather conditions. Much of the weather data research has been done in support of research projects determining the short-term extreme periods of temperature and humidity and also in developing the tables of design weather conditions in the *ASHRAE Handbook—Fundamentals*. He has written numerous papers, articles, and *Handbook* chapters and developed several weather analysis design tools that use historical data on CD-ROMs. Dr. Colliver is a Registered Professional Engineer in the Commonwealth of Kentucky and an ASHRAE Fellow and Distinguished Service Award recipient. He has led numerous ASHRAE committees, the Education and Technology Councils, and currently serves as Society Treasurer.

Andreas Hagen Holm

Andreas Hagen Holm is Senior Research Engineer and head of the modeling group within the hygrothermal division of the Fraunhofer-Institut Bauphysik (IBP). He finished Experimental Physics with a Diploma (M.Sc.) from the Technical University of Munich, Germany. Most recently, he has been involved mainly in the development of the computer code WUFI and WUFI2D and its application for sensitivity and stochastic analysis. He also worked on the combined effect of temperature and humidity on the deterioration process of insulation materials in EIFS, studied the phenomena of moisture transport in concrete, and developed a new measurement technique for detecting the salt and water distributions in building material samples.

Achilles Karagiozis



Achilles Nick Karagiozis is a Senior Research Engineer and the Hygrothermal Project Manager at the Oak Ridge National Laboratory, Building Technology Center (USA). He received a Bachelor's degree and a Master's degree in Mechanical Engineering at UNB (CAN), a second Master's Diploma in Environmental and Applied Fluid Dynamics at the von Karman Institute in Fluid Dynamics (Belgium), and a Ph.D. in Mechanical Engineering at the University of Waterloo (CAN). He has multi-disciplinary knowledge that spans several important technical fields in building science. Dr. Karagiozis is internationally considered a leader in building envelope thermal and moisture analysis. At NRCC (1991–1999) Dr. Karagiozis was responsible for NRC's long-term hygrothermal performance analysis of complex building systems. At NRCC he developed the LATENITE hygrothermal model with Mr. Salonvaara (VTT) and was responsible for the development of the WEATHER-SMART model, the LATENITE hygrothermal pre- and post processor (LPPM) model, and the LATENITE material property database system model. At the Oak Ridge National Laboratory (USA) he has been developing the next generation of software simulation packages for hygrothermal-durability analysis. In collaboration with Dr. Kuenzel and Mr. Holms (IBP, Germany), he co-developed the WUFI-ORNL/IBP model, a state-of-the-art educational and application tool for architects and engineers. At ORNL he developed MOISTURE-EXPERT, a leading edge hygrothermal research model. Dr. Karagiozis is actively participating in International Energy Agency Annex 24 (1992–1996), BETEC, CIB W40, ASHRAE T.C. 4.4, and T.C. 4.2, ASTM E06 on Building Performance. He is also an Adjunct Professor at the University of Waterloo and is collaborating with world-renown institutes (IBP and VTT) in the area of hygrothermal-durability analysis. He is currently involved in holistic building analysis, experimental hygrothermal field monitoring, Stucco clad and EIFS performance, crawlspace hygrothermal performance, and is developing guidelines for performance of walls, roofs, and basements. He has over 70 scientific publications in journals and trade publications.

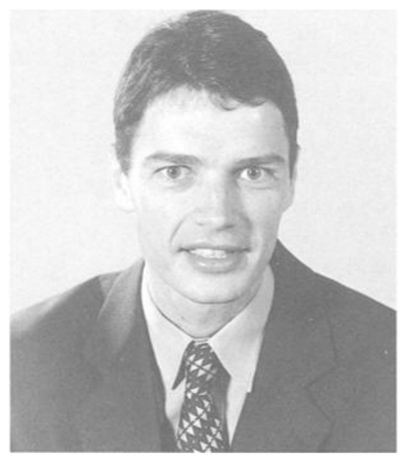
Hartwig Michael Kuenzel

Hartwig Michael Kuenzel is head of the hygrothermal division of the Fraunhofer-Institut Bauphysik (IBP), the largest research establishment in Germany for building physics funded mainly by industrial contracts Having acquired specific knowledge in CFD modeling at the University of Erlangen, he concentrated on transient heat and moisture transfer in building materials and components since entering the IBP in 1987. The computer code WUFI was developed during his Ph.D. thesis, defended at the civil engineering faculty of the University of Stuttgart in 1994. In the same year he became Research Director at IBP for hygrothermal modeling, laboratory, and field testing. He has been active in many international projects (IEA Annex 14 &24), standard committees (ASHRAE, CEN), and continuous education seminars. Dr. Kuenzel has published over 100 scientific articles in trade journals and text books. He is chairing a European CEN working group that will produce a standard for the application of heat and moisture simulation tools in building practice.

Mavinkal K. Kumaran

Mavinkal K. Kumaran (Kumar) is a Senior Research Officer and a Group Leader at the Institute for Research in Construction, the National Research Council of Canada. Dr. Kumaran has an M.Sc. in Pure Chemistry from Kerala University, India (1967) and a Ph.D. in Thermodynamics from University College London, UK (1976). In 1967 he began his career as a lecturer in chemistry. He joined NRC as a Research Associate in the Division of Chemistry in 1981 and continued to contribute to the field of thermodynamics of liquids and liquid mixtures. He joined the Institute for Research in Construction in 1984 and developed an internationally recognized research group on hygrothermal analyses of building envelope materials and components. He has been leading that group's activities since 1986. In recognition of his contributions to building science and technology, he was awarded a senior fellowship by the Japan Society for Promotion of Science in 1992, and another senior fellowship by the Kajima Foundation, Japan in 1996.

Carsten Rode

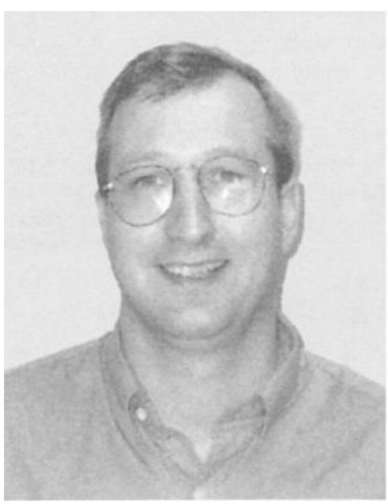


Carsten Rode earned a Master of Science degree in Civil Engineering in 1987. He obtained a Ph.D. in the same subject in 1990, writing a thesis entitled "Combined Heat and Moisture Transfer in Building Constructions." Both degrees were awarded by the Technical University of Denmark. He was a guest researcher with the Oak Ridge National Laboratory in 1989. He is author of the program MATCH for combined heat and moisture transfer in building constructions, which is among the first such transient programs made available to users outside the research community. He was senior researcher with the Danish Building Research Institute from 1992–1996 and has been Associate Professor with the Technical University of Denmark since 1996. He has been a participant in various international research projects, e.g., IEA Annex 24 on Heat, Air and Moisture Transfer in Insulated Envelope Parts, and the EU project COMBINE on Computer Models for the Building Industry in Europe.

Mikael Salonvaara

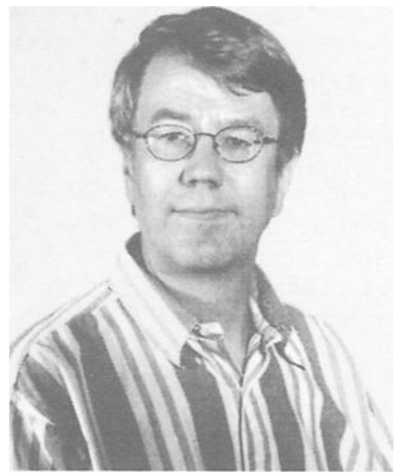
Harri Mikael Salonvaara is a research scientist in the Building Physics and Indoor Climate group at VTT Building Technology, which is one of the nine research institutes of the Technical Research Centre of Finland. He finished his Master's thesis at Lappeenranta University of Technology in 1988 while already working at VTT Building Technology in Espoo, Finland. The result of his thesis was the two-dimensional heat, air, and moisture transfer model TRATMO2. He worked for over two years (Nov. 1993–Jan. 96) as a guest researcher at the Institute for Research in Construction (National Research Council of Canada) where he developed the new heat, air, and moisture transfer simulation model LATENITE with Dr. Karagiozis. He continued the model development at VTT Building Technology as the leader of "Calculation Tools" team. His expertise is heat, air, and moisture transfer in buildings and building envelope parts, effects of moisture on durability and service life, and on emissions from building materials. He has published over 60 scientific and technical publications on hygrothermal performance of buildings. He is active in national and international technical committees and projects dealing with building envelope performance and indoor air quality.

John Straube



John Straube is involved in the areas of building enclosure design, moisture physics, and whole building performance as a consultant, researcher, and educator. He is a faculty member in the Department of Civil Engineering and the School of Architecture at the University of Waterloo, where he teaches courses in structural design and building science to both disciplines. Research interests include driving rain measurement and control, pressure moderation, ventilation drying, and full-scale natural exposure performance monitoring of enclosure systems, and hygrothermal computer modeling of all the above. He has a broad experience in the building industry, having been involved in the design, construction, repair, and restoration of buildings in Europe, Asia, the Caribbean, United States, and Canada. As a structural engineer he has designed with wood, hot-rolled and cold-formed steel, concrete, masonry (brick, concrete, aerated autoclaved concrete, natural stone), aluminum, polymer concrete, carbon and glass FRP, fiber-reinforced concrete and structural plastics (PVC, nylon). He has been a consultant to many building product manufacturers and several government agencies (NRCC/IRC, NRCan, CMHC, DOE, ORNL, PHRC) and is familiar with building-related codes (e.g., NBCC, CSA, NECB, ACI, DIN, etc.) and standards (e.g., CSA, CGSB, ASTM, AAMA, ASHRAE) as well as the measurement and testing procedures of the performance of buildings and their components.

Anton TenWolde

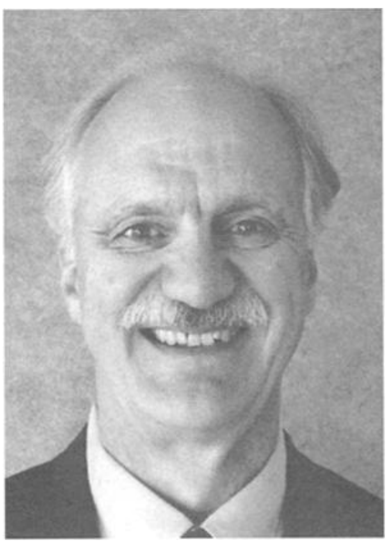


Anton TenWolde is a research physicist at the USDA—Forest Service, Forest Products Laboratory in Madison, Wisconsin. He is Team Leader for the Moisture Control in Buildings Team, located in the Engineered Wood Products and Structures Research Work Unit. The team's mission is to extend the service life of wood products in buildings through improved building design and operation. He holds an M.S. (Ingenieur) in Applied Physics from the Delft University of Technology, Delft, the Netherlands (1973), and an M.S. in Environmental Management from the University of Wisconsin, Madison, Wisconsin (1975). TenWolde is an active member of ASHRAE. He chaired the revision of the *1997 ASHRAE Handbook of Fundamentals* chapters on moisture control in buildings and is chairman of ASHRAE Standard 160P, Design Criteria for Moisture Control in Buildings. He has authored or coauthored more than 45 articles and reports on moisture control in buildings.

Heinz R. Trechsel

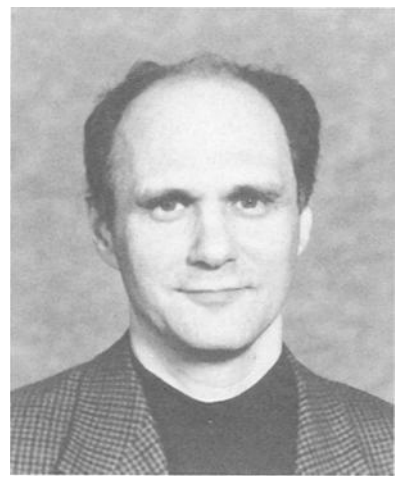
Heinz R. Trechsel is a graduate architect of the Swiss Federal Institute of Technology in Zürich and is a registered architect in the state of New York. As an independent consultant, he investigates and consults on moisture problems in buildings, develops remedial measures, and serves as a witness in cases related to moisture problems in buildings. Trechsel also is a staff architect with the Engineering Field Activity Chesapeake of the Naval Facilities Engineering Command. He was previously employed by the National Bureau of Standards (now National Institute of Standards and Technology), the Applied Research Laboratory of the United States Steel Corporation, and various architectural firms in New York and in Europe. He is a member of ASTM Committee E06 on Performance of Buildings since 1961 and was a member of Committees C16 on Insulations and D20 on Plastics.

George Tsongas



George Tsongas is a private consulting engineer specializing in building science and moisture problems in buildings. After 29 years he retired recently from his faculty position in the Mechanical Engineering Department at Portland State University in Oregon and is now a Professor Emeritus. He has directed a number of field studies for the U.S. DOE of moisture problems in the walls of new and existing site-built and manufactured homes. He also has investigated indoor air quality problems inside existing and new residences, as well as ventilation and dehumidification moisture control strategies. In addition, he has completed extensive computer modeling of the moisture performance of residential roofs, walls, and indoor spaces. He has worked with Doug Burch to modify the MOIST computer program algorithms, and has provided training for NIST on the use of the MOIST software. In addition, he routinely is an expert witness in legal cases involved with residential moisture problems. In that capacity he has inspected many thousands of dwelling units for siding, wall, roof, floor, and indoor moisture problems. He also has completed a number of laboratory studies of the moisture performance of different types of siding, as well as wall moisture intrusion and migration mechanisms. He has about 70 technical publications that include his work. Dr. Tsongas received four engineering degrees from Stanford University.

Hannu Viitanen



Hannu Viitanen was born in 1951 in Turku, Finland and graduated with a Master's degree in biology from the University of Turku in 1980. He obtained a Doctor's degree at SLU, Uppsala, Sweden, in 1996. He has been a senior research scientist at VTT Building Technology since 1980. He has worked as a visiting professor at the Finnish Forest Research Institute from 1996–98. His thesis focused on the modeling of critical conditions of mold growth and decay development in wooden materials. He has more than 120 publications in the field. His expertise is wood preservation, mold growth on wood, and decay problems in buildings. He has been involved in consultation and training concerning conservation and reparation of buildings. He has been an active member of the International Research Group on Wood Preservation since 1988 and has been a national representative in COST E2, Wood Durability, WG1 since 1994.

Glossary

by Mark Albers[1]

2DHAV—a two-dimensional model by Janssens that allows complex airflow paths like cracks, gaps, and permeable materials.

absolute humidity, ($kg{\cdot}m^{-3}$),($lb{\cdot}ft^{-3}$)—the ratio of the mass of water vapor to the total volume of the air sample. In SI units, absolute humidity is expressed as kg/m^3. In inch-pound units, absolute humidity is expressed as lb/ft^3.

absorption coefficient, ($kg{\cdot}m^{-2}{\cdot}s^{-1/2}$), ($lb{\cdot}ft^{-2}{\cdot}s^{-1/2}$)—the coefficient that quantifies the water entry into a building material due to absorption when its surface is just in contact with liquid water. It is defined as the ratio between the change of the amount of water entry across unit area of the surface and the corresponding change in time expressed as the square root. In the early part of an absorption process this ratio remains constant and that constant value is designated as the water absorption coefficient.

adsorption isotherm—the relationship between the vapor pressure (or more often relative humidity, RH) of the surroundings and the moisture content in the material when adsorbing moisture at constant temperature.

air flux, ($kg{\cdot}m^{-2}{\cdot}s^{-1}$), ($lb{\cdot}ft^{-2}{\cdot}s^{-1}$)—the mass of air transported in unit time across unit area of a plane that is perpendicular to the direction of the transport.

air permeability, ($kg{\cdot}m^{-1}{\cdot}Pa^{-1}{\cdot}s^{-1}$), ($lb{\cdot}ft^{-1}{\cdot}in.Hg^{-1}{\cdot}s^{-1}$)—the ratio between the air flux and the magnitude of the pressure gradient in the direction of the airflow.

air permeance, ($kg{\cdot}m^{-2}{\cdot}Pa^{-1}{\cdot}s^{-1}$), ($lb{\cdot}ft^{-2}{\cdot}in.Hg^{-1}{\cdot}s^{-1}$)—the ratio between the air flux and the magnitude of the pressure difference across the bounding surfaces, under steady state conditions.

air retarder—a material or system that adequately impedes airflow under specified conditions.

building envelope—the surrounding building structures such as walls, ceilings, and floors that separate the indoor environment from the outdoor environment.

capillarity—the movement of moisture due to forces of surface tension within small spaces depending on the porosity and structure of a material. Also known as capillary action.

Capillary-active—the term attributed to a material that absorbs water by capillary forces when in contact with liquid water.

[1]Thermal Technology Laboratories, Johns Manville Technical Center, Denver, CO.

capillary conduction—the movement or transport of liquid water through capillaries or very small interstices by forces of surface tension or capillary pressure differences.

capillary pressure—the pressure or adhesive force exerted by water in an enclosed space as a result of surface tension because of the relative attraction of the molecules of the water for each other and for those of the surrounding solid.

capillary saturation—see capillary saturation moisture content.

capillary saturation moisture content—the completely saturated equilibrium moisture content of a material when subjected to 100% RH. This is lower than the maximum moisture content, due to air pockets trapped in the pore structure.

capillary suction stress—the force associated with the negative capillary pressure resulting from changes in water content that produces a liquid transport flux.

capillary transfer—*see* capillary conduction.

capillary transport coefficient—*see* liquid transport coefficient.

condensation—the act of water vapor changing to liquid water, or the resulting water.

critical moisture content—the lowest moisture content necessary to initiate moisture transport in the liquid phase. Below this level is considered the hygroscopic range where moisture is transported only in the vapor phase.

CWEC—Canadian Weather year for Energy Calculations data developed for 47 locations, available from Environment Canada.

CWEEDS—the Canadian Weather Energy and Engineering Data Sets provide weather data for Canada.

degree of saturation—the ratio between the material moisture content and the maximum moisture content that can be attained by the material.

density of airflow rate—*see* air flux.

density of heat flow rate—*see* heat flux.

density of moisture flow rate—*see* moisture flux.

density of vapor flow rate—*see* vapor flux.

density, ($kg{\cdot}m^{-3}$), ($lb{\cdot}ft^{-3}$)—the mass of a unit volume of the dry material. For practical reasons, the phrase "dry material" does not necessarily mean absolutely dry material. For each class of material, such as stony, wooden, or plastic, it may be necessary to adopt prescribed standard conditions; for example, for wood this may correspond to drying at 105°C until the change in mass is within 1% during two successive daily weighings.

desorption—the process of removing sorbed water by the reverse of adsorption or absorption.

desorption isotherm—the relationship between the vapor pressure (or more often relative humidity, RH) of the surroundings and the moisture content in the material when desorbing or removing moisture at a constant temperature. There is often very little difference between this curve and the adsorption isotherm.

dew point—the temperature at which air becomes saturated when cooled without addition of moisture or change of pressure; any further cooling causing condensation.

Dew Point Method—a manual design tool used for evaluating the probability of condensation within exterior envelopes by comparing calculated to saturation vapor pressures.

diffusion resistance factor—the ratio of the resistance to water vapor diffusion of a material, and the resistance of a layer of air of equal thickness.

DIM—a two-dimensional model by Grunewald that calculates transient heat, air, salt, and moisture transfer in porous materials.

dry-bulb—*see* dry-bulb temperature.

dry-bulb temperature—the temperature read from a dry-bulb thermometer.

EMPTIED—an acronym for Envelope Moisture Performance Through Infiltration Exfiltration and Diffusion, EMPTIED is a computer program to estimate moisture accumulation using vapor diffusion and air leakage. The program is useful in wetter and cooler climates. Developed by Handegord for Canada Mortgage and Housing Corporation (CMHC), it is available free.

equilibrium moisture content (EMC)—the balance of material moisture content (MC) with ambient air humidity at steady state.

fiber saturation point (FSP)—the moisture content at which all free water from cell cavities has been lost but when cell walls are still saturated with water.

Fick's Law—the law that the rate of diffusion of either vapor or water across a plane is proportional to the negative of the gradient of the concentration of the diffusing substance in the direction perpendicular to the plane.

FRAME 4.0—a two-dimensional steady-state heat transfer model widely used in North America and especially useful for windows and other lightweight assemblies.

free saturation—*see* capillary saturation.

free water saturation—*see* capillary saturation.

FRET—a two-dimensional simulation program for FREezing-Thawing processes by Matsumoto, Hokoi, and Hatano.

FSEC—a commercially available computer model from the Florida Solar Energy Center simulating whole building problems involving energy, airflow, moisture, contaminants, and air distribution systems.

Glaser Diagram—one of the first one-dimensional moisture models using vapor diffusion only with steady-state boundary conditions to predict condensation. It was originally published in 1958–59 as a graphical method.

grain—the normal unit of weight used for small amounts of water at 1/7000 of a pound (0.0648 grams).

HAM—combined Heat, Air, and Moisture analysis.

heat flux, ($W{\cdot}m^{-2}$), ($Btu{\cdot}ft^{-2}{\cdot}h^{-1}$)—the quantity of heat transported in unit time across unit area of a plane that is perpendicular to the direction of the transport.

HEAT2 and HEAT3—Swedish two- and three-dimensional dynamic heat transfer analysis models that are commercially available.

HEATING 7.2—a heat transfer model program developed at Oak Ridge National Laboratory (ORNL) which can be used to solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates. (Oak Ridge, TN 37831).

HMTRA—a Heat and Mass TRAnsfer two dimensional model by Gawin and Schrefler including soils, high temperatures, and material damage effects.

humidity ratio—the ratio of the mass of water vapor to the mass of dry air contained in a sample. In inch-pound units, humidity ratio is expressed as grains of water vapor per pound of dry air (one grain is equal to 1/7000 of a pound) or as pounds of water vapor per pound of dry air. In SI units, humidity ratio is expressed as grams (g) of water vapor per kilogram (kg) of dry air. (Using the pound per pound units in the inch-pound system has the advantage that the ratio is nondimensional and will be the same for the SI and inch-pound systems. In this case the ratio would also be called the specific humidity.)

hydraulic conductivity, ($kg{\cdot}s^{-1}{\cdot}m^{-1}{\cdot}Pa^{-1}$), ($lb{\cdot}s^{-1}{\cdot}ft^{-1}{\cdot}in.\ Hg^{-1}$)—the time rate of steady state water flow through a unit area of a material induced by a unit suction pressure gradient in a direction perpendicular to that unit area.

hydrostatic—the physics concerning the pressure and equilibrium of water at rest.

hygroscopic—attracting or absorbing moisture from the air.

hygroscopic range—the range of RH in a material where the moisture is still only in an adsorbed state. This varies with material but is usually up to about 98% RH.

hygrothermal analysis—the study of a system involving coupled heat and moisture transfer.

IEA Annex 24—part of the International Energy Agency which publishes documents ("Heat, Air and Moisture Transfer in Insulated Envelope Parts") through the participation of leading physicists and engineers working in this area from around the world.

Kieper Diagram—a simple one-dimensional steady-state moisture model introduced in 1976 using vapor diffusion only to predict condensation.

LATENITE—a one-, two-, or three-dimensional computer model developed by Karagiozis and Salonvaara. Likely the most comprehensive heat air and moisture model available. It is not available for general use.

liquid conduction coefficient, ($m^2 \cdot s^{-1}$), ($ft^2 \cdot s^{-1}$)—the proportionality constant or transport property that taken times the gradient of RH gives the resulting liquid flux.

liquid conductivity—*see* hydraulic conductivity.

liquid diffusivity—*see* liquid conduction coefficient or liquid transport coefficient.

liquid transport coefficient, ($m^2 \cdot s^{-1}$), ($ft^2 \cdot s^{-1}$)—the multiplier or proportionality constant in the diffusion equation between the gradient of water content and the resulting liquid transport flux.

liquid transport flux, ($kg \cdot m^{-2} \cdot s^{-1}$), ($lb \cdot ft^{-2} \cdot s^{-1}$)—the amount and rate of liquid movement through a given area or plane.

MATCH—a one-dimensional computer model by Carsten Rode that is similar to MOIST and uses both sorption and suction curves to define the moisture storage function. It is commercially available.

maximum moisture content—the building material moisture content that corresponds to the saturation state where the open pores are completely filled with water. This is available only experimentally in a vacuum.

maximum water content—*see* maximum moisture content.

MDRY—a Moisture Design Reference Year weather data set that reflects more severe weather conditions perhaps seen one out of ten years.

MOIST—a free public domain one-dimensional thermal and moisture transfer model and computer program developed by Burch while at the U.S. National Institute of Standards and Technology (NIST).

moisture content (MC)—the moisture content of a building material can be defined as either (i) the mass of moisture per unit volume of the dry material [all building materials], or (ii) the mass of moisture per unit mass of the dry material [denser materials], or (iii) the volume of condensed moisture per unit volume of the dry material [lighter materials].

moisture diffusivity, ($m^2 \cdot s^{-1}$), ($ft^2 \cdot s^{-1}$)—the moisture diffusivity in the hygroscopic range is the ratio between vapor permeability and volumetric moisture capacity. Outside that range it is the ratio between moisture permeability and volumetric moisture capacity.

moisture flux, ($kg \cdot m^{-2} \cdot s^{-1}$)—the mass of moisture transported in unit time across unit area of a plane that is perpendicular to the direction of the transport.

moisture load—the amount of moisture added to an environment from various sources.

moisture permeability, ($kg \cdot m^{-1} \cdot Pa^{-1} \cdot s^{-1}$), ($lb \cdot ft^{-1} \cdot in.Hg^{-1} \cdot s^{-1}$)—the ratio between the moisture flux and the magnitude of suction gradient in the direction of the flow. Suction includes capillarity, gravity, and external pressure.

moisture storage function—the function describing the relationship between the ambient relative humidity and the absorbed moisture, composed of sorption isotherms (up to ~95% RH), and suction isotherms (above ~95% RH).

MOISTWALL—a one-dimensional computer model developed at the Forest Products Laboratory that is a numerical version of the Kieper Diagram based on vapor diffusion only.

MOISTWALL2—a one-dimensional computer model with the effect of airflow added to the original MOISTWALL model vapor diffusion.

NCDC—the National Climatic Data Center, which is a source of detailed hourly historical weather data.

open porosity, ($m^3 \cdot m^{-3}$), ($ft^3 \cdot ft^{-3}$)—the volume of pores per unit volume of the material accessible for water vapor.

performance threshold—the conditions under which a material or assembly will cease to perform as intended.

perm—the unit of vapor permeance, defined as the mass rate of water vapor flow through one square foot of a material or construction of one grain per hour induced by a vapor pressure gradient between two surfaces of one inch of mercury (or in other units that equal that flow rate).

permeance coefficient—*see* vapor permeance.

porosity—the ratio, usually expressed as a percentage, of the volume of a material's pores to its total volume.

psychrometric chart—a graph where each point represents a specific condition of an air and water vapor system with regard to temperature, absolute humidity, relative humidity, and wet-bulb temperature.

relative humidity—the ratio, at a specific temperature, of the actual moisture content of the air sample, and the moisture content of the air sample if it were at saturation. It is given as a percentage.

rep—the unit of water vapor resistance equal to 1/perm.

RH—relative humidity.

SAMSON—the Surface Airways Meteorological and Solar Observing Network, a source of historical hourly weather data for the United States.

saturated air—moist air in a state of equilibrium with a plane surface of pure water at the same temperature and pressure, that is, air whose vapor pressure is the saturation vapor pressure and whose relative humidity is 100%.

saturation curve—the psychrometric curve through different temperatures and pressures that represents the dew point or 100% RH.

saturation point—the point at a given temperature and pressure where the air is saturated with moisture and the relative humidity is 100%.

saturation vapor pressure—the vapor pressure that is in equilibrium with a plane surface of water.

SHAM—a Simplified Hygrothermal Analysis Method that extends EMPTIED's model with guidance on things like driving rain and solar radiation.

SIMPLE FULUV—a two-dimensional model by Okland developed to investigate convection in timber frame walls.

sling psychrometer—a device consisting of both a wet-bulb and a dry-bulb thermometer on a handle allowing whirling in the air in order to determine the moisture content or relative humidity of the air.

sorption—the general term used to encompass the processes of adsorption, absorption, and desorption.

sorption curve—*see* sorption isotherm.

sorption isotherm—the relationship between the vapor pressure (or more often relative humidity, RH) of the surroundings and the moisture content in a material at a constant temperature. Since the hysteresis between the adsorption and desorption isotherms is usually not very pronounced, the adsorption isotherm or a mean isotherm is often used.

specific heat capacity, ($J{\cdot}kg^{-1}{\cdot}K^{-1}$), ($Btu{\cdot}lb^{-1}{\cdot}F^{-1}$)—the heat (energy) required to increase the temperature of a dry unit mass of a material by 1 degree.

specific humidity—the ratio of the mass of water vapor to the total mass of the dry air. In inch-pound units, specific humidity is expressed as pounds of water vapor per pounds of dry air. In SI units, specific humidity is expressed as kilograms of water vapor per kilogram of dry air. Because specific humidity is a ratio, and if both the mass of water vapor and the mass of the dry air are measured in the same units (pounds in inch-pound units, kilograms in SI units), the numerical values are the same for inch-pound and for SI units. However, some tables and charts show inch-pound units as grains per pound and metric units as grams per kilogram.

specific moisture capacity, ($kg{\cdot}kg^{-1}{\cdot}Pa^{-1}$), ($lb{\cdot}lb^{-1}{\cdot}in.Hg^{-1}$)—the increase in the mass of moisture in a unit mass of the material that follows a unit increase in vapor pressure or suction.

stack effect—temperature and resulting pressure differences between a building exterior and interior that drives air infiltration or exfiltration.

suction curve—*see* suction isotherm.

suction isotherm—the relationship between the capillary suction pressure and the moisture content in a material at a constant temperature.

TCCC2D—the Transient Coupled Convection and Conduction in 2D structures, an advanced model by Ojanen that also predicts mold growth.

TCCD2—the Transient Coupled Convection and Diffusion 2 Dimensional model, an improvement built upon Kohonen's model, mainly used for framed building walls.

THERM 2.0—a two-dimensional steady-state heat transfer model widely used in North America and especially useful for windows and other lightweight assemblies.

thermal conductivity, ($W{\cdot}m^{-1}{\cdot}K^{-1}$), ($Btu{\cdot}ft^{-1}{\cdot}h^{-1}{\cdot}F^{-1}$) or ($Btu{\cdot}in{\cdot}ft^{-2}{\cdot}h^{-1}{\cdot}F^{-1}$)—the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area.

thermal diffusivity, ($m^2{\cdot}s^{-1}$), ($ft^2{\cdot}s^{-1}$)—the ratio between the thermal conductivity and the volumetric heat capacity of the material.

thermal moisture diffusion coefficient, ($m^2{\cdot}K^{-1}{\cdot}s^{-1}$), ($ft^2{\cdot}F^{-1}{\cdot}s^{-1}$)—the ratio between the thermal moisture permeability and the dry density.

thermal moisture permeability, ($kg{\cdot}m^{-1}{\cdot}K^{-1}{\cdot}s^{-1}$), ($lb{\cdot}ft^{-1}{\cdot}F^{-1}{\cdot}s^{-1}$)—the ratio between the moisture flux and the magnitude of the temperature gradient in the direction of the transport in the absence of any moisture content gradient.

thermal resistance, ($K{\cdot}m^2{\cdot}W^{-1}$), ($F{\cdot}ft^2{\cdot}h{\cdot}Btu^{-1}$)—the quantity determined by the steady state temperature difference between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area.

TMY—Typical Meteorological Year data produced for building energy analysis.

TMY2—an updated set of TMY data for 239 US cities which is available from the National Renewable Energy Laboratory (NREL).

TOOLBOX—a public domain computer program on the psychrometric charts and thermodynamic properties of moist air.

tortuosity factor—the ill-defined degree of being tortuous or full of twists, turns, curves, or windings relating to the microscopic interstices of a material.

transport coefficient—the proportionality constant in a diffusion equation, which taken times the gradient, gives the transport flux or flow density.

TRATMO—the TRansient Analysis code for Thermal and MOisture physical behaviors of constructions was developed by Kohonen and was one of the first computerized building enclosure models.

TRATMO2—TRansient Analysis of Thermal and MOisture behavior of 2-D structures, by Salonvaara. This advanced model considers convection and radiation in porous materials.

vapor concentration, ($kg{\cdot}m^{-3}$), ($lb{\cdot}ft^{-3}$)—the vapor content in a given volume of air (or volume of air in the pores of a building material), defined as the ratio between the mass of water vapor in that volume, and the volume.

vapor diffusion—the movement of water vapor through materials and systems driven by the vapor pressure differences or gradient.

vapor diffusion coefficient, (s)—the same as vapor permeability; however, permeability is usually expressed in English units (perm·in), while the diffusion coefficient is usually expressed in metric units (s).

vapor diffusion thickness, (m), (ft)—the product of a specimen thickness and the vapor resistance factor of the material.

vapor flux, ($kg \cdot m^{-2} \cdot s^{-1}$), ($lb \cdot ft^{-2} \cdot s^{-1}$)—the mass of vapor transported in unit time across unit area of a plane that is perpendicular to the direction of the transport.

vapor permeability, ($ng \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-1}$), ($gr \cdot h^{-1} \cdot ft^{-1} \cdot in.Hg^{-1}$) or (perm·in)—the time rate of water vapor transmission through a unit area of flat material of unit thickness induced by a unit water vapor pressure difference between its two surfaces. In inch-pound units, permeability is given in grains of water per hour for each square foot of area divided by the inches of mercury of vapor pressure difference per thickness in feet (gr/h·ft·in.Hg). In SI units, permeability is given as nanograms of water per second for each square meter of area divided by the Pascals of vapor pressure difference per thickness in meters (ng/s·m·Pa).

vapor permeance ($ng \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}$), ($gr \cdot h^{-1} \cdot ft^{-2} \cdot in.Hg^{-1}$) or (perm)—the time rate of water vapor transmission through unit area of flat material induced by unit water vapor pressure difference between its two surfaces. In inch-pound units, permeance is given in the unit "perm," where one perm equals a transmission rate of one grain of water per hour for each square foot of area per inch of mercury ($gr/h \cdot ft^2 \cdot in.Hg$). (A grain is 1/7000 of a pound.) There is no direct SI equivalent to the perm. However, one perm equals a flow rate of 57 nanograms of water per second for each square meter of area and each Pascal of vapor pressure ($ng/s \cdot m^2 \cdot Pa$).

vapor pressure, (Pa), (in.Hg)—the partial pressure exerted by the vapor at a given temperature, also stated as the component of atmospheric pressure contributed by the presence of water vapor. In inch-pound units, vapor pressure is given most frequently in inches of mercury (in.Hg); in SI units water vapor pressure is given in Pascals (Pa).

vapor resistance and resistivity—the reciprocals of permeance and permeability. The advantage of the use of resistance and resistivity is that in an assembly or sandwich of a construction the resistances and resistivities of the individual layers can be added to arrive at the resistance or resistivity of an assembly, while permeances and permeabilities can not be so added.

vapor resistance factor, (dimensionless)—the ratio between the vapor permeability of stagnant air and that of the material under identical thermodynamic conditions (same temperature and pressure).

vapor resistivity—*see* vapor resistance and resistivity.

vapor retarder—a material or system that adequately impedes the transmission of water vapor under specified conditions.

volumetric heat capacity, ($J \cdot m^{-3} \cdot K^{-1}$), ($Btu \cdot ft^{-3} \cdot F^{-1}$)—the heat (energy) required to increase the temperature of a dry unit volume of the material by one degree.

volumetric moisture capacity, ($kg \cdot m^{-3} \cdot Pa^{-1}$), ($lb \cdot ft^{-3} \cdot in.Hg^{-1}$)—the increase in the moisture content in a unit volume of the material that follows a unit increase in the vapor pressure or suction. For the hygroscopic range, volumetric moisture capacity can be calculated from the slope of the sorption curve, and above critical moisture content it can be calculated as the slope of the suction curve.

WALLDRY—a simple model of the drying of framed wall assemblies using moisture transport by vapor diffusion only.

water absorption coefficient—*see* absorption coefficient.

water vapor content—*see* vapor concentration.

water vapor diffusion—*see* vapor diffusion.

water vapor diffusion coefficient—*see* vapor diffusion coefficient.

water vapor diffusion resistance—*see* vapor resistance.

water vapor permeability—*see* vapor permeability.

water vapor permeance—*see* vapor permeance.

water vapor pressure—*see* vapor pressure.

water vapor resistance—*see* vapor resistance.

water vapor resistivity—*see* vapor resistivity.

wet-bulb—*see* wet-bulb temperature.

wet-bulb temperature—the temperature read from a wet-bulb thermometer resulting from the cooling due to evaporation from its surface.

WUFI—a one- or two-dimensional computer model developed by Hartwig Kuenzel at the Fraunhofer Institut fuer Bauphysik. The model incorporates driving rain, has stable calculations, is easy to use, is well validated with field data, and is commercially available.

WUFI/ORNL/IBP—a one- or two-dimensional advanced computer model originally developed by Kuenzel but extended in a joint research collaboration between Oak Ridge National Laboratory (ORNL) and the Fraunhofer Institute for Building Physics (IBP).

WUFIZ—a two-dimensional version of the WUFI computer model.

WYEC—the Weather Year for Energy Calculations data consists of one year of hourly weather data produced by ASHRAE.

WYEC2—the revised and improved WYEC data for 52 locations in the US and 6 locations in Canada.

1

Moisture Primer

by Heinz R. Trechsel[1]

OVERVIEW AND INTRODUCTION

THE INTENT OF THIS CHAPTER is to provide the practicing building designer with the minimum basic understanding of the hygrothermal phenomena, including moisture movement and transfer, and of its effect on building constructions, necessary to understand the chapters directly related to moisture analysis. It is not the intent of this chapter to replace more detailed handbooks or to supply a complete knowledge of building physics. Readers who wish to study the fundamentals of moisture thermodynamics in greater depth are referred to such excellent publications as the *ASHRAE Handbook of Fundamentals* [*1*], *ASTM MNL 18, Moisture Control in Buildings* [2], and others cited as references.

As indicated in the introduction, this manual is concerned primarily with condensation within and on the building envelope, that is, condensation of water vapor contained in air. In building environments, both outdoors and indoors, air always contains some moisture in the form of water vapor. The amount of water vapor in outdoor air depends on atmospheric conditions, including temperature and elevation above sea level. The amount of water vapor contained in indoor air depends primarily on occupancy factors and on the activities or processes conducted within the building or space. For residential applications, these include primarily occupant density, perspiration, breathing, cooking, and bathing. In commercial and institutional they also include laundries, commercial kitchens, and production processes. Temperature affects the moisture content in air, as air absorbs more moisture when it is warm than when it is cold. Air pressure also affects the ability of air to contain moisture, although for building applications this effect can be ignored except in areas at elevations above approximately 5000 ft.

In terms of the propensity for condensation, the most significant element is the ability of air to contain moisture based on its temperature. Neglecting air pressure for a moment, air at low temperature can contain only small amounts of water vapor; air at high temperature can absorb a greater amount of water vapor. Thus, by raising the temperature, we can increase the ability of air to contain water vapor; conversely, by lowering the temperature, we can decrease the amount of water vapor that can be contained in a specific sample of air.

While raising the temperature increases the ability of air to absorb water vapor, there is a limit to the amount of water vapor that can be contained in air at any one temperature. At that point, the air reaches its saturation point, and the temperature at which this occurs is called the dew point of the air. If the temperature of such saturated air is lowered, the air will no longer be able to contain its moisture. In the atmosphere, the excessive moisture condenses in the form of water droplets to form clouds and eventually rain. Within buildings and within building envelopes, the excessive moisture condenses on any surface that is at a temperature below the dew-point temperature.

Since the propensity of a given mixture of dry air and water vapor to condensation is a function of both the moisture content of the air and its temperature, the term *relative humidity* is used. The relative humidity of a particular sample of air is the ratio of the moisture content of the air and the moisture content of that air at saturation. Accordingly, if a given sample of air contains x kg of moisture per kg of air, and at saturation, based on the air's temperature, the air could contain y kg of moisture, the relative humidity would be x/y expressed as a percentage. Thus, if $x = y$, the RH would be 100%, if $x = 1/2\ y$, the RH would be 50%.

Based on the above, the basic principle for preventing or reducing condensation on or within building envelopes is to reduce the surface relative humidity (that is, the relative humidity of the air in immediate contact with the surfaces) so that the surface temperatures are at all times above the dew point of the air, or, conversely, to raise the temperature of the surfaces so that, again, the surface temperature is above the dew point of the air. Although brief moisture excursions should not cause significant moisture distress in building constructions, there are no firm guidelines as to what constitutes "brief" excursions. As a general rule, when analyzing a construction, no moisture excursions at design conditions should be allowed.

TERMINOLOGY

The following definitions of terms apply to water vapor as contained in air. The first three terms describe ratios of water vapor to air; absolute humidity relates the mass of moisture content to the volume of the moist air sample. Humidity ratio and specific humidity relate to the mass of water vapor and the air in the sample:

[1] H. R. Trechsel Associates, Arlington, VA; Trechsel is also an architect for the Engineering Field Activity Chesapeake, Naval Facilities Engineering Command, Washington, DC. All opinions expressed are his own and do not necessarily reflect those of any Government agency.

- *Absolute humidity*—the ratio of the mass of water vapor to the total volume of the air sample. In SI units, absolute humidity is expressed as kg/m^3. In inch/pound units, absolute humidity is expressed as lb/ft^3.
- *Humidity ratio*—the ratio of mass of water vapor to the mass of dry air contained in the sample. In inch/pound units, humidity ratio is expressed as grains of water vapor per pound of dry air (one grain is equal to 1/7000 of a pound) or as pound of water vapor per pound of dry air. In SI units, humidity ratio is expressed as gram (g) of water vapor per kilogram (kg) of dry air. (Using the pound per pound units in the inch/pound system has the advantages that the ratio is non-dimensional and will be the same for the SI and inch/pound systems).
- *Specific humidity*—the ratio of the mass of water vapor to the total mass of the dry air. In inch/pound units, specific humidity is expressed as pounds of water vapor per pounds of dry air. In SI units, specific humidity is expressed as kilogram of water vapor per kilogram of dry air. Because specific humidity is a ratio and, if both the mass of water vapor and the mass of the dry air are measured in the same units (pounds in inch-pound units, kilograms in SI units), the numerical values are the same for inch-pound and for SI units. However, some tables and charts show inch/pound units as grains per pound and metric units as grams per kilogram.
- *Relative humidity*—the ratio, at a specific temperature, of the moisture content of the air sample if it were at saturation, and the actual moisture content of the air sample. It is given as a percentage.
- *Water vapor pressure*—the partial pressure exerted by the vapor at a given temperature, also stated as the component of atmospheric pressure contributed by the presence of water vapor. In inch/pound units, vapor pressure is given most frequently in inches of mercury (in.Hg); in SI units water vapor pressure is given in Pascals (Pa).
- *Water vapor permeance* or *permeance coefficient*—the time rate of water vapor transmission through unit area of flat product induced by unit water vapor pressure difference between its two surfaces. In inch/pound units, permeance is given in the unit "perm," where 1 perm equals a transmission rate of 1 grain of water per hour for each square foot of area per inch of mercury ($gr/h \cdot ft^2 \cdot in.Hg$). (A grain is 1/7000 of a pound.) There is no direct SI equivalent to the perm. However, 1 perm equals a flow rate of 57 nanograms of water per second for each square metre of area and each Pascal of vapor pressure ($ng/s \cdot m^2 \cdot Pa$).
- *Water vapor permeability*—the time rate of water vapor transmission through unit area of flat material of unit thickness induced by unit water vapor pressure difference between its two surfaces. In inch/pound units, permeability is given in grains of water per hour for each square foot of area divided by the thickness per inches of mercury ($gr/h \cdot ft \cdot in.Hg$). In SI units, permeance is given as nanograms of water per second for each square metre of area divided by the thickness in metres per Pascal of vapor pressure ($ng/s \cdot m \cdot Pa$).
- *Water vapor resistance and resistivity*—the reciprocals of permeance and permeability. The advantage of the use of resistance and resistivity is that in an assembly or sandwich of a construction, the resistances and resistivities of the individual layers can be added to arrive at the resistance or resistivity of an assembly, while permeances and permeancies can not be so added.

PROPERTIES OF AIR

Table 1 illustrates the relationship between temperature, relative humidity, and specific humidity as pounds of water vapor to pounds of dry air in a sample. The ratio does, of course, not change if SI units were used, provided that the same actual temperatures are considered. The values are given for sea level. The humidity ratio in inch/pound units is often given in grains of water vapor per pound of dry air. Since a grain is exactly 1/7000 of a pound, the values given in the table can be multiplied by 7000 to arrive at the humidity ratio in grains of water vapor per pound of dry air. In SI units, the humidity ratio is given in grams of moisture per kg of dry air, and the values given in the table can be converted into SI humidity ratios by multiplying them by 1000.

Table 2 was prepared to provide an illustration of the effect of temperature, relative humidity, and altitude (elevation above sea level) on the density or weight of air. The table shows the elevation both in feet and in metres, and the volume of 1 lb of air in cubic feet (1 kg of air in cubic metres). As can be seen, temperature is the major factor affecting the density of air at temperatures above 50°F (10°C). Altitude becomes a significant factor only above 4000 ft (1220 m). RH becomes a major factor only at temperatures above 50°F (10°C).

Table 3 provides an example of the mass of air and the amount of moisture that might be contained in a typical bedroom, small residence, and classroom, based on three assumed relative humidity levels. The indoor temperature is uniformly assumed to be 70°F (21°C) and the altitude is sea level. The table also illustrates that the actual moisture content is directly proportional to the relative humidity. As shown below, the lowering of the RH level within building environments is the single most effective means of reducing the propensity for moisture problems in buildings. However, there are both practical limits to the degree the RH can be lowered, as well as physiological limits to both low and high RH levels in buildings for human occupancies.

While the information in Tables 1, 2, and 3 and in similar tables available in the literature is useful in illustrating the magnitude of the various factors involved in moisture control in buildings, tabular information is of limited value to the designer, who needs to understand the overall relation-

TABLE 1—Humidity ratio as a function of temperature and relative humidity (in pound of moisture per pound of dry air or kilogram of moisture per kilogram of dry air).

Temperature		Relative Humidity 25%	50%	75%	100%
0°F	(−18°C)	0.0002	0.0004	0.0006	0.0008
20°F	(−7°C)	0.0005	0.0011	0.0016	0.0021
40°F	(4°C)	0.0013	0.0026	0.0026	0.0052
60°C	(16°C)	0.0027	0.0055	0.0082	0.0110
80°F	(27°C)	0.0054	0.0109	0.0165	0.0223
100°F	(38°C)	0.0102	0.0208	0.0318	0.0431

TABLE 2—Volume of 1 lb of air in cubic feet (1 kg of air in cubic metres).

	25°F (−4°C)		50°F (10°C)		100°F (38°C)	
Altitude	25% RH	75% RH	25% RH	75% RH	25% RH	75% RH
Sea Level	12.23	12.25	12.88	12.96	14.34	14.82
	0.763152	0.7644	0.803712	0.808704	0.894816	0.924768
1000 ft	12.69	12.72	13.37	13.45	14.88	15.41
300 m	0.791856	0.793728	0.834288	0.83928	0.928512	0.961584
2000 ft	13.16	13.19	13.87	13.93	15.45	16.02
600 m	0.821184	0.823056	0.865488	0.869232	0.96408	0.999648
4000 ft	14.17	14.21	14.93	15.04	16.65	17.32
1200 m	0.884208	0.886704	0.931632	0.938496	1.03896	1.080768
8000 ft	16.42	16.47	17.13	17.46	19.36	20.25
2400 m	1.024608	1.027728	1.068912	1.089504	1.208064	1.2636

TABLE 3—Approximate moisture content in building spaces at differing RH levels.

				Lb of H_2O (kg of H_2O)		
Space	Size	Volume	Mass Air, lb (kg)	at RH = 25	at RH = 50	at RH = 75
Bedroom	10 ft by 14 ft	1120 ft^3	90 lb	0.36 lb	0.72 lb	1.10 lb
	(3.05 m by 4.27 m)	(31.7 m^3)	(41 kg)	(0.16 kg)	(0.33 kg)	0.50 kg)
House	1800 ft^2	14 400 ft^3	1100 lb	4.4 lb	8.8 lb	13.2 lb
	(170 m^2)	(408 m^3)	(500 kg)	(2.0 kg)	(4.0 kg)	(6.0 kg)
Classroom	30 ft by 30 ft	9000 ft^3	990 lb	4.0 lb	7.9 lb	11.9 lb
	(9.14 m by 9.14 m)	(255 m^3)	(450 kg)	1.8 kg)	(3.6 kg)	(5.4 kg)

ship of the various factors. The most commonly used source of such information are the psychrometric charts developed by ASHRAE. Figure 1 is the chart reproduced from the *ASHRAE Handbook of Fundamentals* [3]. Although ASHRAE publishes five charts, only chart number 1 is relevant for most building designers. It applies to sea level and dry-bulb temperatures from about 30 to 120°F (−1 to 49°C) and from wet bulb temperatures from about 30 to 95°F (−1 to 35°C). For extreme cold conditions from about −8°F (−40°C), chart number 2 should be used. For construction at high altitudes, chart number 4 is for 5000 ft (1524 m) elevation and chart number 5 is for 7500 ft (2286 m) elevation.

The charts also can be used to determine the relative humidities and dew point from measurements of dry-bulb and wet-bulb temperatures. Such measurements were performed with so-called "sling psychrometers" before the availability of reliable electronic devices. These instruments consisted of two thermometers side by side, one of which had its mercury bulb enclosed in a wet fabric wick. To take measurements, the two thermometers were swung for a few minutes, after which time the temperatures of the two thermometers were read. The temperature of the thermometer with the wick was the "wet-bulb" temperature; the temperature of the bare bulb thermometer was the "dry-bulb" temperature. By means of tables or psychrometric charts, the RH level and the dew-point temperature could be determined.

Because the ASHRAE chart is a reproduction of a larger chart, it is difficult to read at the scale used here in Fig. 1. Accordingly, to better illustrate the meaning and significance of the information contained, we have prepared a simplified format of that chart in Fig. 2. However, for analysis, the original ASHRAE chart, or similar charts produced by HVAC manufacturers, should be used.

The psychrometric charts provided on the x-axis the dry-bulb temperature and on the y-axis the moisture content. The steep diagonal lines represent the volume of dry air for unit mass, and the low slope diagonals represent the wet-bulb temperatures. The curved lines represent the lines of equal relative humidity, and the last curve to the left represents 100% RH or saturation.

Many psychrometric calculations can be conveniently done by the use of the psychrometric chart. Figures 3 through 7 illustrate some common calculations that can be performed readily through the use of the psychrometric chart.

Problem 1, Fig. 3: Given are the dry-bulb temperature as 30°C and the relative humidity as 40%. Find the dew-point temperature.
Solution: Find the dry-bulb temperature on the horizontal (30°C in the example) and move up the near vertical 30°C line until it intersects with the curved RH line (40% in the sample). From this intersection, move horizontally to its intersection with the last curved line on the left, which represents 100% relative humidity or saturation. The value is the dew-point temperature of the air/vapor mixture (15°C in the example). Although the chart is in SI units, the procedure would be exactly the same for an inch/pound chart, except that the temperatures for dry-bulb and for dew point would be in °F.

Problem 2, Fig. 4: Given are the dry-bulb temperature of 35°C and the dew-point temperature of 20°C. Find the relative humidity.
Solution: Find the dew-point temperature on the saturation or dew-point curve (20°C in the example) and move horizontally until the intersection with the near vertical over the dry-bulb temperature (35°C in the example). By examining the location of the closest intersection with the curved RH lines, the RH of the air and vapor mixture can be estimated as 43%.

Problem 3, Fig. 5: Given are the dry-bulb temperature of 10°C and the relative humidity as 50%. Find the humidity ratio.

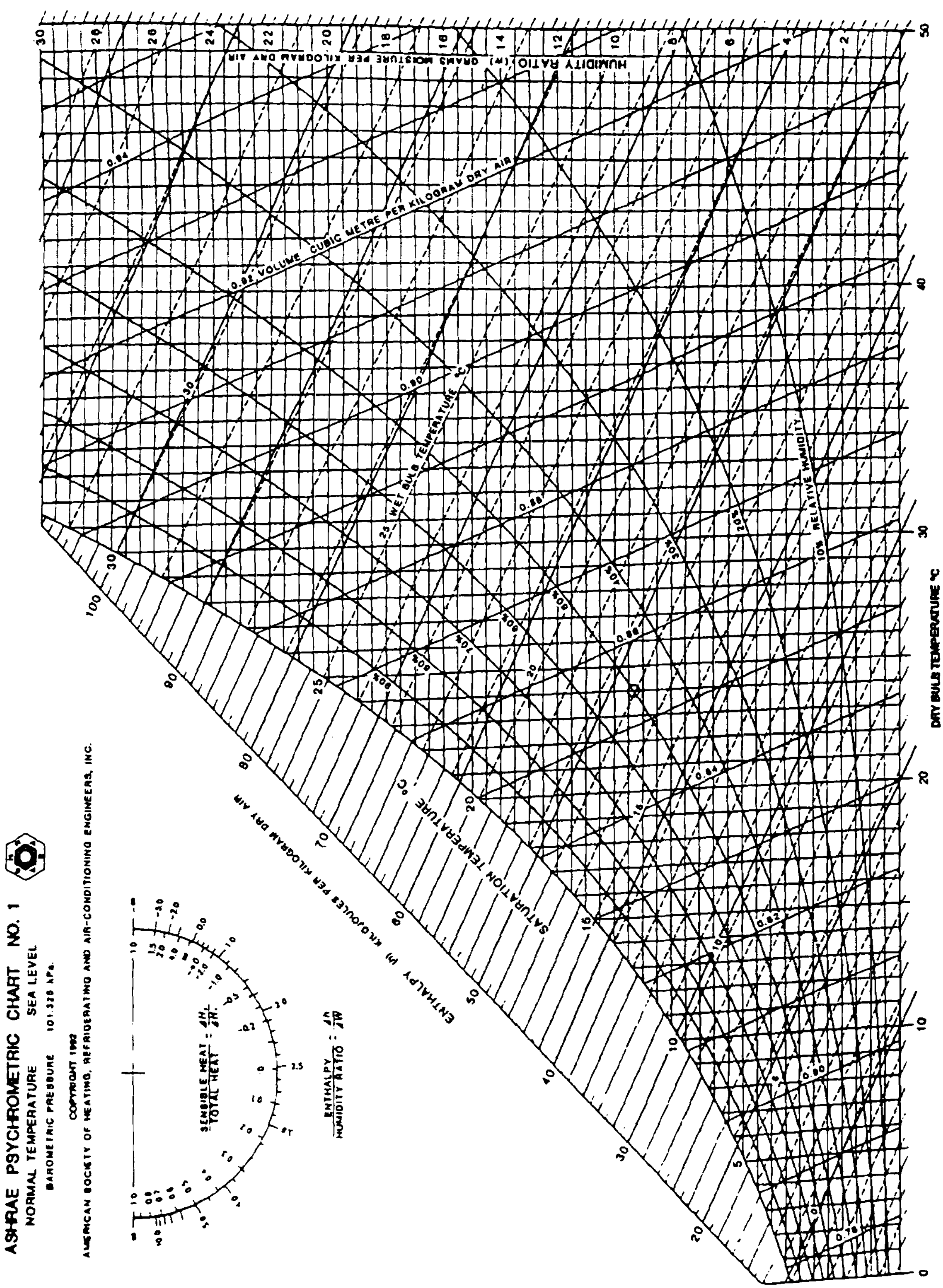


FIG. 1—ASHRAE Psychrometric Chart No. 1—Normal temperature, 0 to 50°C, sea level, barometric pressure 1.01.325 kPa. Reprinted with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers from the 1997 *ASHRAE Handbook—Fundamentals.*

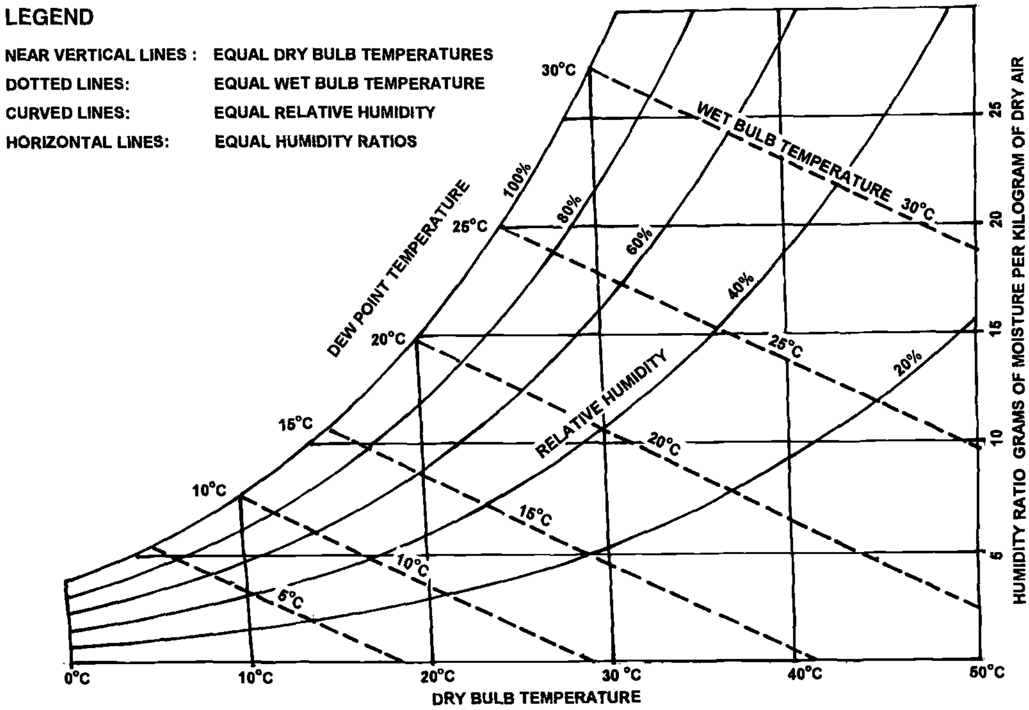


FIG. 2—Simplified psychrometric chart based on ASHRAE Chart shown on Fig. 1.

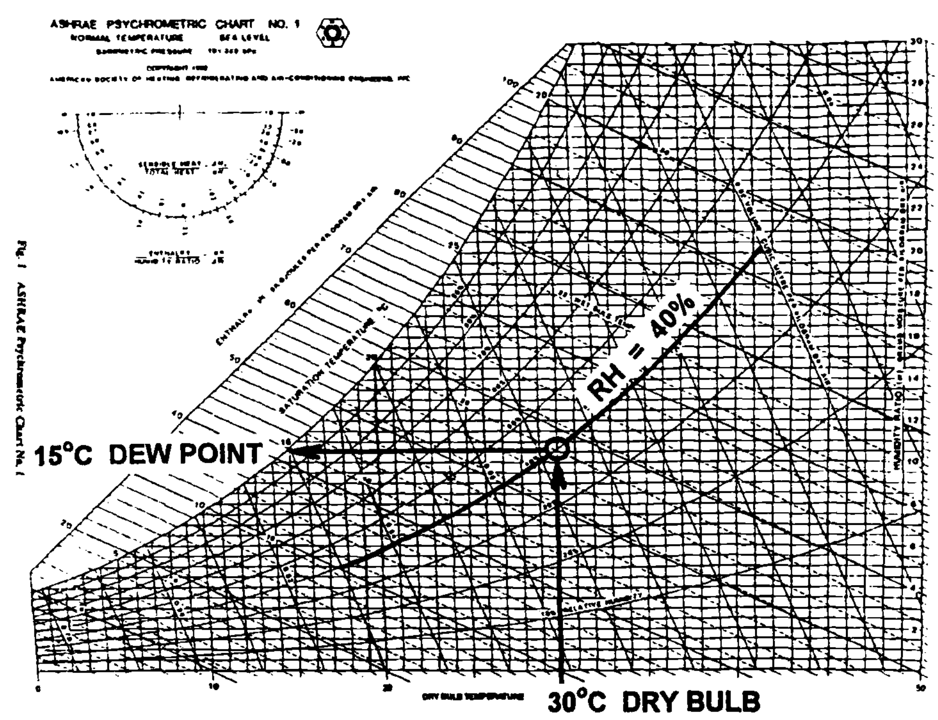


FIG. 3—Calculation of dew-point temperature based on dry-bulb temperature and relative humidity.

Solution: Find the dry-bulb temperature on the horizontal dry-bulb line (10°C in the example) and move up the near vertical line to its intersection with the 50% RH curve. From that intersection, move horizontally to the right to the humidity ratio scale. The humidity ratio is 4 g of moisture per kilogram of dry air.

Problem 4, Fig. 6: Given is the dew point of 5°C. Find the humidity ratio.

Solution: Find the dew-point temperature on the dew-point or saturation curve (or 100% relative humidity curve) (5°C in the example). From that point move horizontally to the right until its intersection with the humidity ratio scale. The

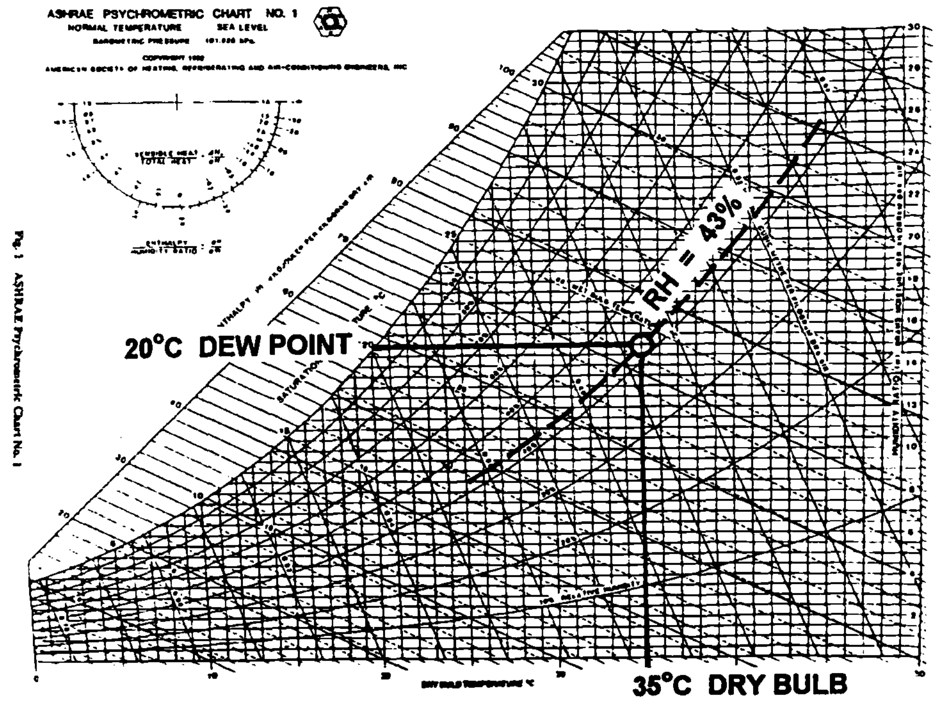


FIG. 4—Calculation of relative humidity based on dry-bulb temperature and on dew-point temperature.

humidity ratio in the example is 5.5 g of moisture per kilogram of dry air.

Problem 5, Fig. 7: Given are the dry-bulb temperature of 35°C and the wet-bulb temperature of 25°C. Find the relative humidity, dew-point, and humidity ratio.
Solution: Find the dry-bulb temperature on the horizontal line (35°C in the example) and move up the near vertical line to its intersection with the diagonal wet-bulb temperature line of 25°C. The relative humidity is the nearest relative humidity curve (45% in the example). If desired, the dew point temperature can then be determined by moving horizontally to the left to the saturation curve. The dew-point is 21°C in the example. To determine the humidity ratio, move from the intersection of the dry-bulb and the wet-bulb temperature to the right and find the humidity ratio as 16 g of moist air per kilogram of dry air.

While the use of psychrometric charts is simple, it must be noted that calculations based on the charts are approximate only. However, for purposes of moisture analysis, the results are generally sufficiently accurate.

Also available are the ASHRAE published tables on the thermodynamic properties of moist air [*4*]. These allow in general greater accuracy, but are less convenient to use for the envelope design professional.

In addition, there are several computer programs on the market that simplify the calculations. Two of these programs are included on the CD Rom in the back cover pocket.

One of the programs, developed by the Trane Company, is one module out of a broader program developed for solving many thermodynamic tasks. It is based on inch/pound units as used in the United States.

The other program was developed by Carsten Rode and allows the use of both metric (SI) units of measurements and of inch/pound units.

With the computer programs, the need for using psychrometric charts and tables will be greatly reduced, although it is recommended that the novice moisture analyst familiarize himself or herself with the use of psychrometric charts, as the charts do provide a useful graphic depiction of the relationship between the various values. Instructions for access and downloading of the two programs are provided with the disks.

MOISTURE SOURCES

In cold climates, condensation control in buildings is concerned mainly with indoor moisture sources. In air-conditioned buildings in warm and humid climates, infiltrating warm and humid air is the primary concern. In all climates, special consideration must be given to indoor moisture sources such as indoor swimming pools and spas, commercial laundries and kitchens, and moisture-producing industrial processes must be considered on a case-by-case basis. Except as noted, the following is summarized and abstracted from Christian [*5*]. For consistency, all values of moisture were converted to pounds (lb) for the inch/pound system and to kilograms (kg) for the SI system.

Indoor Sources

People

All buildings designed for human occupancies must account for the body moisture generated by people. The mois-

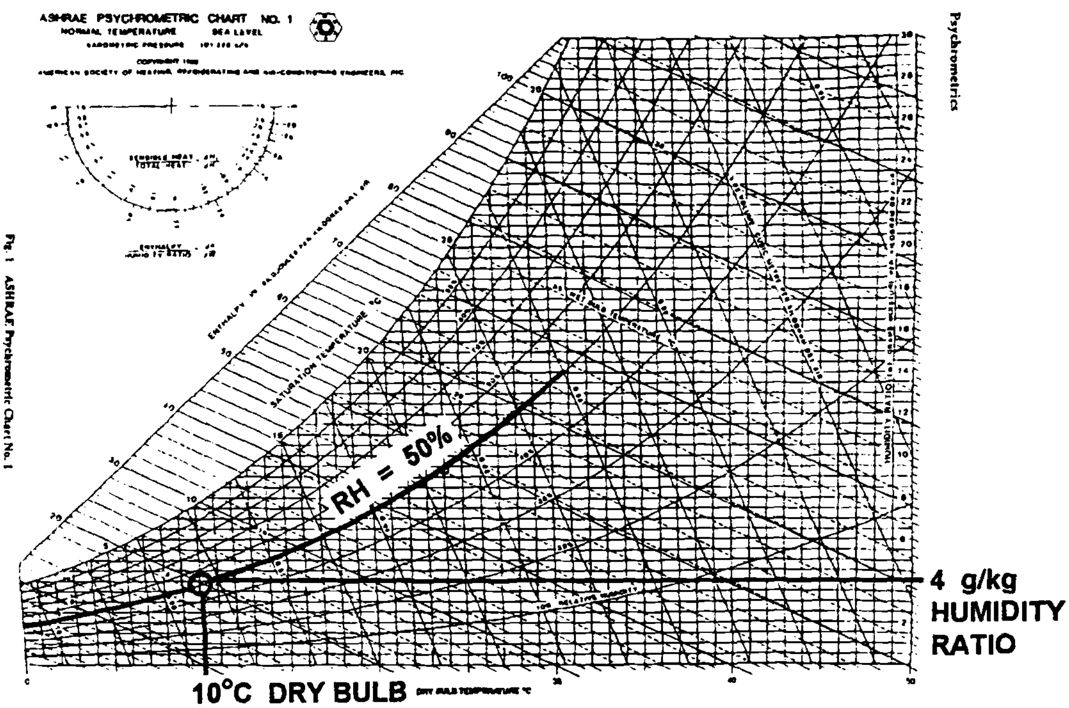


FIG. 5—Calculation of humidity ratio based on dry-bulb temperature and relative humidity.

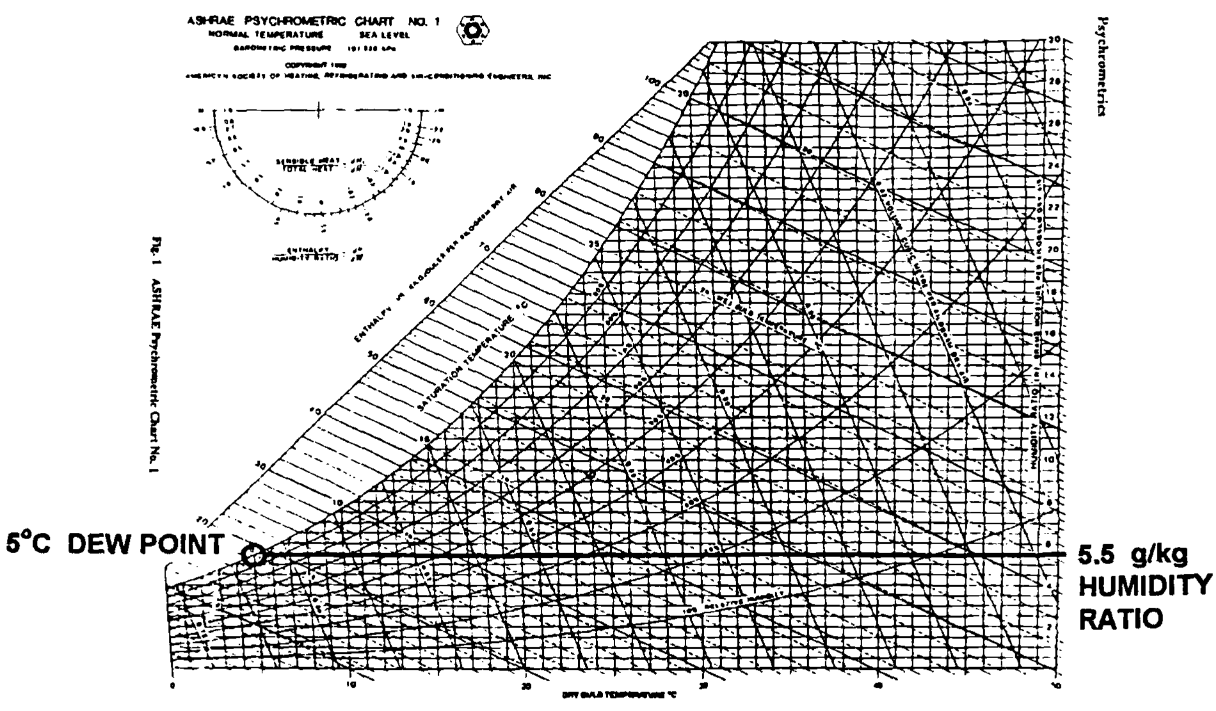


FIG. 6—Calculation of humidity ratio based on dew-point temperature.

ture release from respiration and perspiration depends on the activity level and air temperature. Ehrhorn and Gertis [6] estimate the following ranges of moisture release for three activity ranges at 68°F (20°C):

Light activity: From 0.07 lb/h (0.03 kg/h) to 0.26 lb/h (0.12 kg/h)

Medium activity: From 0.26 lb/h (0.12 kg/h) to 0.44 lb/h (0.2 kg/h)

Hard work: From 0.44 lb/h (0.2 kg/h) to 0.66 lb/h (0.3 kg/h)

Commercial and Institutional

Based on the above data and assuming light to medium activity levels for schools, offices, and light industrial occupancies, a daily per capital moisture source of approximately 2.2 lb/day (1 kg/day) per 8-h shift seems a reasonable assumption.

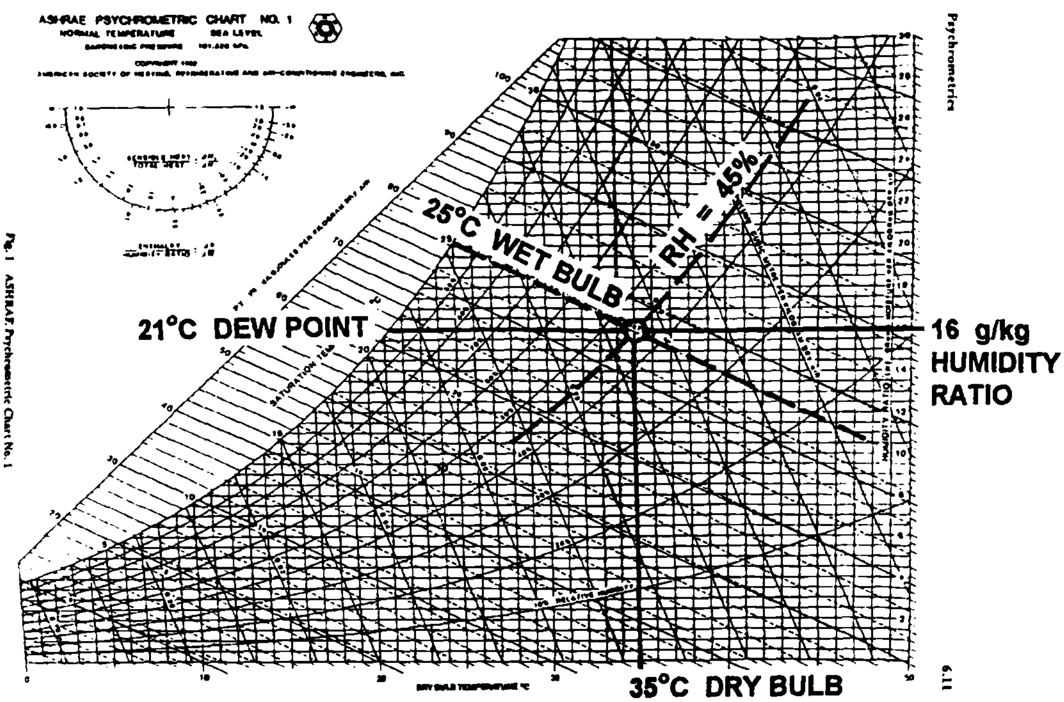


FIG. 7—Calculation of relative humidity from wet-bulb and dry-bulb temperature.

Residential

Based on assorted references, the internal moisture load for single family residences can vary from a low of 9.4 to 50.7 lb/day (4.3 to 23 kg/day), although the upper range can be significantly exceeded by unvented cloth dryers, use of unvented kerosene heaters, attached greenhouses, or swimming pools.

Bathrooms

A 5-min tub bath generates 1.3 lb (0.6 kg) of water vapor, but that number may be low, considering the time it takes to fill and empty the tub.

Residential kitchens

Cooking and dish washing for a family of four generates approximately 3.3 lb/day (1.5 kg/day).

Floor mopping

0.33 lb/ft^2 (1.61 kg/m^2).

Indoor firewood storage

420 to 705 lb (190 to 320 kg) over six months of storage.

Cloth drying indoors, not vented

4.8 to 6.44 lb/load (2.2 to 2.92 kg/load).

Swimming pools

Christian provides the formula and necessary table to estimate the moisture evaporation from swimming pools. This evaporation depends on the water temperature and the RH and temperature of the air.

Indoor plants and aquariums

Indoor plants can also add significantly to the moisture load of a building. Almost all water used to water plants enters the air. A small plant may add only 0.22 lb/day (0.1 kg/day), larger single plants emit between 0.37 and 0.79 pt/day (0.17 and 0.36 kg/day), and young trees, as may be used in lobbies of commercial buildings or shopping malls, can emit 110 to 220 pt/day (50 to 100 kg/day) each. The contribution of aquariums depends on their area of water surface and can be calculated as for swimming pools.

Based on the above, it is obvious that estimating the moisture load of a planned structure is more of an art than a science. Since the designer seldom has much control over the operation of the building, it seems prudent to assume a moisture load near the upper limit for the intended occupancy. For a more detailed analysis of indoor moisture sources, the reader is referred to Christian [5].

Construction moisture

Cast-in-place concrete releases about 198 lb of water per cubic yard (90 kg per cubic metre) over the first two years after construction. Rousseau estimates that moisture released by a newly constructed house can amount to 5730 lb (2600 kg) of water from concrete foundations and construction lumber [7]. Quirouette estimates that a typical house may release 22 lb (10 kg) or more per day during the first winter, and 11 lb (5 kg) during the second year [9]. Thus, construction moisture, specifically in concrete and masonry buildings, can be a serious moisture source during the first years of occupancy, but it should not be a long-term problem. However, during the process of drying out of a construction, such moisture can be significant, especially with moisture-retarding construction (installation of vapor retarders) and insufficient ventilation. Early occupancy before substantial drying out should therefore be avoided.

Outdoor Moisture Sources

Sources of moisture entering the indoor environment range from rain, fog, blowing snow, to groundwater and infiltrating humid air.

Rainwater

If water in the form of rain is allowed entrance into the building or into wall and roof constructions, this source can overwhelm all interior or other exterior sources. A single significant rainwater leak has been observed by this author to allow 22 to 44 lb/h (10 to 20 kg/h) to leak into building walls during a heavy rainstorm, or, assuming a 5-h rainstorm, 110 to 220 lb/day (50 to 100 kg/day). Although a small leak during a rare tropical storm is unlikely to cause any long-term moisture distress, small leaks can cause moisture to accumulate within building cavities, and can then evaporate during warm weather, only to condense on interior, colder surfaces in walls of air-conditioned buildings. The first priority of the designer of a building wall and roof is to provide an envelope that is essentially rain proof. Apart from outright leaks, rainwater can be a significant contributor to the moisture balance within wall constructions and cavities if it is allowed to soak into exterior building materials. Specifically in warm climates, but also during warm weather in colder climates, the moisture within such materials can evaporate and move as water vapor into the colder interior of air-conditioned buildings.

Flooded and damp basements and crawl spaces

The moisture contributed by flooded or wet basements and crawl spaces can be significant. A 645 ft^2 (60 m^2) wet basement may emit approximately 13 lb (6 kg) per hour, or 320 lb (145 kg) per day. Although some of this moisture may be ventilated to the outdoors, in practice much of it will find its way into the structure above through floor penetrations, ducts, and access stairs. It is obvious then that the designer needs to control, or better prevent, moisture from entering basements and crawl spaces. The first of the preventive measures should be to provide adequate slope of the grade away from the building and the installation of a vapor-retarding ground cover in crawl spaces. This simple measure can often reduce or eliminate moist basements and crawl spaces. In persistent cases, the installation of a foundation drainage system, capillary breaks, and vapor retarders below floor slab may be necessary. A vapor retarder should always be installed under slabs on grade in new buildings.

Humid air

In cooling climates, a major source of moisture within a building and within building envelope element cavities is the intrusion of warm, humid outside air. Although some approximations are provided in the *ASHRAE Handbook of Fundamentals* [9] and in ASTM MNL 18, Chapter 8 [5], the designer of a building envelope will not be able to predict accurately or even approximately the as-built air leakage performance of the envelope, specifically since he or she often has little control over field quality control during construction and has generally no control over the operation and maintenance of the building, all of which will largely determine the air infiltration rate. The designer should, however, include in the specifications adequate provisions for field quality control, design the wall to be inherently resistant to air infiltration, and detail the wall consistent with the quality of workmanship to be specified and expected.

BUILDING MATERIALS

Building materials can be affected both by moisture and can affect the moisture performance of a building and its elements. The properties relevant to moisture analysis are discussed in more detail in Chapter 3 on Materials, and failure criteria are discussed in Chapter 4. The following is a brief summary of moisture-related concerns for building materials.

The properties primarily relevant to moisture analysis and to moisture control in the buildings are:

- moisture transmission
- moisture absorption and moisture storage
- linear shrinkage
- surface deterioration

The type of building materials of particular concerns are:

- membranes and paints
- thermal insulating materials
- concrete
- masonry units and mortar

Water Vapor Transmission

In terms of moisture analysis, the most important characteristic of materials is the transmission rate of water vapor. The terms *permeance* and *permeability* were defined under *Terminology* above. Permeance is a measure of a specific product's rate of water vapor transmission, such as an asphalt-laminated kraft paper or a 3/4 in. (19 mm) thick extruded polystyrene board. Permeability is a measure of a material's rate of water vapor transmission per unit thickness. Thus, the permeance of the above-mentioned 3/4 in. extruded polystyrene board is 0.9 perm (50 ng/s · m^2 · Pa), but the permeability of extruded polystyrene material is 1.2 perm per inch thickness (30 ng/s · m · Pa per metre thickness). Other useful terms are water vapor resistance and resistivity, which are the reciprocal values of permeance and permeability.

The water vapor transmission rate through material is not only dependent on that particular material and its thickness, but also on the vapor pressure acting across the material or, assuming equal temperature, on the relative humidity on both sides of the material. The most frequently used test method is ASTM E 96, Test Methods for Water Vapor Transmission of Materials. The test essentially consists of installing the material in a dish (or cup), which contains either a desiccant (Desiccant or Dry-Cup method) or contains water (Water or Wet-Cup method). The dish is then placed in a cabinet with controlled temperature and humidity and is weighed at regular intervals. When the increase (Desiccant method) or decrease (Water method) reaches a steady rate, the water vapor transmission rate can be calculated. The results of the two tests for some materials will differ significantly, as the water transmission rate is dependent on the moisture content of the air on both sides of the specimen.

The results of the tests, reported in Chapters 3 and 4 of MNL 18 [2], in general are based on either the Desiccant or the Water method. Where the designer has a choice, the results from Desiccant tests should be used where relatively low relative humidity will predominate, while results from Water tests should be used in conditions where high relative humidities will predominate. In the past, data for most materials were available only for either the Water method or the Desiccant method. Thanks to work by such organizations as the International Energy Agency and various research institutions, data for water vapor permeability is now available for ranges of relative humidities and temperatures. Chapter 3 of this manual provides such new data.

Moisture Absorption

Many building materials have the ability to absorb moisture. In a well-designed building, moisture absorption in building materials should not be of concern; however, excessive moisture content of some building materials can lead to premature deterioration and even failure. Serious decay in wood occurs at and above fiber saturation of about 30% moisture content and between 50°F (10°C) and 100°F (38°C) [*10*]. High moisture content in thermal insulation materials can degrade the thermal resistance of thermal insulating materials [*11*]. In some materials, freeze and thaw cycles can lead to failure. Surface wetting (by liquid water or by condensation) can lead to mold growth, rust on unprotected steel, and to the deterioration of finishes. Chapters 3 on Materials and 4 on Failure Criteria in this manual will elaborate on these issues.

Dimensional Changes in Wood

While wood is dimensionally stable at fiber saturation, it changes dimensions as it gains and loses moisture below this point. In general such changes are not of catastrophic significance in buildings; however, they can cause uneven settlement, loosened connectors, warpage with attendant unsightliness, splitting of boards, and can, therefore, reduce the ability to shed rainwater. The greatest moisture-induced dimensional changes are in the direction of the annual growth rings (tangential), about half as much across the rings (radial), and only slightly along the grain of the wood. Readers interested in greater details of moisture-related shrinkage of wood and of other wood-related properties of wood are referred to Ref *10*, from which the above was extracted.

Vapor Retarders

To prevent excessive moisture movement into and through building walls, vapor retarders (formerly called vapor barriers) are frequently used. These are mostly membrane-type materials or, more rarely, paints with a low moisture transmission rate. ASTM C 755, Practice for Selection of Vapor Retarders for Thermal Insulation, defines vapor retarders as "materials or systems which adequately retard the transmission water vapor under specified conditions." It goes on to state that "for practical purposes it is assumed that the permeance of an adequate retarder will not exceed 1 perm, although at present this value may be adequate only for residential construction." Regardless of the qualification, the 1-perm value is currently accepted as the working definition of a vapor retarder. To be effective, vapor retarders should also be essentially airtight to prevent the passage of moist air.

Air Retarders

While the purpose of vapor retarders is the prevention of excessive diffusion into and through walls and wall elements, the purpose of air retarders (AR) is to prevent excessive air leakage into and through building walls and wall elements, while being highly permeable to water vapor. ASTM E 1677, specifications for Air Retarder (AR) Material or System for Low-Rise Framed Building Walls, does not specify a level of required water vapor permeance. However, materials are available in the 10 to 50 perm (570 to 2850 ng/s · m Pa) range and may be considered appropriate. According to ASTM E 1677, the air leakage rate of an AR should not exceed 0.06 cfm/ft^2 at 0.3 in. of water ($0.3 \cdot 10^{-3}/(s \cdot m^2)$ at 75 Pa) when tested in accordance with ASTM Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen (E 283). Alternatively to installing a separate air retarder, other materials, such as interior gypsum board in cold climates, can provide an adequate air seal if the boards are properly caulked at the sill, head, and at all joints such as windows, doors, and at plumbing penetrations [*12*]. Since airtightness of the AR is critical to its performance, and, since the performance of seals is primarily a function of field workmanship, adequate provisions for quality control should be included in the building specifications so that the installed AR will meet the intent of ASTM E 1677. In cold climates, air retarders installed outside of the insulation enhance the effectiveness of the insulation by preventing cold air from entering the wall cavity.

Combined Vapor Retarders and Air Retarder

A combination vapor retarder and air retarder system will prevent moisture movement both by diffusion and by mass transport. The system can consist of a single element that is both air and water vapor resistant, or it can consist of two elements, a vapor retarder and an air barrier.

ACCEPTABLE MOISTURE LEVELS

In buildings, there are three components that limit acceptable moisture levels: human health and comfort, the deterioration of a building's contents—for example the storage of hygroscopic materials such as antiquities (in museums) or chemicals, and the need to safeguard the building's structure itself from moisture-related deterioration. While for most buildings RH levels in the 30 to 50% should be acceptable, for specialized buildings other allowable RH and temperature limits may need to be observed.

Human Health and Comfort

Within a fairly broad range, moisture in the air is of no great significance to human health and comfort. In other words, humans are tolerant of a wide range of moisture and temperature conditions of the air. ASHRAE suggests the indoor levels of temperature and moisture content for human occupancies as shown in Fig. 8 [*13*]. As shown on that chart, during winter, the relative humidity level should not fall significantly below 30% and should not exceed 70%. Other authorities recommend 40 to 60% [*14*].

As summarized by Burge, Su, and Spengler [*15*], several studies have indicated a significant association of home dampness and/or mold and respiratory symptoms in children. Although some of these studies showed conflicting results, it appears that excessive RH levels such as higher than 75%, and any surface mold growth, should be avoided. Surface mold can grow without the presence of liquid (condensed) water, and high relative surface humidities alone can

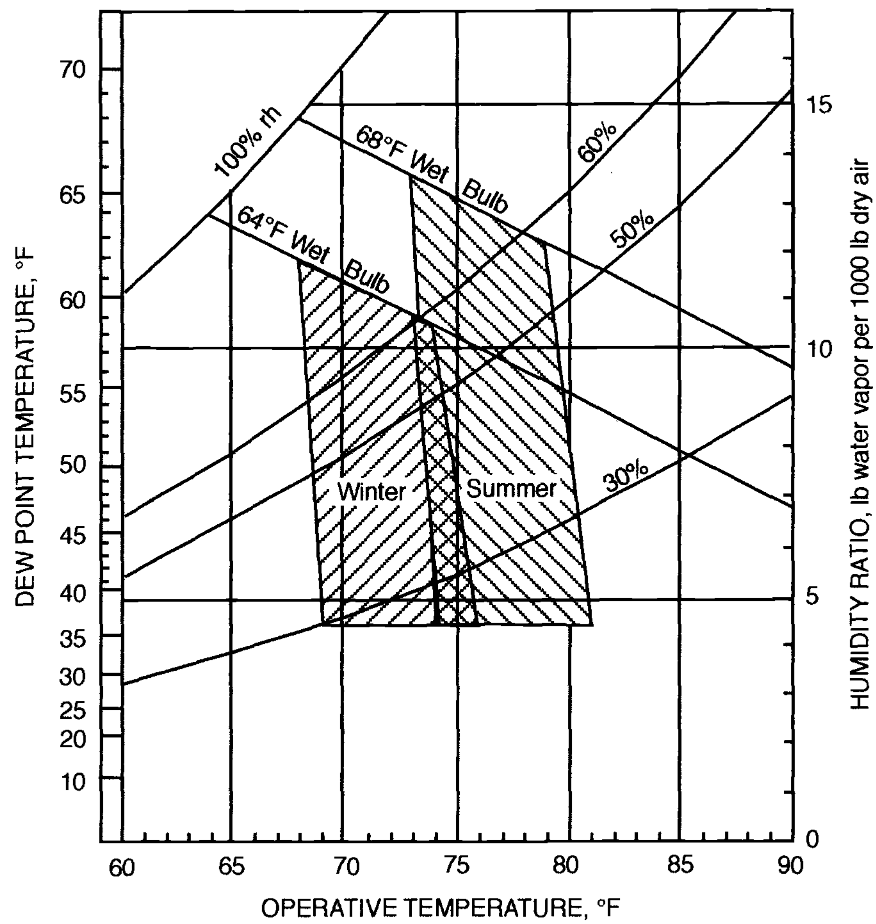


FIG. 8—ASHRAE summer and winter comfort zones (acceptable levels of operative temperature and humidity for people in typical summer and winter clothing during primary sedentary activity). Reprinted with permission of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers from the 1997 *ASHRAE Handbook—Fundamentals.*

cause mold growth. The International Energy Agency has determined that surface mold can grow at surface relative humidities of 80% or higher [*16*]; other researchers have recommended that surface RH should not exceed 70% [*12*]. Accordingly, health and comfort require that both the RH level in the occupied spaces and the surface relative humidity be controlled within the above suggested limits.

Building Contents

Buildings containing antiquities and precious artworks have their own moisture/temperature requirements. In general, somewhat higher levels of RH will be desirable. Plenderleight and Werner [*17*] recommend RH limits of a minimum of 50% to a maximum of 65% within a temperature range of 60 to 75°F (16 to 25°C), except for picture galleries for which a constant RH of 58 and 63°F (17°C) is recommended. However, it appears that artifacts are more sensitive to rapid changes in temperature and RH levels than to absolute values. Because the recommended RH levels are above those recommended for buildings in general, the storing and presenting of important artifacts in climate-controlled cabinets should be considered.

For the storage of hygrostatic materials and for some industrial processes, specialized temperature and RH levels may be required. These must be known to the designer before attempting to design the building envelope, but no general guidelines can be provided.

Building Structure

The temperature and RH levels recommended for health and comfort of building occupants in general are acceptable for the building structure. Also, the prevention of mold growth will also reduce the potential for premature deterioration of interior finishes. Where significant and regular condensation is allowed to form on steel constructions, corrosion could become a problem. This is one reason that the thickness of any one part of structural steel sections as a rule should not be less than 1/4 in. thick, although thinner, cold-formed light-gage galvanized steel shapes are routinely used as secondary elements, such as for supporting metal curtain walls.

General Recommendations

Since most calculations of temperatures and relative humidities are based on design values and do not include local discontinuities in insulation, thermal bridges, and air and rainwater leaks, it is recommended that designers use conservative estimates and allow indoor RH levels well within the comfort zone, surface RH levels below the 70%, and moisture content of wood structures not over 20%, unless exacting field quality control mechanisms are in place and unless maintenance and operations can be expected to meet rigorous standards. This may be more likely to be accomplished in major commercial and institutional buildings than in one- and two-family dwellings.

MOISTURE MOVEMENT

Moisture in the form of water vapor moves from one place to another either through mass transport, that is, by the movement of moist air, or through diffusion. The driving force of mass transport is air pressure; the driving force of diffusion is vapor pressure. The movement of liquid water can also result from wind pressure moving raindrops through cracks and joints, but as a general rule follows gravity forces.

Mass Transport

Driving Force

The flow of water vapor as part of airflow follows the same laws as the flow of air. The driving force of airflow into and across the building envelope is the air pressure difference acting on the envelope. When the air pressure within the building is greater than the pressure outside the building, the building is said to be under positive pressure. If the pressure indoors is lower than the pressure outside, the building is said to be under negative pressure. Note that the pressure differential is not necessarily the same for the entire building; it can vary depending on orientation or building level, both in magnitude and in direction, that is positive and negative. Air pressures and resulting air movements within the building can also be affected by interior partitions and shafts (such as for elevators and stairs).

The practitioner is seldom required to establish either the total pressure difference nor the resulting total air-leakage rate. However, building designers should be aware of the factors that affect the total driving forces and resulting air infiltration so that he or she can place the needed emphasis on those design and detail parameters that primarily affect the overall moisture resistance of the envelop.

- *Wind pressure* acts as a positive pressure on the windward side of the building and as a negative pressure on the leeward side of the building. Since wind speed is a function of height above ground, the wind pressure acting on a building wall will also vary with height above ground. Wind pressure is lowest at ground level and increases with building height. It is generally largest near corners and in high or unusually shaped buildings; only extensive analysis and wind tunnel studies can reliably predict the pressure distribution over the surface of the building envelope. Wind pressure also is affected by surrounding geographic features, other nearby buildings, and by trees and shrubbery. Windbreaks in the form of trees, bushes, and fences can effectively lower wind impingement and resulting air infiltration from prevailing wind. Both wind direction and wind speed can vary rapidly. For a more detailed discussion of wind pressure as a result of airflow around buildings, see ASHRAE [*18*].
- *Stack effect* in buildings is the result of temperature differences between the building interior and the atmosphere. During cold weather, heated air in the building is less dense and tends to rise. This will cause a negative indoor pressure on the lower floors, and a positive pressure on the upper floors and on the roof, and will result in exfiltration of indoor air at the top of the building and in infiltration of outdoor air at the bottom of the building. During warm weather in an air-conditioned building, the process is reversed, with air infiltration taking place at the top of the building and exfiltration at the bottom. As a general rule, the stack effect is greater during winter, since the temperature differences are greater. For a detailed discussion of stack effect and of calculating methods to determine the resulting pressure differentials, see ASHRAE [*18*].
- *Mechanical ventilation* acts on the entire building envelope to either provide positive or negative pressure and results in either a net outflow of inside air or a net inflow of outside air, while wind pressure and stack effect result in equal amounts of air being infiltrated as being exfiltrated. Mechanical systems that include fresh air intakes allow for adjustments to provide for either positive or negative indoor pressure depending on damper settings. In residential buildings, combustion furnaces and boilers can cause air pressure difference and air movement, even in the absence of mechanical ventilation fans.
- *Combined driving forces:* Although the three driving forces discussed above can be determined separately, the resulting airflow rates can not simply be added up, but the total pressure differential must be established and the infiltration must be determined on the basis of the leakage openings and the total pressure [*18*].

Air Leakage Sites

Of equal importance to the total air and moisture mass transport movement are the leakage sites, their size, effective leakage area (ELA), and, to a degree, their location. It is understood that the larger the opening, the greater the potential air movement. However, some types of openings produce different air leakage rates, depending on the direction of airflow. Based on a model developed by the Lawrence Berkeley Laboratory, ASHRAE [*18*] provides a table of typical effective air leakage areas (ELA) through building components at a nominal pressure difference of 0.016 in. of water (4 Pa). Note that the leakage areas can be converted from the reference pressure to airflow rates at other pressures, using equations also given in ASHRAE [*18*]. ASHRAE also presents a method for relating air infiltration rates to effective leakage area.

Diffusion

Water vapor can move through materials by diffusion. The driving force for such movement is the difference in water vapor pressure (as defined above) between the two sides of the material. Water vapor pressure depends on the moisture content of the air and its temperature or its relative humidity. Diffusion is a much less effective moisture transport mechanism than mass transport, but it can not be ignored and, under certain conditions, diffusion can be the controlling mechanism.

For practical purposes, the flow of moisture through a material is proportional to the area of the material, to the vapor pressure differential between the two faces of the material, and to a coefficient which is a function of the material, and is inversely proportional to the thickness of the material, *d*. The equation of diffusion through a material then is [*19*]:

$$WV = \mu \cdot A \cdot \theta \cdot \Delta p / l$$

where

WV = total mass of vapor transmitted, grains (grams),
μ = average permeability of material, grains/hour · sft · in.Hg/in (ng/s · m^2 · Pa/m),
A = area of cross section of the flow path, square feet (square metre),
θ = time during which transmission occurred, hours (seconds),
Δp = water vapor pressure difference across material, inch mercury (Pascals), and
l = thickness of material in inches (metre).

For a product with a specific thickness and known permeance, the equation then reads:

$$WV = A \cdot \mu \cdot \theta \cdot \Delta p$$

Discussion of Relative Significance of Mass Transport and Diffusion

As a rule, mass transport can be the more significant mechanism in moisture movements. Moisture-laden air can contain significant amounts of moisture, and where significant air movement takes place, significant amounts of moisture can be moved within a short time. On the other hand, as indicated in this Manual's introduction, the driving force of air movements is frequently transient with changing, increasing, or abating wind; the direction of the air movement may change within time frames of minutes to days. Also, the distribution of leaking air within the building envelope is not evenly distributed over the entire surface of the wall or roof, but it is often randomly concentrated in relatively few major leakage sites. It is for this reason that the design practitioner must develop thermal envelope details to preclude significant amounts of moist air into and through building wall and roof elements. Because of the random and unknown location of air leaks that invariably exist in both new and existing building envelopes, the analysis tools suitable for the designer do not, or not always, include the effect of air leaks. Similarly, the tools can not reliably account for water leaks that also are generally located at individual, unknown leakage sites unevenly distributed over the entire wall or roof. In other words, airtightness and rainwater resistance must be designed into walls and roofs. Analysis should not be relied upon to judge the adequacy of details to prevent air and water leakage into walls, roofs, and buildings.

In contrast, vapor diffusion acts evenly distributed over large areas of wall and roofs, and, while variable, both with regard to direction and quantity, it generally acts over longer periods of days to whole seasons. Furthermore, the air tightness, the specific air leakage sites, and the location and extent of rainwater leaks in a building is seldom, if ever, known during the design stage. (One exception might be where a building and wall design has been extensively tested and where, based on such tests, close approximations might be possible.) For all these reasons, the designer can confidently use moisture models such as MOIST (Chapter 8) and WUFI ORNL/IBP (Chapter 9) which do not include liquid water and mass transport of water vapor. (WUFI ORNL/IBP does include the effect of surface wetting.)

Specialized, more sophisticated models are available that are useful for conducting research to gain a better understanding of the hygrothermal mechanisms in building envelopes, which allow the evaluation of innovative wall and roof systems and which are excellent tools for investigating the effect of individual performance parameters. Most of these research models require highly trained operators and mainframe computers; they may be available to practitioners on a contract basis.

There is little argument that rainwater leaks, where they occur in a building, can admit copious amounts of water. There is also no argument that moisture movement by mass transport can be very significant. This is illustrated below by comparing the moisture movement by air infiltration with potential moisture movement of moisture by diffusion.

For the comparison we choose air infiltration data from an example given in ASHRAE [*18*]. The house has a volume of about 9000 ft^3 (255 m^3), has an effective air leakage area (EL) of 107 $in.^2$ (0.07 m^2), and is located in an area with buildings and trees within 30 ft (9 m) in most directions. Table 4 shows the assumptions and the calculated hourly moisture movement due to infiltration. The total calculated moisture movement rate due to air infiltration for the house would be 2.8 lb (1.2 kg) per hour.

Table 5 shows the calculated moisture movement that could occur through diffusion. The calculations are based

TABLE 4—Calculated moisture infiltration rate due to air infiltration.

	In./Lb Units	SI Units
Volume of house	9000 ft^3	255 m^3
Effective leakage area	107 $in.^2$	0.07 m^2
Air change rate	0.56 ach	0.56 ach
Infiltration rate	5000 ft^3/h	140 m^3/h
Relative humidity	50%	50%
Air temperature	70°F	21°C
Specific volume of air	13.5 ft^3/lb	0.84 m^3/kg
Specific weight of air	0.07 lb/ft^3	1.2 kg/m^3
Humidity ratio (lb/lb . . . kg/kg)	0.008	0.008
Mass of infiltrated air	350 lb/h	160 kg/h
Mass of infiltrated moisture	2.8 lb/h	1.2 kg/h

TABLE 5—Calculated moisture movement through building envelope by diffusion.

	In./Lb Units	SI Units
Exterior building envelope	2500 ft^2	230 m^2
Average wall/ceiling permeance	1 perm	57 SI perm equ.
Vapor pressure difference	0.3 hg	100 Pa
Hourly moisture movement by diffusion	0.11 lb/h	0.05 kg/L

again on hourly moisture movement by infiltration rate. That same house may have a total above-ground thermal envelope of approximately 2500 ft^2 (232 m^2). Assuming that the envelope has an average water vapor permeance of 1 perm or 1 grain/h · sft · in.Hg (57 ng/s · m^2 · Pa) and the vapor pressure differential between outdoors and indoors were 0.3 in.Hg (100 Pa), the total moisture movement by diffusion would be approximately $2500 \times 0.3 = 750$ grains per hour or 0.11 lb (0.05 kg) per hour.

As can be seen, in this example, the amount of moisture movement across the building envelope by infiltration is approximately 25 times the amount of moisture moved by diffusion. Of course, had the envelope been assumed to be less permeable to water vapor, say only 0.5 perm, the moisture movement by diffusion would be even lower; conversely, had the effective leakage been smaller, the moisture movement by mass transport had been lower. This illustrates the importance of designing airtightness into the envelope, of assuring that the design airtightness is achieved on the building site, and of maintaining such airtightness throughout the life of the building.

However, in terms of preventing moisture and mold problems in or on the building envelope, much of the moisture transported by moist air infiltration can be expected to move harmlessly through cracks, discrete openings, and discontinuities and to escape to the indoor environment in the case of air infiltration or to the outdoor atmosphere in the case of exfiltration. Only where moist air impinges on, or remains in contact with building surfaces and condenses, or where it increases the surface RH levels above safe values will mold growth or material deteriorations occur. On the other hand, moisture moving through a wall or material by the diffusion mechanism will be uniformly distributed over the entire surface, will be in intimate contact with such materials over a relatively long duration, and, under appropriate conditions, can condense and/or cause elevated surface relative humidity with the attendant potential for deterioration over the entire surface. In other words, the fact that air leakage moves greater amounts of moisture than diffusion does not mean that the potential moisture damage is proportional to the moisture movement and does not justify the neglect of diffusion in the design of building envelopes.

In addition, because of the discrete locations of most air leakage sites, any damage that does occur from mass transport may be restricted to a few locations in the envelope, but where deteriorations are in critical locations, they can lead to catastrophic failures and thus can not be ignored. By contrast, moisture moving by diffusion is more likely to involve the entire surface or major parts of the thermal envelope, and repairs, if necessary, may be much more costly and disruptive than repairs of air or water leaks. It is for all these reasons that, in the absence of reliable methods for accounting for air and water leakage sites, moisture analysis based on diffusion alone is still very useful to the designer for selecting materials so that condensation within envelope constructions can be avoided and for determining whether a separate vapor retarder is needed or not.

Capillarity

Where relatively porous materials are used below and at ground level, moisture from the ground can rise within a wall by capillarity and create what is referred to as *rising damp*. Rising damp has not generally been a major issue in the United States, but has been a source of great concern in Great Britain. The reason for this discrepancy is not clear, but it appears to be related to climate and building materials.

Capillarity refers to the movement of moisture due to forces of surface tension within small tubes. Generally, the narrower the tube, the higher will be the rise against the force of gravity. Accordingly, capillarity in a material depends on the structure of the material. Oliver estimates that for a pore radius of $4 \cdot 10^{-4}$ in. (0.01 mm), a rise of 60 in. (1.5 m) can be anticipated, and for a pore radius of $44 \cdot 10^{-5}$ in. (0.001 mm), a rise of 4500 ft (1500 m) can be anticipated. In typical moisture analysis in the United States, capillarity is neglected. However, in areas where rising damp is known to be a problem, its effect should be considered in design by specifying capillary breaks below concrete basement slabs and the installation of damp proof courses in walls [*20*].

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2

Weather Data*

by Anton TenWolde[2] and Donald G. Colliver[2]

RECOMMENDATIONS FOR MOISTURE CONTROL in buildings should be based on the specific climatic conditions that the building experiences or will experience. In Chapter 23, "Thermal and Moisture Control in Insulated Assemblies—Applications," in the 1997 ASHRAE handbook [*1*], three climate types are delineated for the purposes of moisture control: heating, cooling, and mixed climates. However, the definitions of these climate types are somewhat arbitrary, and they are used only to formulate a set of prescriptive and generic moisture control strategies. Neither the definition of climate type nor the moisture control strategies in the 1997 ASHRAE handbook are supported by analyses of the performance of buildings under design weather conditions and under standard indoor moisture design loads. At present, a standard for such moisture design loads is under development within ASHRAE (SPC 160P—Design Criteria for Moisture Control in Buildings). It will include criteria for moisture design weather data but will not provide the actual weather data. Until such design weather data are available, a moisture analysis has to be conducted with currently available weather data or design weather data generated by the user.

Building moisture analysis can provide specific information on the expected moisture levels in specific building constructions during a specific period of time. If the analysis is done for design purposes, the input data should reflect design conditions for the interior as well as the exterior of the building. The kind of weather data needed for moisture analysis depends on the analytical tool used and the purpose of the analysis. Generally, building moisture analysis requires more detailed weather data than building energy analysis or air-conditioning equipment sizing and design. In addition to temperature, wind, and solar radiation data, the analysis requires a measure of outdoor humidity (vapor pressure, wet-bulb temperature, dew point temperature, or humidity ratio) and often calls for precipitation data.

SOURCES OF WEATHER DATA

Detailed historical hourly weather data are available from the National Climatic Data Center (NCDC). The World Data Center for Meteorology at the NCDC in Ashville, NC, can provide archived weather data from around the world. The Surface Airways Meteorological and Solar Observing Network (SAMSON) data set contains historical hourly data for the United States, and the Canadian Weather Energy and Engineering Data Sets (CWEEDS) provide data for Canada. Some of this information is available on the Word Wide Web. Data sets have been derived from these historical data using statistical criteria that depend on the intended use of the data. A brief description of some of these data sets follows.

Chapter 26, "Climatic Design Information," in the 1997 *ASHRAE Handbook* [*1*] provides weather information that is useful for the design and sizing of heating, ventilating, air-conditioning, or dehumidification equipment. These data help determine peak operating conditions for the equipment. However, the weather conditions described occur only rarely. The summer conditions given are exceeded only 0.4, 1, or 2% of the time, and the winter design conditions are based on a 0.4 and 1% frequency (also referred to as 99.6 and 99% annual percentiles). The 1997 annual frequency data replaced data at 1, 2.5, and 5% frequency for summer and 1 and 2.5% frequency for winter [*1*], which were included in the ASTM *Manual on Moisture Control in Buildings* [*2*]. Data of such extremity would rarely be called for in moisture analysis.

ASHRAE has produced one year of hourly weather data known as Weather Year for Energy Calculations (WYEC) data [*3*]. The data were recently revised, improved, and reissued as WYEC Version 2, or WYEC2 data, for 52 locations in the United States and 6 locations in Canada [*4*]. The MOIST building moisture analysis computer program uses WYEC data [*5*]. The WYEC data represent typical conditions from the viewpoint of building energy consumption and do not include precipitation.

Typical Meteorological Year (TMY) data were produced for building energy analysis as well. An updated set, TMY2, for 239 cities in the United States is available from the National Renewable Energy Laboratory [*6*]. The Canadian Weather Year for Energy Calculations (CWEC) data were developed for 47 locations, using the TMY algorithm and software and is available from Environment Canada. The TMY data do not include precipitation.

CLIMATE DEFINITIONS FOR MOISTURE CONTROL

Recommendations for moisture control strategies are usually given by climate type. For instance, the 1997 ASHRAE handbook provides recommendations for heating climates,

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TABLE 1a—Mean monthly dry-bulb and dew-point temperatures (°C) over 30 years (1961-1990) for United States locations.

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
AK	26451	Anchorage	-9.2	-13.3	2.2	-4.4	14.7	9.2	1.6	-2.8
AK	25308	Annette	1.3	-2.2	6.1	1.6	14.3	10.3	8.3	5.3
AK	27502	Barrow	-25.2	-28.6	-18.7	-21.7	3.9	2	-10.1	-12
AK	26615	Bethel	-14	-17.2	-4.5	-7.6	12.7	9	-1.4	-3.8
AK	26533	Bettles	-24.5	-28.3	-5.9	-11.2	15.5	8.9	-7.3	-10.5
AK	26415	Big Delta	-20.1	-24.6	-0.1	-8.6	15.9	8.4	-3.7	-7.6
AK	25624	Cold Bay	-1.6	-3.9	0.7	-2	10	7.8	4.3	1.4
AK	26411	Fairbanks	-23.4	-27.3	-0.3	-8.7	17	9.3	-3.8	-8
AK	26425	Gulkana	-21.3	-24.8	0.2	-7.2	14.7	6.9	-2.2	-6.2
AK	25503	King Salmon	-9.3	-12.7	-0.3	-5.1	12.4	8.3	0.4	-2.9
AK	25501	Kodiak	-0.6	-4.3	2.9	-2	12.3	9.2	4.7	0.3
AK	26616	Kotzebue	-18.2	-21.9	-11.1	-14.4	12.1	8.7	-4.9	-7.9
AK	26510	McGrath	-22.3	-25.7	-2.4	-9.1	14.9	8.7	-3.9	-7.3
AK	26617	Nome	-13.6	-17.4	-7.3	-11.3	11.1	7.2	-1.9	-6.1
AK	25713	St. Paul Is.	-2.6	-4.9	-1.7	-3.9	7.7	6.7	3.5	0.7
AK	26528	Talkeetna	-11.3	-15.4	1.3	-4.7	15.1	10	-0.1	-3.4
AK	25339	Yakutat	-3.7	-6.3	2.6	-0.6	12.1	9.9	4.9	2.8
AL	13876	Birmingham	5.4	-0.2	16.9	9.3	26.1	20.7	16.7	10.7
AL	3856	Huntsville	3.8	-1.2	16.3	8.4	25.8	20.3	16	9.8
AL	13894	Mobile	9.7	4.3	19.6	13.2	27	22.1	19.7	13.6
AL	13895	Montgomery	7.4	1.6	18.2	11.1	26.7	21.6	18.2	12
AR	13964	Fort Smith	2.3	-3.2	16.3	8.5	27.3	20.3	16.3	9.8
AR	13963	Little Rock	3.8	-1.7	16.8	9.8	27.3	21.2	16.8	10.7
AZ	3103	Flagstaff	-1.9	-9	6.1	-6.4	18.9	6.6	8.2	-2.6
AZ	23183	Phoenix	11.7	0.2	21.6	-0.1	34.3	13.4	23.5	6.1
AZ	23184	Prescott	2.5	-5.8	11.4	-4.6	24.1	9.1	13.5	0.2
AZ	23160	Tucson	10.3	-2	19.1	-2.9	29.8	13.3	20.9	4.1
CA	24283	Arcata	7.7	4.5	9.4	6.1	13.4	10.9	11.5	9.2
CA	23155	Bakersfield	8.4	4.1	17.1	5.6	29.2	10.8	19.9	8.2
CA	23161	Daggett	8.9	-3.3	18.3	-0.9	31.9	6.9	20.4	1.3
CA	93193	Fresno	7.1	4.1	16	6.3	27.9	11.3	18	8.6
CA	23129	Long Beach	12.9	5.1	16.1	8.9	21.6	15.2	19.3	12.2
CA	23174	Los Angeles	13.3	5.2	15.3	9.5	20	15.6	18.8	12.4
CA	23232	Sacramento	7	4.1	14.2	6.6	23.2	11.8	16.9	8.7
CA	23188	San Diego	13.9	6.1	16.4	9.8	21	16.2	19.6	13.1
CA	23234	San Francisco	9.1	5.2	12.5	6.9	16	10.8	15.3	9.7
CA	23273	Santa Maria	10.7	4.6	13	7.6	16.9	11.8	16	9.7
CO	23061	Alamosa	-10.1	-14.2	5.7	-7.1	18.2	7.2	6.5	-3.7
CO	94018	Boulder	-1.6	-10.6	9.1	-3.2	22.7	9.2	10.4	-1.8
CO	93037	Colorado Springs	-2.1	-12.1	8	-5.2	21.3	8.8	9.8	-3.2
CO	23063	Eagle	-8	-12.1	5.7	-4.3	19.2	6.7	6.4	-2.7
CO	23066	Grand Junction	-4.2	-9.3	11.1	-4.1	25.9	6.5	12.1	-1.1
CO	93058	Pueblo	-1.2	-9.4	11.7	-2.8	25.2	11.3	12.4	-0.7
CT	94702	Bridgeport	-1.6	-7.4	9	1.6	23.1	17.4	13.4	7.6
CT	14740	Hartford	-3.9	-10	9.2	0.2	23	16.1	11.1	5
DE	13781	Wilmington	-0.7	-6.3	11.2	3.2	24.5	18.1	13.4	7.6
FL	12834	Daytona Beach	13.9	9.1	20.7	14.2	26.6	22.1	22.8	17.8
FL	13889	Jacksonville	11.2	6.3	19.8	13.2	27	22.4	20.7	16.4
FL	12836	Key West	20.8	16.3	24.8	18.8	29.1	23.5	26.4	21.6
FL	12839	Miami	19.6	14.2	23.9	17	27.9	22.8	25.5	20.4
FL	93805	Tallahassee	10.1	5.1	19.2	12.4	26.4	22.3	19.8	14.3
FL	12842	Tampa	14.9	10.1	21.7	15.1	27.3	22.6	23.2	17.9
FL	12844	West Palm Beach	18.5	13.2	23	16.2	27.5	22.8	25.1	19.8
GA	13873	Athens	5.2	-0.9	16.4	8.3	25.7	20.4	16.4	10.5
GA	13874	Atlanta	4.8	-1.5	16.3	7.7	25.3	19.9	16.4	9.8
GA	3820	Augusta	6.3	0.4	17	9.1	26.4	20.7	16.9	11.2
GA	93842	Columbus	7.4	1.7	18.2	10.3	26.9	21.4	18.4	12.2
GA	3813	Macon	7.3	1.4	18	10.2	26.7	21.1	17.9	11.8
GA	3822	Savannah	8.9	2.9	18.6	11	26.9	21.8	19.2	13.6
HI	21504	Hilo	21.6	17.1	22.1	18.4	24	20.1	23.8	20
HI	22521	Honolulu	22.4	17.2	23.8	17.2	26.3	18.9	25.9	19.3
HI	22516	Kahului	22.2	17.2	23.5	17.6	25.9	19.2	25.4	19.3
HI	22536	Lihue	21.8	17.3	23.1	18.3	25.7	20.6	25.1	20.5
IA	14933	Des Moines	-6.9	-11.5	10.4	2.8	24.6	17.7	11.7	5.1
IA	14940	Mason City	-10.3	-14.1	7.8	1.6	22.6	16.9	9.4	3.9
IA	14943	Sioux City	-7.9	-12.3	10.1	1.9	24.2	17.7	10.8	3.9
IA	94910	Waterloo	-9.4	-13.4	8.7	1.9	22.9	17.1	9.9	4.1
ID	24131	Boise	-1.7	-5.8	9.6	-1	23.7	6.2	10.7	0.4

TABLE 1a—Mean monthly dry-bulb and dew-point temperatures (°C) over 30 years (1961-1990) for United States locations. (*continued*)

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
ID	24156	Pocatello	−4.8	−8.7	7.3	−2.9	21.8	6.2	8.7	−1.6
IL	94846	Chicago	−5.8	−10.2	9.2	2.2	23.1	16.5	11.6	5.4
IL	14923	Moline	−6.5	−11.2	10.3	3	24.1	17.8	11.6	5.3
IL	14842	Peoria	−5.7	−9.7	10.7	3.6	23.9	18	11.8	5.9
IL	94822	Rockford	−7.4	−11.1	8.9	2.1	23.1	16.9	10.7	5.2
IL	93822	Springfield	−4.2	−8.3	11.9	4.8	24.8	18.5	13	6.6
IN	93817	Evansville	−0.9	−5.7	13.7	6.4	25.5	19.3	13.7	7.5
IN	14827	Fort Wayne	−4.9	−8.7	9.6	2.9	23.1	16.6	11.3	5.8
IN	93819	Indianapolis	−3.6	−7.6	11.3	4.4	24	18.3	12.3	6.7
IN	14848	South Bend	−4.7	−8.3	9.3	2.6	22.8	16.5	11.4	6.1
KS	13985	Dodge City	−1.8	−8.2	12.3	2.6	26.6	15.6	13.6	4.1
KS	23065	Goodland	−2.8	−9.1	9.6	0.2	24.1	13.8	10.9	1.1
KS	13996	Topeka	−3	−8.2	12.9	5.4	25.9	19.3	13.6	6.9
KS	3928	Wichita	−1.6	−6.8	13.6	5.8	27.4	17.6	14.6	7.2
KY	93814	Covington	−2.1	−6.7	11.9	4.2	23.9	17.9	12.7	6.6
KY	93820	Lexington	−0.7	−5.2	12.7	5	24.1	18.2	13.5	7.3
KY	93821	Louisville	−0.1	−5.5	13.7	5.5	25.2	19	14.1	7.9
LA	13970	Baton Rouge	9.6	4.7	19.9	13.8	27.1	22.3	19.7	13.9
LA	3937	Lake Charles	9.9	5.9	19.9	15	27.2	23.1	20.1	14.9
LA	12916	New Orleans	10.8	6.2	20.5	15.1	27.2	23.1	20.5	15.4
LA	13957	Shreveport	7.1	1.8	18.6	12.2	27.6	21.6	18.7	12.7
MA	14739	Boston	−1.8	−8.6	8.6	0.9	22.8	16.1	12.2	6
MA	94746	Worchester	−5	−10.8	6.9	−1.3	20.9	14.8	9.9	4
MD	93721	Baltimore	−0.1	−6.7	12	3.2	24.8	18.1	13.6	7.6
ME	14607	Caribou	−11.9	−15.9	3.3	−2.8	18.7	13.5	6.2	2
ME	14764	Portland	−5.8	−11.2	6.1	−0.5	20.2	15.1	9.3	4.3
MI	94849	Alpena	−7.2	−10.9	5.2	−1.5	19.9	13.6	8.3	3.7
MI	94847	Detroit	−4.8	−8.8	8.4	1.7	22.4	15.8	10.6	5.2
MI	14826	Flint	−5.5	−9.3	7.8	1.1	21.7	15.2	10.1	5.1
MI	94860	Grand Rapids	−5.3	−8.7	7.9	1.3	22.1	15.6	10.1	5.3
MI	94814	Houghton	−8.1	−11.2	5.4	−1.1	20.3	13.9	8.3	4.1
MI	14836	Lansing	−5.7	−8.9	7.8	1.4	21.9	15.8	9.9	5.3
MI	14840	Muskegon	−4.9	−8.2	7.4	0.6	21.4	15.4	10.4	5.6
MI	14847	Sault Ste.	−10.2	−13.4	3.6	−2.1	17.9	13.2	6.9	3.5
MI	14850	Traverse City	−6.4	−9.8	5.9	−0.7	20.9	14.1	9.4	4.6
MN	14913	Duluth	−13.4	−17.4	3.6	−3.5	18.8	12.8	6.4	1.1
MN	14918	International Falls	−16.6	−20.7	4	−3.7	19.4	13.4	5.7	1
MN	14920	La Crosse	−9.4	−13.5	8.6	1.2	22.8	16.9	10	4.4
MN	14922	Minneapolis	−10.9	−15.4	8	−0.2	23.2	15.6	9.4	3.3
MN	14925	Rochester	−11.1	−14.4	7.1	0.9	21.5	15.8	8.7	3.3
MN	14926	Saint Cloud	−12.9	−16.5	6.4	−0.8	21.7	15.3	7.8	2.5
MO	3945	Columbia	−2.5	−7.4	12.8	5.1	25.3	18.7	13.5	6.8
MO	3947	Kansas City	−2.7	−8.2	13.1	4.8	26.2	18.8	14.2	6.7
MO	13995	Springfield	−0.6	−6.2	13.4	6.1	25.2	18.9	14	7.4
MO	13994	St. Louis	−1.8	−6.5	13.5	5.7	26.2	19.2	14.3	7.8
MS	3940	Jackson	6.8	2.3	18.2	12.1	26.9	21.9	17.8	12.3
MS	13865	Meridian	6.7	1.8	17.8	11.3	26.3	21.4	17.2	11.7
MT	24033	Billings	−5.2	−12.2	7.3	−2.9	22.3	8.5	9.2	−1.2
MT	24137	Cut Bank	−8.3	−13.8	4.8	−4.4	18.6	6.3	7	−2.4
MT	94008	Glasgow	−11.7	−15.4	6.6	−2.6	21.7	9.4	7.4	−1
MT	24143	Great Falls	−5.8	−12.2	6.5	−3.6	20.8	6.7	8.6	−1.8
MT	24144	Helena	−6.6	−11.9	6.2	−3.5	20.2	6.5	6.9	−1.7
MT	24146	Kalispell	−5.9	−9.2	6.2	−1.8	18.6	8.4	5.3	0.1
MT	24036	Lewistown	−6.4	−11.6	5.1	−2.9	19.1	8.3	7.2	−1.7
MT	24037	Miles City	−9.1	−13.3	7.7	−1.4	23.9	10.1	8.6	0.1
MT	24153	Missoula	−5.3	−8.1	6.7	−1.2	19.6	7.6	6.1	0.4
NC	3812	Asheville	1.6	−3.6	12.7	5.2	22.2	18.3	12.6	8.1
NC	93729	Cape Hatteras	7.1	2.7	15.1	9.7	25.8	22.1	18.6	13.9
NC	13881	Charlotte	4.1	−2.6	15.6	6.5	25.4	19.5	15.8	9.5
NC	13723	Greensboro	2.5	−3.7	14.4	5.8	24.7	19.5	14.4	8.7
NC	13722	Raleigh	3.6	−2.8	14.9	6.3	24.9	19.8	15.2	9.7
NC	13748	Wilmington	7	1.4	16.8	9.8	26.4	22	17.8	12.9
ND	24011	Bismarck	−12.2	−16.4	6.2	−1.9	21.7	12.8	7.4	0
ND	14914	Fargo	−14.3	−18.1	6.2	−0.8	22	14.8	7.6	1.6
ND	24013	Minot	−13.1	−17.8	5.6	−2.3	21.1	12.2	7.1	−0.2
NE	14935	Grand Island	−5.7	−10.8	10.3	1.9	24.6	16.7	11.1	3.3
NE	14941	Norfolk	−6.7	−11.9	10.6	1.3	25.1	16.6	11.2	2.9
NE	24023	North Platte	−6	−11.2	9	0.1	23.4	14.9	9.6	1.2

TABLE 1a—Mean monthly dry-bulb and dew-point temperatures (°C) over 30 years (1961-1990) for United States locations. (*continued*)

State	WBAN	Location	January Mean DB	January Mean DP	April Mean DB	April Mean DP	July Mean DB	July Mean DP	October Mean DB	October Mean DP
NE	94918	Omaha	−5.9	−10.6	11.2	2.9	25.1	18.2	11.9	5.2
NE	24028	Scottsbluff	−4.2	−10.6	8.3	−1.5	23.1	12.3	9.2	−0.7
NH	14745	Concord	−6.7	−11.9	6.9	−1.1	21.1	15.1	8.9	3.6
NJ	93730	Atlantic City	−0.4	−5.6	10.3	3.4	23.7	18.2	13	8.1
NJ	14734	Newark	−0.7	−6.8	11.1	1.9	24.9	16.9	13.9	7.1
NM	23050	Albuquerque	0.9	−7.8	13.1	−5.9	25.2	9.5	13.7	0.3
NM	23048	Tucumcari	2.3	−6.5	14.4	−0.7	26.3	13.8	14.8	3.2
NV	24121	Elko	−4.1	−8.7	7.1	−3.7	22.4	2.9	8.3	−3.6
NV	23154	Ely	−4.7	−10.8	5.4	−5.6	20.5	1.9	7.3	−4.2
NV	23169	Las Vegas	7	−5.5	18.2	−4.4	32.8	4.8	19.7	−0.9
NV	23185	Reno	−0.1	−5.9	9.1	−3.6	22.3	4.3	10.3	−1.2
NV	23153	Tonopah	−0.8	−8	9.4	−6.6	24.4	0.4	11.5	−4.7
NV	24128	Winnemucca	−1.6	−6.8	8.3	−4.4	23.6	1.5	9.3	−3.6
NY	14735	Albany		−10.5		0.1		15.7		4.7
NY	4725	Binghamton	−5.9	−10	6.8	−0.2	20.5	14.7	9.3	4.4
NY	14733	Buffalo	−4.7	−8.4	7.2	0.8	21.7	15	10.5	5.4
NY	94725	Massena	−9.4	−12.9	6.1	−0.2	20.9	15.1	8.4	4.2
NY	94728	New York City	−0.3	−7.3	10.6	2	24.4	16.8	14.1	7.1
NY	14768	Rochester	−4.5	−8.6	7.7	1.2	21.9	15.5	10.5	5.7
NY	14771	Syracuse	−5.1	−9.2	7.7	0.7	21.7	15.5	10.3	5.4
OH	14895	Akron	−3.9	−8.1	9.2	1.8	22.1	15.9	11.2	5.4
OH	14820	Cleveland	−3.8	−8.1	8.8	2.1	22.3	16.1	11.5	5.9
OH	14821	Columbus	−3	−7.6	10.7	3.1	23.2	17.1	11.9	5.9
OH	93815	Dayton	−3.3	−7.7	10.7	3.4	23.5	16.9	12	5.9
OH	14891	Mansfield	−4.1	−7.8	9.3	2.4	22.5	16.3	11.4	5.6
OH	94830	Toledo	−5	−8.9	8.8	2	22.3	16.3	10.6	5.3
OH	14852	Youngstown	−4.5	−8.4	8.5	1.6	21.3	15.6	10.6	5.3
OK	13967	Oklahoma City	1.8	−4.5	15.9	7.4	27.6	18.6	16.4	8.8
OK	13968	Tulsa	1.6	−4.7	16.3	7.8	28.3	19.9	16.5	9.3
OR	94224	Astoria	5.6	2.7	8.8	5.2	15.4	11.8	11.5	8.5
OR	94185	Burns	−3.6	−6.8	6.5	−3.1	20.7	4.3	8.1	−1.2
OR	24221	Eugene	4.3	2.3	9.7	5.3	19.3	11	11.4	7.8
OR	24225	Medford	2.8	0.2	10.2	3	22.3	9.1	11.6	5.3
OR	24284	North Bend	7.2	4.2	9.6	5.8	15	11.4	12.2	9.1
OR	24155	Pendleton	0.8	−3.1	10.1	1.3	23.1	5.8	11	2.3
OR	24229	Portland	4.2	0.9	10.4	4.9	19.6	11.6	12.3	8
OR	24230	Redmond	−0.4	−5.2	6.8	−2.3	19.2	5.2	8.7	−0.3
OR	24232	Salem	4.2	1.4	9.6	4.6	19.1	10.9	11.2	7.2
PA	14737	Allentown	−2.9	−8.1	9.9	1.6	23.3	16.6	11.8	6.3
PA	4751	Bradford	−6.9	−10.2	5.9	−0.4	18.7	14.1	8.1	3.8
PA	14860	Erie	−3.8	−7.9	7.3	1.2	21.3	15.7	11.1	5.7
PA	14751	Harrisburg	−1.8	−8	10.9	2.3	24.1	17.3	12.4	6.7
PA	13739	Philadelphia	−0.8	−6.8	11.3	2.8	24.6	18.1	13.4	7.7
PA	94823	Pittsburgh	−3.2	−8.2	9.8	1.4	22.2	15.6	11.2	4.9
PA	14777	Wilkes-Barre	−3.9	−8.8	8.8	0.6	21.9	15.8	10.7	5.3
PA	14778	Williamsport	−3.6	−8.6	9.6	1.4	22.2	16.8	10.8	6
	41415	Guam	25.4	22	26.2	22.4	26.5	23.8	26.4	23.8
PR	11641	San Juan	24.7	19.6	25.9	20.1	27.8	23	27.2	22.6
RI	14765	Providence	−2.2	−8.6	8.7	0.7	22.6	16.4	11.7	5.9
SC	13880	Charleston	8.2	2.2	17.8	10.8	26.7	21.9	18.6	13.3
SC	13883	Columbia	6.2	0.1	17.3	8.6	26.4	20.7	16.9	11.1
SC	3870	Greenville	4.3	−2.3	15.5	6.7	25.1	19.7	15.5	9.3
SD	14936	Huron	−10.3	−14.5	7.9	1	23.5	15.8	8.9	2.2
SD	24025	Pierre	−8.4	−13	8.2	−0.1	24.4	14.2	9.7	1.2
SD	24090	Rapid City	−5.5	−11.7	7.4	−1.6	22.5	12.1	9.2	−0.9
SD	14944	Sioux Falls	−9.8	−14.1	8.3	1	23.6	16	9.2	2.7
TN	13877	Bristol	1	−4.1	13	5	23.1	18.2	13.3	7.6
TN	13882	Chattanooga	2.9	−2.3	15.3	7.4	25.4	20.1	15.1	9.8
TN	13891	Knoxville	2.6	−2.4	14.9	7	24.7	19.6	14.7	9.3
TN	13893	Memphis	3.9	−1.9	17.2	9.2	27.8	21.1	17.2	10.1
TN	13897	Nashville	2.3	−3	15.2	7.3	25.8	20	15.5	9.1
TX	13962	Abilene	5.6	−2.6	18.3	7.7	28.3	16.9	18.6	9.8
TX	23047	Amarillo	1	−7.6	13.7	0.6	25.7	14.3	14.3	4.1
TX	13958	Austin	9	2.4	20.3	12.8	28.6	20.5	20.7	13.7
TX	12919	Brownsville	14.8	10.8	23.4	18.4	28.6	22.8	23.7	18.7
TX	12924	Corpus Christi	12.6	8.2	22.2	17.3	28.5	23.1	22.9	17.8
TX	23044	El Paso	6.3	−4.8	18.2	−3.7	27.9	12.7	17.6	4.3
TX	3927	Fort Worth	6.1	−0.3	18.6	11.1	29.3	19.8	19.3	11.8

TABLE 1a—Mean monthly dry-bulb and dew-point temperatures (°C) over 30 years (1961-1990) for United States locations. (*continued*)

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
TX	12960	Houston	10.4	5.4	20.4	15	27.8	22.4	20.7	15.3
TX	23042	Lubbock	3.1	-5.8	16.1	2.4	26.3	15.4	15.9	6.6
TX	93987	Lufkin	8.4	3.4	19.7	13.6	27.7	22.1	19.4	13.6
TX	23023	Midland	5.4	-4.2	17.9	2.9	27.2	14.9	17.5	8.2
TX	12917	Port Arthur	10.3	6.3	20.3	15.7	27.5	23.6	20.6	15.8
TX	23034	San Angelo	6.7	-1.5	19.2	7.9	28.2	16.9	18.7	11.1
TX	12921	San Antonio	9.6	2.8	20.7	13.2	28.6	20.6	21.1	13.9
TX	12912	Victoria	11.4	6.7	21.4	15.8	28.3	22.6	21.8	16.3
TX	13959	Waco	7.1	1.5	19.4	12.4	29.4	20.1	20.1	13.1
TX	13966	Wichita Falls	3.8	-2.8	17.4	8.9	29.2	18.3	17.8	10.3
UT	93129	Cedar City	-1.7	-7.8	8.8	-4.2	23.7	4.9	10.8	-1.8
UT	24127	Salt Lake City	-2.3	-6.7	9.9	-0.6	25.6	7.5	11.2	1.4
VA	13733	Lynchburg	1.7	-5.7	13.9	3.9	24.5	18.4	14.2	7.5
VA	13737	Norfolk	4	-2.3	14.1	6.2	25.6	20.1	16.3	10.8
VA	13740	Richmond	2.1	-3.9	14.1	5.4	25.2	19.8	14.6	9.2
VA	13741	Roanoke	1.3	-6.1	13.3	3.6	24	17.8	13.6	7.1
VA	93738	Sterling	-0.6	-6.3	11.8	3.7	24.2	18.3	12.8	7.3
VT	14742	Burlington	-8.1	-13.2	6.2	-0.9	21.1	14.6	8.9	3.8
WA	24227	Olympia	3.4	1.4	8.7	3.9	17.2	11.2	9.8	7.1
WA	94240	Quillayute	4.8	2.7	7.9	4.6	14.4	11.1	10.2	7.8
WA	24233	Seattle	4.5	0.6	9.3	3.8	18	10.8	11.2	7.3
WA	24157	Spokane	-2.8	-5.5	7.8	-0.1	20.8	6.5	8.2	1.6
WA	24243	Yakima	-1.4	-4.9	10.1	-0.6	21.9	7.9	9.3	1.8
WI	14991	Eau Claire	-11.4	-15.2	7.5	0	22.2	15.7	8.8	3.4
WI	14898	Green Bay	-9.4	-13.2	6.6	0.3	21.3	15.4	8.9	4.2
WI	14837	Madison	-8.5	-12.3	7.8	1.1	22.1	16	9.6	4.4
WI	14839	Milwaukee	-7	-11.2	7	1	21.8	15.9	10.4	5.2
WV	13866	Charleston	0.1	-5.3	12.9	3.7	23.3	18.3	12.9	7.3
WV	13729	Elkins	-2.4	-6.8	9.3	2.7	20.1	16.5	9.8	5.2
WV	3860	Huntington	0.2	-5.2	13.1	4.2	23.7	18.7	13.3	7.4
WY	24089	Casper	-5	-11.1	5.8	-3.4	21.6	6.6	7.7	-2.9
WY	24018	Cheyenne	-2.8	-12.1	5.8	-4.3	20.1	8	8	-3.6
WY	24021	Lander	-7.2	-13.2	6.2	-4.4	21.7	5.7	7.8	-2.8
WY	24027	Rock Springs	-6.5	-10.9	4.7	-5.1	20.2	3.1	6.6	-4
WY	24029	Sheridan	-6.1	-11.7	6.8	-2.1	21.4	9	8	-1.2

Source: Colliver, D. G. 1999. Mean monthly dry-bulb and dew-point temperatures determined from the Samson data set. Biosystems and Agricultural Engineering, University of Kentucky, Lexington.

warm and humid cooling climates, and mixed climates [*1*]. The definitions of these climates are somewhat arbitrary. In the ASHRAE handbook, heating climates are defined as climates with 4000 heating degree days (base 65°F (18°C)) or more. Cooling climates are defined as warm, humid climates where one or both of the following conditions occur: (i) a 67°F (19°C) or higher wet-bulb temperature for 3000 or more hours during the warmest six consecutive months of the year; (ii) a 73°F (23°C) or higher wet-bulb temperature for 1500 or more hours during the warmest six consecutive months of the year. Mixed climates are all other climates that are neither heating nor cooling. In addition to temperature and humidity criteria, these climates can be further subdivided by the amount of rainfall, creating six different climate definitions.

Although these definitions are useful for broad, prescriptive recommendations, it is often difficult to determine in which climate zone a particular location fits. Climate zone definitions also make an assumption about which part of the season is most critical for moisture control, the heating or cooling season. While this approach is often adequate for broad prescriptive measures in extreme climates, it is far more problematic in more moderate climates. In such climates, we recommend an individual analysis.

WEATHER DATA FOR MOISTURE ANALYSIS

Building moisture analysis is most often done to analyze the design of new buildings, changes in design or use of an existing building, or for forensic purposes to investigate building failures. Weather data for forensic purposes ideally should be hourly site data, or as close to that as possible. Weather data for design analysis, however, require more careful consideration. If average weather data are used for design, such as TMY or WYEC data, a load factor should be used to account for the fact that average data do not reflect more severe weather conditions that undoubtedly will occur during the life of the building [7]. However, no guidance is given in the literature to arrive at a value for this load factor. A better approach is to select the level of severity desired for the design climate data and to create a set of design weather data based on that criterion. Such a set has been called a moisture design reference year or MDRY [7]. A consensus is

TABLE 1b—Mean monthly dry-bulb and dew-point temperatures (°F) over 30 Years (1961-1990) for United States locations.

State	WBAN	Location	January Mean DB	January Mean DP	April Mean DB	April Mean DP	July Mean DB	July Mean DP	October Mean DB	October Mean DP
AK	26451	Anchorage	15.4	8.1	36.0	24.1	58.5	48.6	34.9	27.0
AK	25308	Annette	34.3	28.0	43.0	34.9	57.7	50.5	46.9	41.5
AK	27502	Barrow	−13.4	−19.5	−1.7	−7.1	39.0	35.6	13.8	10.4
AK	26615	Bethel	6.8	1.0	23.9	18.3	54.9	48.2	29.5	25.2
AK	26533	Bettles	−12.1	−18.9	21.4	11.8	59.9	48.0	18.9	13.1
AK	26415	Big Delta	−4.2	−12.3	31.8	16.5	60.6	47.1	25.3	18.3
AK	25624	Cold Bay	29.1	25.0	33.3	28.4	50.0	46.0	39.7	34.5
AK	26411	Fairbanks	−10.1	−17.1	31.5	16.3	62.6	48.7	25.2	17.6
AK	26425	Gulkana	−6.3	−12.6	32.4	19.0	58.5	44.4	28.0	20.8
AK	25503	King Salmon	15.3	9.1	31.5	22.8	54.3	46.9	32.7	26.8
AK	25501	Kodiak	30.9	24.3	37.2	28.4	54.1	48.6	40.5	32.5
AK	26616	Kotzebue	−0.8	−7.4	12.0	6.1	53.8	47.7	23.2	17.8
AK	26510	McGrath	−8.1	−14.3	27.7	15.6	58.8	47.7	25.0	18.9
AK	26617	Nome	7.5	0.7	18.9	11.7	52.0	45.0	28.6	21.0
AK	25713	St. Paul Is.	27.3	23.2	28.9	25.0	45.9	44.1	38.3	33.3
AK	26528	Talkeetna	11.7	4.3	34.3	23.5	59.2	50.0	31.8	25.9
AK	25339	Yakutat	25.3	20.7	36.7	30.9	53.8	49.8	40.8	37.0
AL	13876	Birmingham	41.7	31.6	62.4	48.7	79.0	69.3	62.1	51.3
AL	3856	Huntsville	38.8	29.8	61.3	47.1	78.4	68.5	60.8	49.6
AL	13894	Mobile	49.5	39.7	67.3	55.8	80.6	71.8	67.5	56.5
AL	13895	Montgomery	45.3	34.9	64.8	52.0	80.1	70.9	64.8	53.6
AR	13964	Fort Smith	36.1	26.2	61.3	47.3	81.1	68.5	61.3	49.6
AR	13963	Little Rock	38.8	28.9	62.2	49.6	81.1	70.2	62.2	51.3
AZ	3103	Flagstaff	28.6	15.8	43.0	20.5	66.0	43.9	46.8	27.3
AZ	23183	Phoenix	53.1	32.4	70.9	31.8	93.7	56.1	74.3	43.0
AZ	23184	Prescott	36.5	21.6	52.5	23.7	75.4	48.4	56.3	32.4
AZ	23160	Tucson	50.5	28.4	66.4	26.8	85.6	55.9	69.6	39.4
CA	24283	Arcata	45.9	40.1	48.9	43.0	56.1	51.6	52.7	48.6
CA	23155	Bakersfield	47.1	39.4	62.8	42.1	84.6	51.4	67.8	46.8
CA	23161	Daggett	48.0	26.1	64.9	30.4	89.4	44.4	68.7	34.3
CA	93193	Fresno	44.8	39.4	60.8	43.3	82.2	52.3	64.4	47.5
CA	23129	Long Beach	55.2	41.2	61.0	48.0	70.9	59.4	66.7	54.0
CA	23174	Los Angeles	55.9	41.4	59.5	49.1	68.0	60.1	65.8	54.3
CA	23232	Sacramento	44.6	39.4	57.6	43.9	73.8	53.2	62.4	47.7
CA	23188	San Diego	57.0	43.0	61.5	49.6	69.8	61.2	67.3	55.6
CA	23234	San Francisco	48.4	41.4	54.5	44.4	60.8	51.4	59.5	49.5
CA	23273	Santa Maria	51.3	40.3	55.4	45.7	62.4	53.2	60.8	49.5
CO	23061	Alamosa	13.8	6.4	42.3	19.2	64.8	45.0	43.7	25.3
CO	94018	Boulder	29.1	12.9	48.4	26.2	72.9	48.6	50.7	28.8
CO	93037	Colorado Springs	28.2	10.2	46.4	22.6	70.3	47.8	49.6	26.2
CO	23063	Eagle	17.6	10.2	42.3	24.3	66.6	44.1	43.5	27.1
CO	23066	Grand Junction	24.4	15.3	52.0	24.6	78.6	43.7	53.8	30.0
CO	93058	Pueblo	29.8	15.1	53.1	27.0	77.4	52.3	54.3	30.7
CT	94702	Bridgeport	29.1	18.7	48.2	34.9	73.6	63.3	56.1	45.7
CT	14740	Hartford	25.0	14.0	48.6	32.4	73.4	61.0	52.0	41.0
DE	13781	Wilmington	30.7	20.7	52.2	37.8	76.1	64.6	56.1	45.7
FL	12834	Daytona Beach	57.0	48.4	69.3	57.6	79.9	71.8	73.0	64.0
FL	13889	Jacksonville	52.2	43.3	67.6	55.8	80.6	72.3	69.3	61.5
FL	12836	Key West	69.4	61.3	76.6	65.8	84.4	74.3	79.5	70.9
FL	12839	Miami	67.3	57.6	75.0	62.6	82.2	73.0	77.9	68.7
FL	93805	Tallahassee	50.2	41.2	66.6	54.3	79.5	72.1	67.6	57.7
FL	12842	Tampa	58.8	50.2	71.1	59.2	81.1	72.7	73.8	64.2
FL	12844	West Palm Beach	65.3	55.8	73.4	61.2	81.5	73.0	77.2	67.6
GA	13873	Athens	41.4	30.4	61.5	46.9	78.3	68.7	61.5	50.9
GA	13874	Atlanta	40.6	29.3	61.3	45.9	77.5	67.8	61.5	49.6
GA	3820	Augusta	43.3	32.7	62.6	48.4	79.5	69.3	62.4	52.2
GA	93842	Columbus	45.3	35.1	64.8	50.5	80.4	70.5	65.1	54.0
GA	3813	Macon	45.1	34.5	64.4	50.4	80.1	70.0	64.2	53.2
GA	3822	Savannah	48.0	37.2	65.5	51.8	80.4	71.2	66.6	56.5
HI	21504	Hilo	70.9	62.8	71.8	65.1	75.2	68.2	74.8	68.0
HI	22521	Honolulu	72.3	63.0	74.8	63.0	79.3	66.0	78.6	66.7
HI	22516	Kahului	72.0	63.0	74.3	63.7	78.6	66.6	77.7	66.7
HI	22536	Lihue	71.2	63.1	73.6	64.9	78.3	69.1	77.2	68.9
IA	14933	Des Moines	19.6	11.3	50.7	37.0	76.3	63.9	53.1	41.2
IA	14940	Mason City	13.5	6.6	46.0	34.9	72.7	62.4	48.9	39.0
IA	14943	Sioux City	17.8	9.9	50.2	35.4	75.6	63.9	51.4	39.0
IA	94910	Waterloo	15.1	7.9	47.7	35.4	73.2	62.8	49.8	39.4
ID	24131	Boise	28.9	21.6	49.3	30.2	74.7	43.2	51.3	32.7

TABLE 1b—Mean monthly dry-bulb and dew-point temperatures (°F) over 30 Years (1961-1990) for United States locations. (*continued*)

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
ID	24156	Pocatello	23.4	16.3	45.1	26.8	71.2	43.2	47.7	29.1
IL	94846	Chicago	21.6	13.6	48.6	36.0	73.6	61.7	52.9	41.7
IL	14923	Moline	20.3	11.8	50.5	37.4	75.4	64.0	52.9	41.5
IL	14842	Peoria	21.7	14.5	51.3	38.5	75.0	64.4	53.2	42.6
IL	94822	Rockford	18.7	12.0	48.0	35.8	73.6	62.4	51.3	41.4
IL	93822	Springfield	24.4	17.1	53.4	40.6	76.6	65.3	55.4	43.9
IN	93817	Evansville	30.4	21.7	56.7	43.5	77.9	66.7	56.7	45.5
IN	14827	Fort Wayne	23.2	16.3	49.3	37.2	73.6	61.9	52.3	42.4
IN	93819	Indianapolis	25.5	18.3	52.3	39.9	75.2	64.9	54.1	44.1
IN	14848	South Bend	23.5	17.1	48.7	36.7	73.0	61.7	52.5	43.0
KS	13985	Dodge City	28.8	17.2	54.1	36.7	79.9	60.1	56.5	39.4
KS	23065	Goodland	27.0	15.6	49.3	32.4	75.4	56.8	51.6	34.0
KS	13996	Topeka	26.6	17.2	55.2	41.7	78.6	66.7	56.5	44.4
KS	3928	Wichita	29.1	19.8	56.5	42.4	81.3	63.7	58.3	45.0
KY	93814	Covington	28.2	19.9	53.4	39.6	75.0	64.2	54.9	43.9
KY	93820	Lexington	30.7	22.6	54.9	41.0	75.4	64.8	56.3	45.1
KY	93821	Louisville	31.8	22.1	56.7	41.9	77.4	66.2	57.4	46.2
LA	13970	Baton Rouge	49.3	40.5	67.8	56.8	80.8	72.1	67.5	57.0
LA	3937	Lake Charles	49.8	42.6	67.8	59.0	81.0	73.6	68.2	58.8
LA	12916	New Orleans	51.4	43.2	68.9	59.2	81.0	73.6	68.9	59.7
LA	13957	Shreveport	44.8	35.2	65.5	54.0	81.7	70.9	65.7	54.9
MA	14739	Boston	28.8	16.5	47.5	33.6	73.0	61.0	54.0	42.8
MA	94746	Worchester	23.0	12.6	44.4	29.7	69.6	58.6	49.8	39.2
MD	93721	Baltimore	31.8	19.9	53.6	37.8	76.6	64.6	56.5	45.7
ME	14607	Caribou	10.6	3.4	37.9	27.0	65.7	56.3	43.2	35.6
ME	14764	Portland	21.6	11.8	43.0	31.1	68.4	59.2	48.7	39.7
MI	94849	Alpena	19.0	12.4	41.4	29.3	67.8	56.5	46.9	38.7
MI	94847	Detroit	23.4	16.2	47.1	35.1	72.3	60.4	51.1	41.4
MI	14826	Flint	22.1	15.3	46.0	34.0	71.1	59.4	50.2	41.2
MI	94860	Grand Rapids	22.5	16.3	46.2	34.3	71.8	60.1	50.2	41.5
MI	94814	Houghton	17.4	11.8	41.7	30.0	68.5	57.0	46.9	39.4
MI	14836	Lansing	21.7	16.0	46.0	34.5	71.4	60.4	49.8	41.5
MI	14840	Muskegon	23.2	17.2	45.3	33.1	70.5	59.7	50.7	42.1
MI	14847	Sault Ste. Marie	13.6	7.9	38.5	28.2	64.2	55.8	44.4	38.3
MI	14850	Traverse City	20.5	14.4	42.6	30.7	69.6	57.4	48.9	40.3
MN	14913	Duluth	7.9	0.7	38.5	25.7	65.8	55.0	43.5	34.0
MN	14918	International Falls	2.1	−5.3	39.2	25.3	66.9	56.1	42.3	33.8
MN	14920	La Crosse	15.1	7.7	47.5	34.2	73.0	62.4	50.0	39.9
MN	14922	Minneapolis	12.4	4.3	46.4	31.6	73.8	60.1	48.9	37.9
MN	14925	Rochester	12.0	6.1	44.8	33.6	70.7	60.4	47.7	37.9
MN	14926	Saint Cloud	8.8	2.3	43.5	30.6	71.1	59.5	46.0	36.5
MO	3945	Columbia	27.5	18.7	55.0	41.2	77.5	65.7	56.3	44.2
MO	3947	Kansas City	27.1	17.2	55.6	40.6	79.2	65.8	57.6	44.1
MO	13995	Springfield	30.9	20.8	56.1	43.0	77.4	66.0	57.2	45.3
MO	13994	St. Louis	28.8	20.3	56.3	42.3	79.2	66.6	57.7	46.0
MS	3940	Jackson	44.2	36.1	64.8	53.8	80.4	71.4	64.0	54.1
MS	13865	Meridian	44.1	35.2	64.0	52.3	79.3	70.5	63.0	53.1
MT	24033	Billings	22.6	10.0	45.1	26.8	72.1	47.3	48.6	29.8
MT	24137	Cut Bank	17.1	7.2	40.6	24.1	65.5	43.3	44.6	27.7
MT	94008	Glasgow	10.9	4.3	43.9	27.3	71.1	48.9	45.3	30.2
MT	24143	Great Falls	21.6	10.0	43.7	25.5	69.4	44.1	47.5	28.8
MT	24144	Helena	20.1	10.6	43.2	25.7	68.4	43.7	44.4	28.9
MT	24146	Kalispell	21.4	15.4	43.2	28.8	65.5	47.1	41.5	32.2
MT	24036	Lewistown	20.5	11.1	41.2	26.8	66.4	46.9	45.0	28.9
MT	24037	Miles City	15.6	8.1	45.9	29.5	75.0	50.2	47.5	32.2
MT	24153	Missoula	22.5	17.4	44.1	29.8	67.3	45.7	43.0	32.7
NC	3812	Asheville	34.9	25.5	54.9	41.4	72.0	64.9	54.7	46.6
NC	93729	Cape Hatteras	44.8	36.9	59.2	49.5	78.4	71.8	65.5	57.0
NC	13881	Charlotte	39.4	27.3	60.1	43.7	77.7	67.1	60.4	49.1
NC	13723	Greensboro	36.5	25.3	57.9	42.4	76.5	67.1	57.9	47.7
NC	13722	Raleigh	38.5	27.0	58.8	43.3	76.8	67.6	59.4	49.5
NC	13748	Wilmington	44.6	34.5	62.2	49.6	79.5	71.6	64.0	55.2
ND	24011	Bismarck	10.0	2.5	43.2	28.6	71.1	55.0	45.3	32.0
ND	14914	Fargo	6.3	−0.6	43.2	30.6	71.6	58.6	45.7	34.9
ND	24013	Minot	8.4	0.0	42.1	27.9	70.0	54.0	44.8	31.6
NE	14935	Grand Island	21.7	12.6	50.5	35.4	76.3	62.1	52.0	37.9
NE	14941	Norfolk	19.9	10.6	51.1	34.3	77.2	61.9	52.2	37.2
NE	24023	North Platte	21.2	11.8	48.2	32.2	74.1	58.8	49.3	34.2

TABLE 1b—Mean monthly dry-bulb and dew-point temperatures (°F) over 30 Years (1961-1990) for United States locations. (*continued*)

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
NE	94918	Omaha	21.4	12.9	52.2	37.2	77.2	64.8	53.4	41.4
NE	24028	Scottsbluff	24.4	12.9	46.9	29.3	73.6	54.1	48.6	30.7
NH	14745	Concord	19.9	10.6	44.4	30.0	70.0	59.2	48.0	38.5
NJ	93730	Atlantic City	31.3	21.9	50.5	38.1	74.7	64.8	55.4	46.6
NJ	14734	Newark	30.7	19.8	52.0	35.4	76.8	62.4	57.0	44.8
NM	23050	Albuquerque	33.6	18.0	55.6	21.4	77.4	49.1	56.7	32.5
NM	23048	Tucumcari	36.1	20.3	57.9	30.7	79.3	56.8	58.6	37.8
NV	24121	Elko	24.6	16.3	44.8	25.3	72.3	37.2	46.9	25.5
NV	23154	Ely	23.5	12.6	41.7	21.9	68.9	35.4	45.1	24.4
NV	23169	Las Vegas	44.6	22.1	64.8	24.1	91.0	40.6	67.5	30.4
NV	23185	Reno	31.8	21.4	48.4	25.5	72.1	39.7	50.5	29.8
NV	23153	Tonopah	30.6	17.6	48.9	20.1	75.9	32.7	52.7	23.5
NV	24128	Winnemucca	29.1	19.8	46.9	24.1	74.5	34.7	48.7	25.5
NY	14735	Albany	32.0	13.2	32.0	32.1	32.0	60.2	32.0	40.4
NY	4725	Binghamton	21.4	14.0	44.2	31.6	68.9	58.5	48.7	39.9
NY	14733	Buffalo	23.5	16.9	45.0	33.4	71.1	59.0	50.9	41.7
NY	94725	Massena	15.1	8.8	43.0	31.6	69.6	59.2	47.1	39.6
NY	94728	New York City	31.5	18.9	51.1	35.6	75.9	62.2	57.4	44.8
NY	14768	Rochester	23.9	16.5	45.9	34.2	71.4	59.9	50.9	42.3
NY	14771	Syracuse	22.8	15.4	45.9	33.3	71.1	59.9	50.5	41.7
OH	14895	Akron	25.0	17.4	48.6	35.2	71.8	60.6	52.2	41.7
OH	14820	Cleveland	25.2	17.4	47.8	35.8	72.1	61.0	52.7	42.6
OH	14821	Columbus	26.6	18.3	51.3	37.6	73.8	62.8	53.4	42.6
OH	93815	Dayton	26.1	18.1	51.3	38.1	74.3	62.4	53.6	42.6
OH	14891	Mansfield	24.6	18.0	48.7	36.3	72.5	61.3	52.5	42.1
OH	94830	Toledo	23.0	16.0	47.8	35.6	72.1	61.3	51.1	41.5
OH	14852	Youngstown	23.9	16.9	47.3	34.9	70.3	60.1	51.1	41.5
OK	13967	Oklahoma City	35.2	23.9	60.6	45.3	81.7	65.5	61.5	47.8
OK	13968	Tulsa	34.9	23.5	61.3	46.0	82.9	67.8	61.7	48.7
OR	94224	Astoria	42.1	36.9	47.8	41.4	59.7	53.2	52.7	47.3
OR	94185	Burns	25.5	19.8	43.7	26.4	69.3	39.7	46.6	29.8
OR	24221	Eugene	39.7	36.1	49.5	41.5	66.7	51.8	52.5	46.0
OR	24225	Medford	37.0	32.4	50.4	37.4	72.1	48.4	52.9	41.5
OR	24284	North Bend	45.0	39.6	49.3	42.4	59.0	52.5	54.0	48.4
OR	24155	Pendleton	33.4	26.4	50.2	34.3	73.6	42.4	51.8	36.1
OR	24229	Portland	39.6	33.6	50.7	40.8	67.3	52.9	54.1	46.4
OR	24230	Redmond	31.3	22.6	44.2	27.9	66.6	41.4	47.7	31.5
OR	24232	Salem	39.6	34.5	49.3	40.3	66.4	51.6	52.2	45.0
PA	14737	Allentown	26.8	17.4	49.8	34.9	73.9	61.9	53.2	43.3
PA	4751	Bradford	19.6	13.6	42.6	31.3	65.7	57.4	46.6	38.8
PA	14860	Erie	25.2	17.8	45.1	34.2	70.3	60.3	52.0	42.3
PA	14751	Harrisburg	28.8	17.6	51.6	36.1	75.4	63.1	54.3	44.1
PA	13739	Philadelphia	30.6	19.8	52.3	37.0	76.3	64.6	56.1	45.9
PA	94823	Pittsburgh	26.2	17.2	49.6	34.5	72.0	60.1	52.2	40.8
PA	14777	Wilkes-Barre	25.0	16.2	47.8	33.1	71.4	60.4	51.3	41.5
PA	14778	Williamsport	25.5	16.5	49.3	34.5	72.0	62.2	51.4	42.8
	41415	Guam	77.7	71.6	79.2	72.3	79.7	74.8	79.5	74.8
PR	11641	San Juan	76.5	67.3	78.6	68.2	82.0	73.4	81.0	72.7
RI	14765	Providence	28.0	16.5	47.7	33.3	72.7	61.5	53.1	42.6
SC	13880	Charleston	46.8	36.0	64.0	51.4	80.1	71.4	65.5	55.9
SC	13883	Columbia	43.2	32.2	63.1	47.5	79.5	69.3	62.4	52.0
SC	3870	Greenville	39.7	27.9	59.9	44.1	77.2	67.5	59.9	48.7
SD	14936	Huron	13.5	5.9	46.2	33.8	74.3	60.4	48.0	36.0
SD	24025	Pierre	16.9	8.6	46.8	31.8	75.9	57.6	49.5	34.2
SD	24090	Rapid City	22.1	10.9	45.3	29.1	72.5	53.8	48.6	30.4
SD	14944	Sioux Falls	14.4	6.6	46.9	33.8	74.5	60.8	48.6	36.9
TN	13877	Bristol	33.8	24.6	55.4	41.0	73.6	64.8	55.9	45.7
TN	13882	Chattanooga	37.2	27.9	59.5	45.3	77.7	68.2	59.2	49.6
TN	13891	Knoxville	36.7	27.7	58.8	44.6	76.5	67.3	58.5	48.7
TN	13893	Memphis	39.0	28.6	63.0	48.6	82.0	70.0	63.0	50.2
TN	13897	Nashville	36.1	26.6	59.4	45.1	78.4	68.0	59.9	48.4
TX	13962	Abilene	42.1	27.3	64.9	45.9	82.9	62.4	65.5	49.6
TX	23047	Amarillo	33.8	18.3	56.7	33.1	78.3	57.7	57.7	39.4
TX	13958	Austin	48.2	36.3	68.5	55.0	83.5	68.9	69.3	56.7
TX	12919	Brownsville	58.6	51.4	74.1	65.1	83.5	73.0	74.7	65.7
TX	12924	Corpus Christi	54.7	46.8	72.0	63.1	83.3	73.6	73.2	64.0
TX	23044	El Paso	43.3	23.4	64.8	25.3	82.2	54.9	63.7	39.7
TX	3927	Fort Worth	43.0	31.5	65.5	52.0	84.7	67.6	66.7	53.2

TABLE 1b—Mean monthly dry-bulb and dew-point temperatures (°F) over 30 Years (1961-1990) for United States locations. (*continued*)

			January		April		July		October	
State	WBAN	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
TX	12960	Houston	50.7	41.7	68.7	59.0	82.0	72.3	69.3	59.5
TX	23042	Lubbock	37.6	21.6	61.0	36.3	79.3	59.7	60.6	43.9
TX	93987	Lufkin	47.1	38.1	67.5	56.5	81.9	71.8	66.9	56.5
TX	23023	Midland	41.7	24.4	64.2	37.2	81.0	58.8	63.5	46.8
TX	12917	Port Arthur	50.5	43.3	68.5	60.3	81.5	74.5	69.1	60.4
TX	23034	San Angelo	44.1	29.3	66.6	46.2	82.8	62.4	65.7	52.0
TX	12921	San Antonio	49.3	37.0	69.3	55.8	83.5	69.1	70.0	57.0
TX	12912	Victoria	52.5	44.1	70.5	60.4	82.9	72.7	71.2	61.3
TX	13959	Waco	44.8	34.7	66.9	54.3	84.9	68.2	68.2	55.6
TX	13966	Wichita Falls	38.8	27.0	63.3	48.0	84.6	64.9	64.0	50.5
UT	93129	Cedar City	28.9	18.0	47.8	24.4	74.7	40.8	51.4	28.8
UT	24127	Salt Lake City	27.9	19.9	49.8	30.9	78.1	45.5	52.2	34.5
VA	13733	Lynchburg	35.1	21.7	57.0	39.0	76.1	65.1	57.6	45.5
VA	13737	Norfolk	39.2	27.9	57.4	43.2	78.1	68.2	61.3	51.4
VA	13740	Richmond	35.8	25.0	57.4	41.7	77.4	67.6	58.3	48.6
VA	13741	Roanoke	34.3	21.0	55.9	38.5	75.2	64.0	56.5	44.8
VA	93738	Sterling	30.9	20.7	53.2	38.7	75.6	64.9	55.0	45.1
VT	14742	Burlington	17.4	8.2	43.2	30.4	70.0	58.3	48.0	38.8
WA	24227	Olympia	38.1	34.5	47.7	39.0	63.0	52.2	49.6	44.8
WA	94240	Quillayute	40.6	36.9	46.2	40.3	57.9	52.0	50.4	46.0
WA	24233	Seattle	40.1	33.1	48.7	38.8	64.4	51.4	52.2	45.1
WA	24157	Spokane	27.0	22.1	46.0	31.8	69.4	43.7	46.8	34.9
WA	24243	Yakima	29.5	23.2	50.2	30.9	71.4	46.2	48.7	35.2
WI	14991	Eau Claire	11.5	4.6	45.5	32.0	72.0	60.3	47.8	38.1
WI	14898	Green Bay	15.1	8.2	43.9	32.5	70.3	59.7	48.0	39.6
WI	14837	Madison	16.7	9.9	46.0	34.0	71.8	60.8	49.3	39.9
WI	14839	Milwaukee	19.4	11.8	44.6	33.8	71.2	60.6	50.7	41.4
WV	13866	Charleston	32.2	22.5	55.2	38.7	73.9	64.9	55.2	45.1
WV	13729	Elkins	27.7	19.8	48.7	36.9	68.2	61.7	49.6	41.4
WV	3860	Huntington	32.4	22.6	55.6	39.6	74.7	65.7	55.9	45.3
WY	24089	Casper	23.0	12.0	42.4	25.9	70.9	43.9	45.9	26.8
WY	24018	Cheyenne	27.0	10.2	42.4	24.3	68.2	46.4	46.4	25.5
WY	24021	Lander	19.0	8.2	43.2	24.1	71.1	42.3	46.0	27.0
WY	24027	Rock Springs	20.3	12.4	40.5	22.8	68.4	37.6	43.9	24.8
WY	24029	Sheridan	21.0	10.9	44.2	28.2	70.5	48.2	46.4	29.8

Source: Colliver, D. G. 1999. Mean monthly dry-bulb and dew-point temperatures determined from the Samson data set. Biosystems and Agricultural Engineering, University of Kentucky, Lexington.

emerging that 10% is the appropriate level of severity, meaning that one out of ten years will be as severe or more severe than the MDRY weather conditions [*8*]. Creation of a MDRY involves analyzing moisture accumulation in a number of selected building components, using a computer model and historical weather data, and selecting the design weather year based on the results. This means that the choice of MDRY may depend on the construction selected. Moreover, to this date, methodologies for creating MDRY data have focused on cold climates, and no methodology as yet exists to create a MDRY for warm or mixed climates. The procedure to select the MDRY needs to be simplified and generalized so it applies to all building types and climates. Better yet, specific MDRY data sets for locations in the U.S., Canada, and elsewhere should be developed and made available. In the interim, because such MDRY data are not yet available, using a sequence of 10 years of actual weather data is a reasonable alternative.

Some moisture analysis methods allow the use of time-averaged weather data. Kuenzel determined that, when analyzing the drying of a cellular concrete roof, using time-averaged data led to errors [*9*]. Hourly weather data produced more accurate results than time-averaged weather data, and the error was not affected very much by the choice of averaging period, for example, daily, monthly, or six-month means. This indicates that accurate results can most likely only be obtained with hourly data. If average data are used, the averaging period is probably not very important. If use of hourly data is not feasible, or hourly data are not available, approximate moisture accumulation calculations may be done using daily or monthly average weather data, but large errors may occur with such calculations.

The following tables provide monthly average dry-bulb and dew-point temperatures for the months of January, April, July, and October for use in simplified approximate moisture calculations, such as dew point calculations (see Chapter 7). The data represent weather conditions during the four seasons and can be used to estimate whether drying or wetting of the assembly is likely to occur. Table 1 contains locations in the United States. The data in Table 1 are based on hourly or 3-h measured data for the period 1961 to 1990 and were determined from the SAMSON data set [*10*]. Table 2 contains locations in Canada, based on 1973 to 1993 data. Table 3 contains data for a few selected international locations. More information on climate for U.S. and international locations can be found on the Word Wide Web at the NCDC web site (www.ncdc.noaa.gov). Canadian weather data can be found at the Environment Canada's Canadian Meteorological Centre web site (www.cmc.ec.gc.ca/climate).

TABLE 2a—Mean monthly dry-bulb and dew-point temperatures (°C) for Canadian locations.

		January		April		July		October	
Province	Location	DB	DP	DB	DP	DB	DP	DB	DP
Alberta	Calgary	−7.2	−13.9	5.0	−4.4	16.7	7.8	6.1	−2.8
	Edmonton	−11.7	−16.1	4.4	−3.3	16.1	10.6	4.4	−1.7
	Grande Prairie	−15.8	−16.7	2.5	−2.2	15.8	9.4	4.2	0.0
	Lethbridge	−8.9	−11.7	5.6	−1.1	17.8	10.0	6.4	1.1
	Medicine Hat	−11.1	−13.3	7.2	0.0	20.8	11.1	7.5	1.7
	Peace River	−15.3	−16.7	3.3	−4.4	16.7	8.9	4.2	0.0
	Red Deer	−12.2	−13.3	3.3	−1.7	15.8	11.7	4.7	0.0
BC	Fort Nelson	−21.7	−22.2	2.2	−5.0	16.9	10.6	1.1	−1.7
	Penticton	−3.1	−6.7	8.9	1.1	20.3	11.1	9.2	4.4
	Prince George	−10.6	−11.7	4.7	−1.7	15.3	9.4	5.0	1.1
	Prince Rupert	1.4	−0.6	6.4	2.8	13.1	11.1	8.6	6.7
	Quesnel	−9.7	−15.0	5.8	−0.6	16.7	10.6	5.8	1.1
	Smithers	−9.4	−9.4	5.0	−0.6	15.0	9.4	4.7	1.7
	Vancouver	3.3	0.6	9.4	5.0	17.2	12.2	10.6	7.8
	Victoria	3.9	1.7	8.9	4.4	16.1	11.1	10.0	6.7
Manitoba	Brandon	−19.2	−18.3	3.3	−2.2	18.6	13.3	4.4	0.6
	Churchill	−25.0	−30.0	−9.4	−12.8	12.2	7.2	−1.7	−4.4
	Dauphin	−17.8	−17.8	3.3	−3.3	19.4	14.4	5.3	2.8
	The Pas	−22.5	−23.3	0.6	−5.6	18.1	12.8	1.9	0.6
	Winnipeg	−16.7	−18.9	4.4	−2.8	20.0	13.9	5.6	0.0
New Brunswick	Fredericton	−10.3	−12.8	3.9	−0.6	18.9	15.6	7.5	4.4
	Moncton	−8.9	−10.6	3.3	−1.1	18.6	14.4	7.8	4.4
	Saint John	−7.8	−12.2	3.9	−1.7	17.2	12.8	7.8	3.9
Newfoundland	Cartwright	−14.4	−16.1	−2.8	−4.4	13.1	10.0	3.3	1.7
	St. John's	−4.4	−7.2	1.7	−1.7	15.6	11.7	7.2	3.9
Northwest Territories	Fort Smith	−25.3	−22.8	−3.3	−5.0	16.1	10.6	−0.3	0.6
	Iqualuit (Frobisher)	−25.6	−30.6	−15.0	−18.3	7.8	3.3	−5.0	−7.8
	Inuvik	−26.1	−29.4	−12.8	−17.8	13.9	6.7	−8.3	−11.1
	Resolute	−30.6	−35.6	−22.2	−26.7	4.4	1.7	−15.0	−17.2
	Yellowknife	−25.0	−29.4	−5.0	−11.7	16.7	7.8	−1.7	−5.0
Nova Scotia	Halifax	−5.6	−9.4	4.4	−0.6	18.3	13.3	8.3	5.0
	Sydney	−5.6	−8.9	2.2	−1.7	17.2	13.3	8.3	4.4
	Yarmouth	−2.8	−5.6	5.0	1.1	16.1	13.9	9.4	6.1
Ontario	Kapuskasing	−18.9	−19.4	−0.6	−3.9	16.9	11.7	3.9	1.7
	Kenora	−17.8	−16.7	2.2	−2.8	19.4	13.9	4.7	2.0
	London	−5.6	−6.7	6.4	1.7	20.8	16.1	9.2	6.7
	North Bay	−12.2	−16.1	3.9	−3.3	18.9	12.8	6.1	1.7
	Ottawa	−10.0	−14.4	6.1	−1.7	21.1	13.9	7.8	2.8
	Toronto	−6.1	−8.9	6.7	0.6	21.1	14.4	8.9	4.4
	Wiarton	−5.8	−7.2	5.0	0.6	18.6	14.4	9.7	6.1
Prince Edward Island	Charlottetown	−7.8	−10.0	2.5	−0.6	18.6	15.6	8.6	5.6
	Summerside	−8.1	−7.2	2.5	0.0	18.6	13.9	8.3	5.0
Quebec	Baie Comeau	−14.4	−12.8	0.8	−2.2	16.4	13.3	5.0	2.8
	Mont Joli	−11.1	−12.8	1.7	−2.2	18.1	13.3	6.4	2.8
	Quebec	−12.2	−16.7	3.9	−2.8	19.4	13.9	6.7	1.1
	Riviere Du Loup	−11.1	−12.8	1.7	−2.2	18.1	13.3	6.4	2.8
	Sherbrooke	−10.0	−12.2	4.4	−0.6	19.7	15.6	7.5	4.4
	Val d'Or	−16.7	−17.8	1.4	−3.9	17.2	11.1	5.6	0.6
Saskatchewan	Estevan	−16.1	−15.0	3.9	−1.1	19.4	13.9	5.8	1.7
	Moose Jaw	−15.6	−15.6	4.2	−0.6	18.9	12.2	4.4	1.7
	North Battleford	−18.3	−21.1	3.9	−2.2	18.3	12.2	4.7	−1.1
	Prince Albert	−20.3	−18.9	2.5	−2.8	17.5	12.8	3.6	0.6
	Regina	−18.1	−16.1	3.3	−1.7	18.3	12.2	4.2	0.0
	Saskatoon	−18.3	−18.3	3.1	−2.2	18.1	11.1	3.9	0.0
	Swift Current	−13.6	−14.4	5.3	−0.6	19.2	11.7	5.8	1.1
	Yorkton	−20.0	−18.3	1.9	−2.2	18.3	12.8	3.9	0.6
Yukon Territory	Whitehorse	−15.0	−13.9	−0.3	−6.1	13.3	6.7	1.4	−1.7

Source: NCDC. 1995. International Station Meteorological Climate Summary Ver 3.0. Fleet Numerical Meteorology and Oceanography Detachment, USAFETAC OL-A, National Climatic Data Center. Ashville, NC.

TABLE 2b—Mean monthly dry-bulb and dew-point temperatures (°F) for Canadian locations.

		January		April		July		October	
Province	Location	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP	Mean DB	Mean DP
Alberta	Calgary	19.0	7.0	41.0	24.0	62.0	46.0	43.0	27.0
	Edmonton	11.0	3.0	40.0	26.0	61.0	51.0	40.0	29.0
	Grande Prairie	3.5	2.0	36.5	28.0	60.5	49.0	39.5	32.0
	Lethbridge	16.0	11.0	42.0	30.0	64.0	50.0	43.5	34.0
	Medicine Hat	12.0	8.0	45.0	32.0	69.5	52.0	45.5	35.0
	Peace River	4.5	2.0	38.0	24.0	62.0	48.0	39.5	32.0
	Red Deer	10.0	8.0	38.0	29.0	60.5	53.0	40.5	32.0
BC	Fort Nelson	−7.0	−8.0	36.0	23.0	62.5	51.0	34.0	29.0
	Penticton	26.5	20.0	48.0	34.0	68.5	52.0	48.5	40.0
	Prince George	13.0	11.0	40.5	29.0	59.5	49.0	41.0	34.0
	Prince Rupert	34.5	31.0	43.5	37.0	55.5	52.0	47.5	44.0
	Quesnel	14.5	5.0	42.5	31.0	62.0	51.0	42.5	34.0
	Smithers	15.0	15.0	41.0	31.0	59.0	49.0	40.5	35.0
	Vancouver	38.0	33.0	49.0	41.0	63.0	54.0	51.0	46.0
	Victoria	39.0	35.0	48.0	40.0	61.0	52.0	50.0	44.0
Manitoba	Brandon	−2.5	−1.0	38.0	28.0	65.5	56.0	40.0	33.0
	Churchill	−13.0	−22.0	15.0	9.0	54.0	45.0	29.0	24.0
	Dauphin	0.0	0.0	38.0	26.0	67.0	58.0	41.5	37.0
	The Pas	−8.5	−10.0	33.0	22.0	64.5	55.0	35.5	33.0
	Winnipeg	2.0	−2.0	40.0	27.0	68.0	57.0	42.0	32.0
New Brunswick	Fredericton	13.5	9.0	39.0	31.0	66.0	60.0	45.5	40.0
	Moncton	16.0	13.0	38.0	30.0	65.5	58.0	46.0	40.0
	Saint John	18.0	10.0	39.0	29.0	63.0	55.0	46.0	39.0
Newfoundland	Cartwright	6.0	3.0	27.0	24.0	55.5	50.0	38.0	35.0
	St. John's	24.0	19.0	35.0	29.0	60.0	53.0	45.0	39.0
Northwest Territories	Fort Smith	−13.5	−9.0	26.0	23.0	61.0	51.0	31.5	33.0
	Iqualuit (Frobisher)	−14.0	−23.0	5.0	−1.0	46.0	38.0	23.0	18.0
	Inuvik	−15.0	−21.0	9.0	0.0	57.0	44.0	17.0	12.0
	Resolute	−23.0	−32.0	−8.0	−16.0	40.0	35.0	5.0	1.0
	Yellowknife	−13.0	−21.0	23.0	11.0	62.0	46.0	29.0	23.0
Nova Scotia	Halifax	22.0	15.0	40.0	31.0	65.0	56.0	47.0	41.0
	Sydney	22.0	16.0	36.0	29.0	63.0	56.0	47.0	40.0
	Yarmouth	27.0	22.0	41.0	34.0	61.0	57.0	49.0	43.0
Ontario	Kapuskasing	−2.0	−3.0	31.0	25.0	62.5	53.0	39.0	35.0
	Kenora	0.0	2.0	36.0	27.0	67.0	57.0	40.5	36.0
	London	22.0	20.0	43.5	35.0	69.5	61.0	48.5	44.0
	North Bay	10.0	3.0	39.0	26.0	66.0	55.0	43.0	35.0
	Ottawa	14.0	6.0	43.0	29.0	70.0	57.0	46.0	37.0
	Toronto	21.0	16.0	44.0	33.0	70.0	58.0	48.0	40.0
	Wiarton	21.5	19.0	41.0	33.0	65.5	58.0	49.5	43.0
Prince Edward Island	Charlottetown	18.0	14.0	36.5	31.0	65.5	60.0	47.5	42.0
	Summerside	17.5	19.0	36.5	32.0	65.5	57.0	47.0	41.0
Quebec	Baie Comeau	6.0	9.0	33.5	28.0	61.5	56.0	41.0	37.0
	Mont Joli	12.0	9.0	35.0	28.0	64.5	56.0	43.5	37.0
	Quebec	10.0	2.0	39.0	27.0	67.0	57.0	44.0	34.0
	Riviere Du Loup	12.0	9.0	35.0	28.0	64.5	56.0	43.5	37.0
	Sherbrooke	14.0	10.0	40.0	31.0	67.5	60.0	45.5	40.0
	Val d'Or	2.0	0.0	34.5	25.0	63.0	52.0	42.0	33.0
Saskatchewan	Estevan	3.0	5.0	39.0	30.0	67.0	57.0	42.5	35.0
	Moose Jaw	4.0	4.0	39.5	31.0	66.0	54.0	40.0	35.0
	North Battleford	−1.0	−6.0	39.0	28.0	65.0	54.0	40.5	30.0
	Prince Albert	−4.5	−2.0	36.5	27.0	63.5	55.0	38.5	33.0
	Regina	−0.5	3.0	38.0	29.0	65.0	54.0	39.5	32.0
	Saskatoon	−1.0	−1.0	37.5	28.0	64.5	52.0	39.0	32.0
	Swift Current	7.5	6.0	41.5	31.0	66.5	53.0	42.5	34.0
	Yorkton	−4.0	−1.0	35.5	28.0	65.0	55.0	39.0	33.0
Yukon Territory	Whitehorse	5.0	7.0	31.5	21.0	56.0	44.0	34.5	29.0

Source: NCDC. 1995. International Station Meteorological Climate Summary Ver 3.0. Fleet Numerical Meteorology and Oceanography Detachment, USAFETAC 0L-A, National Climatic Data Center. Ashville, NC.

TABLE 3a—Mean monthly dry-bulb and dew-point temperatures (°C) for international locations.

Country	Location	January Mean DB	January Mean DP	April Mean DB	April Mean DP	July Mean DB	July Mean DP	October Mean DB	October Mean DP
Argentina	Buenos Aires	23.9	16.1	16.7	12.2	10.0	6.1	16.1	10.6
Australia	Sydney AP	22.8	16.7	18.9	13.3	12.2	5.6	17.8	10.6
Austria	Vienna	0.0	−3.3	9.4	2.2	20.0	11.7	10.6	5.6
Belgium	Brussels	3.3	1.1	8.9	3.9	17.8	12.8	11.1	7.8
Brazil	Rio de Janeiro/Galeao	28.3	21.7	26.1	20.6	22.2	16.7	24.4	18.3
Bulgaria	Sofia	−1.1	−5.0	10.0	2.8	20.0	11.7	11.7	5.0
Chili	Santiago	21.1	11.1	15.0	8.3	8.3	5.0	14.4	8.3
China	Beijing	−3.3	−16.1	13.9	0.6	26.1	20.6	13.9	4.4
Finland	Helsinki/Vantaa	−5.6	−7.8	3.3	−1.7	16.7	11.1	5.0	2.8
France	Paris/Orly	3.9	1.1	10.0	3.9	19.4	12.8	11.7	8.3
Germany	Berlin/Schonefeld	−0.6	−2.8	7.8	1.7	18.3	11.7	9.4	6.1
Greece	Athens	10.0	3.9	15.0	8.3	27.2	14.4	19.4	11.7
Hungary	Budapest/Ferihegy	−0.6	−3.9	10.6	3.3	20.6	12.8	10.6	5.6
Ireland	Dublin AP	5.6	2.8	8.3	4.4	15.6	11.7	10.6	7.2
Italy	Rome/Fiumicino	8.3	4.4	12.8	8.9	23.9	19.4	17.8	13.3
Japan	Tokyo Intl	5.6	−3.9	13.9	7.8	25.0	21.1	17.8	12.2
Malaysia	Kuala Lumpur	27.2	22.8	28.3	23.9	27.8	23.3	27.8	23.3
Mexico	Mexico City	13.9	3.9	18.9	6.1	18.3	11.1	17.2	8.9
New Zealand	Auckland Intl AP	20.0	14.4	16.1	12.8	11.1	8.3	14.4	10.6
Poland	Warsaw	−1.7	−3.9	7.8	2.2	17.8	12.8	8.3	5.6
Russia	Moscow/Sheremetievo	−8.9	−11.1	5.6	−0.6	17.2	12.2	3.9	1.1
South Africa	Pretoria	23.3	14.4	18.9	10.0	12.8	1.7	21.1	9.4
South Korea	Seoul/Kimpo	−3.3	−9.4	11.7	4.4	25.0	20.6	13.3	7.8
Spain	Madrid	5.6	1.1	11.7	4.4	24.4	11.1	14.4	7.8
Sweden	Stockholm/Essa	−2.8	−5.0	3.9	−1.1	17.2	10.6	6.1	3.9
United Kingdom	London/Heathrow	5.0	2.8	8.9	3.9	18.3	12.2	11.1	8.3
Ukraine	Kiev	−6.1	−8.3	7.8	2.2	18.3	12.8	7.2	3.3
Venezuela	Caracas/La Carlotas	21.1	16.1	23.9	18.3	23.3	18.9	23.3	18.9

Source: NCDC. 1995. International Station Meteorological Climate Summary Ver 3.0. Fleet Numerical Meteorology and Oceanography Detachment, USAFETAC 0L-A, National Climatic Data Center. Ashville, NC.

TABLE 3b—Mean monthly dry-bulb and dew-point temperatures (°F) for international locations.

Country	Location	January Mean DB	January Mean DP	April Mean DB	April Mean DP	July Mean DB	July Mean DP	October Mean DB	October Mean DP
Argentina	Buenos Aires	75	61	62	54	50	43	61	51
Australia	Sydney AP	73	62	66	56	54	42	64	51
Austria	Vienna	32	26	49	36	68	53	51	42
Belgium	Brussels	38	34	48	39	64	55	52	46
Brazil	Rio de Janeiro/Galeao	83	71	79	69	72	62	76	65
Bulgaria	Sofia	30	23	50	37	68	53	53	41
Chili	Santiago	70	52	59	47	47	41	58	47
China	Beijing	26	3	57	33	79	69	57	40
Finland	Helsinki/Vantaa	22	18	38	29	62	52	41	37
France	Paris/Orly	39	34	50	39	67	55	53	47
Germany	Berlin/Schonefeld	31	27	46	35	65	53	49	43
Greece	Athens	50	39	59	47	81	58	67	53
Hungary	Budapest/Ferihegy	31	25	51	38	69	55	51	42
Ireland	Dublin AP	42	37	47	40	60	53	51	45
Italy	Rome/Fiumicino	47	40	55	48	75	67	64	56
Japan	Tokyo Intl	42	25	57	46	77	70	64	54
Malaysia	Kuala Lumpur	81	73	83	75	82	74	82	74
Mexico	Mexico City	57	39	66	43	65	52	63	48
New Zealand	Auckland Intl AP	68	58	61	55	52	47	58	51
Poland	Warsaw	29	25	46	36	64	55	47	42
Russia	Moscow/Sheremetievo	16	12	42	31	63	54	39	34
South Africa	Pretoria	74	58	66	50	55	35	70	49
South Korea	Seoul/Kimpo	26	15	53	40	77	69	56	46
Spain	Madrid	42	34	53	40	76	52	58	46
Sweden	Stockholm/Essa	27	23	39	30	63	51	43	39
United Kingdom	London/Heathrow	41	37	48	39	65	54	52	47
Ukraine	Kiev	21	17	46	36	65	55	45	38
Venezuela	Caracas/La Carlotas	70	61	75	65	74	66	74	66

Source: NCDC. 1995. International Station Meteorological Climate Summary Ver 3.0. Fleet Numerical Meteorology and Oceanography Detachment, USAFETAC 0L-A, National Climatic Data Center. Ashville, NC.

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3

Hygrothermal Properties of Building Materials

by M. K. Kumaran [1]

THE ENVELOPE OF ANY BUILDING continuously responds to the changes in indoor and outdoor temperature, pressure, and humidity conditions. This results in an exchange of energy and mass (air as well as moisture) between the indoor and outdoor environments through the envelope. Building physicists refer to this phenomenon as "heat, air, and moisture transport" through building materials and components. Designers and builders are always interested in knowing the long-term performance of the building envelope, as subjected to the transport processes. But the global differences in construction practices, building materials, weather conditions, and indoor climate are so large that it is impractical to develop this knowledge only through experimental investigations. However, such knowledge, as and when required, can be generated through calculations. Building physicists, over the past four or five decades, have been attempting to develop reliable calculation methods for this purpose. These attempts, especially with the advance in computer technology, have resulted in a diverse set of procedures and computer models [*1*]. All such procedures, in spite of any diversity, make use of the following two axioms:

1. The transport of any entity B through a medium is given by the expression

   Rate of transport of B = A property of the medium x, a driving force responsible for the transport
2. During the transport of B, in any given volume, V, of the medium, the following balance exists:

Rate of storage of B in V = Rate of B entering V through its bounding surfaces + rate of generation of B in V

The first axiom gives rise to a variety of equations used in calculations, and these equations are called transport equations. They are usually of the form

$$\dot{J}_B = \kappa \cdot \text{grad}\,\Phi \tag{1}$$

which introduces three types of physical quantities in all calculations. The quantity $\dot{J}_B$ is referred to as a "flux of B" or a "density of B flow rate" and the quantity κ as a transport property of the medium. The driving potential is defined as the gradient of an appropriate physical quantity Φ.

The second axiom, when used in calculations, introduces another set of equations called the "conservation equations." These equations, in turn, also introduce new physical quantities. The term on the left-hand side of the balance equation results in physical quantities that define the storage of B in the medium. These are referred to as "capacitive" properties [*2*]. The first term on the right hand side of the balance equation, though only a divergent of J_B, often may result in a set of derived physical quantities defined in terms of a transport property and a capacitive property. These properties are referred to as combined properties [*2*].

Building materials continually evolve. The main consequence is a noticeable change in the properties of these materials. Hence, the properties reported in the literature may have become "nonrepresentative" of contemporary products. This demands continuous updating of the hygrothermal properties. Otherwise, however, sophisticated the calculation method that one employs may be, the results will not be representative of the hygrothermal behavior of the building component under consideration.

DEFINITIONS, SYMBOLS, AND UNITS OF HYGROTHERMAL PROPERTIES

Density of heat flow rate or *heat flux* (symbol: $\dot{q}$; unit: W · m^{-2})
The density of heat flow rate in a material at a point is expressed as the quantity of heat transported in unit time across the unit area of a plane that includes the point and is perpendicular to the direction of the transport.

Density of vapor flow rate or *vapor flux* (symbol: $\dot{m}_V$; unit: kg · m^{-2} · s^{-1})
The density of vapor flow rate in a material at a point is defined as the mass of vapor transported in unit time across the unit area of a plane that includes the point and is perpendicular to the direction of the transport.

Density of moisture flow rate or *moisture flux* (symbol: $\dot{m}_m$; unit: kg · m^{-2} · s^{-1})
The density of moisture flow rate in a material at a point is defined as the mass of moisture transported in unit time across the unit area of a plane that includes the point and is perpendicular to the direction of the transport.

Density of air flow rate or *air flux* (symbol: $\dot{m}_a$; unit: kg · m^{-2} · s^{-1})
The density of airflow rate in a material at a point is defined as the mass of air transported in unit time across the unit area of a plane that includes the point and is perpendicular to the direction of the transport.

Density (symbol: ρ_0; unit: kg · m^{-3})
Density of a building material is defined as the mass of 1 m^3 of the dry material.

[1] Building Envelope and Structure, Institute for Research in Construction, National Research Council, Canada.

For practical reasons, the phrase "dry material" does not necessarily mean absolutely dry material. For each class of material, such as stony, wooden, or plastic, it may be necessary to adopt prescribed standard conditions; for example, for wood this may correspond to drying at 105°C until the change in mass is within 1% during two successive daily weighings.

Moisture content (symbol (i); w; unit: $kg \cdot m^{-3}$) or (symbol (ii): u; unit: $kg \cdot kg^{-1}$) or (symbol (iii): ψ; unit: $m^3 \cdot m^{-3}$)

Moisture content of a building material is defined as:

(i) mass of moisture per unit volume of the dry material, or
(ii) mass of moisture per unit mass of the dry material, or
(iii) volume of condensed moisture per unit volume of the dry material.

The definition (i) is generally used with reference to all building materials, while it is a common practice to use (ii) with reference to denser building materials such as concrete, brick, and wood products and to use (iii) with reference to lighter materials such as insulation.

Many building materials are porous bodies. In these porous bodies the moisture content may vary between the dry state referred to above and a fully saturated state when the open pores are completely filled with water. The moisture content that corresponds to the saturation state is called the *maximum moisture content* (symbols: w_{max} or u_{max} or ψ_{max}). Experimentally, a building material absorbs moisture to the maximum moisture content level if the process is carried out in vacuum. Otherwise, the saturation is complete at a lower moisture content level. This moisture content is referred to as *capillary saturation moisture content* (symbols: w_{cap} or u_{cap} or ψ_{cap}). Between the dry and saturated states, the moisture content varies with the water vapor pressure of the surroundings in a non-linear way. An example is shown in Fig. 1. The relation between vapor pressure (or more often relative humidity, RH) of the surroundings and the moisture content in the material is called the *sorption curve*. In the lower humidity range, the moisture is in an adsorbed state. This range varies from material to material, and for certain materials could be up to 98% RH. The range of RH until 98% is called the *hygroscopic range* of a material. At the higher end of the adsorption range, moisture from the surroundings begins to condense in the pores, but initially without any continuity of the liquid at a macroscopic level. This continues until a *critical moisture content* (symbols: w_{cr} or u_{cr} or ψ_{cr}) is established. Thus, critical moisture content can be defined as the lowest moisture content necessary to initiate moisture transport in the liquid phase. Below this level, due to macroscopic discontinuity of the liquid, moisture is transported only in the vapor phase (and partly by surface movement in the adsorbed layer).

Degree of saturation (Symbol: S; unit: dimensionless)
The degree of saturation of a material at a given moisture content is defined as the ratio between that moisture content and the maximum moisture content that can be attained by the material.

Specific heat capacity (Symbol: c_0; unit: $J \cdot kg^{-1} \cdot K^{-1}$)
Specific heat capacity of a material is defined as the heat (energy) required to increase the temperature of unit mass of the material by 1 K.

The mass in the above definition refers to dry mass. If the material is wet, the specific heat capacity c is to be calculated as:

$$c = c_0 + 4187 \cdot (w/\rho_0) \tag{2}$$

The above relation assumes that the specific heat capacity of water is a constant equal to 4187 $J \cdot kg^{-1} \cdot K^{-1}$.

Volumetric heat capacity (Symbol: $\rho_0 c_0$; unit: $J \cdot m^{-3} \cdot K^{-1}$)
The volumetric heat capacity of a material is defined as the heat (energy) required to increase the temperature of unit volume of the material by 1 K.

If the material is wet, the volumetric heat capacity $\rho_0 c$ is calculated as:

$$\rho_0 c = \rho_0 c_0 + 4187 \cdot w \tag{3}$$

Equation 3 also assumes that the heat capacity of water is constant at 4187 $J \cdot kg^{-1} \cdot K^{-1}$.

Thermal conductivity (Symbol: λ; unit: $W \cdot m^{-1} \cdot K^{-1}$)
The thermal conductivity of a material at a point is defined as the ratio between the density of heat flow rate and the magnitude of the thermal gradient at that point in the direction of the flow.

The definition for thermal conductivity stems from Fourier equation for heat conduction:

$$\dot{q} = -\lambda \cdot \text{grad } T \tag{4}$$

But in a dry building material the heat transfer is a result of conduction, radiation from the surfaces of the pores, and convection within the pores, and in a practical definition of thermal conductivity all three modes of heat transfer are included. If the material is wet, heat transferred by moisture in the capillaries and the enthalpy changes that accompany phase transitions also add to the density of heat flow rate.

Thermal resistance (Symbol: R; unit: $K \cdot m^2 \cdot W^{-1}$)
The thermal resistance of a specimen of a material bound by two parallel surfaces is defined as the ratio between the magnitude of the temperature difference across the two bounding surfaces and the density of heat flow rate across the specimen under a steady state condition.

Thermal diffusivity (Symbol: a; unit: $m^2 \cdot s^{-1}$)
The thermal diffusivity at a point in a material is defined as the ratio between the thermal conductivity at that point and the volumetric heat capacity of the material.

Vapor concentration (Symbol: ρ_v; unit: $kg \cdot m^{-3}$)
The vapor concentration in a given volume of air (or volume of air in the pores of a building material) is defined as the ratio between the mass of water vapor in that volume and the volume.

Vapor permeability (Symbol: δ_p; unit: $kg \cdot m^{-1} \cdot Pa^{-1} \cdot s^{-1}$)
The vapor permeability at a point is defined as the ratio between the density of vapor flow rate at that point and the

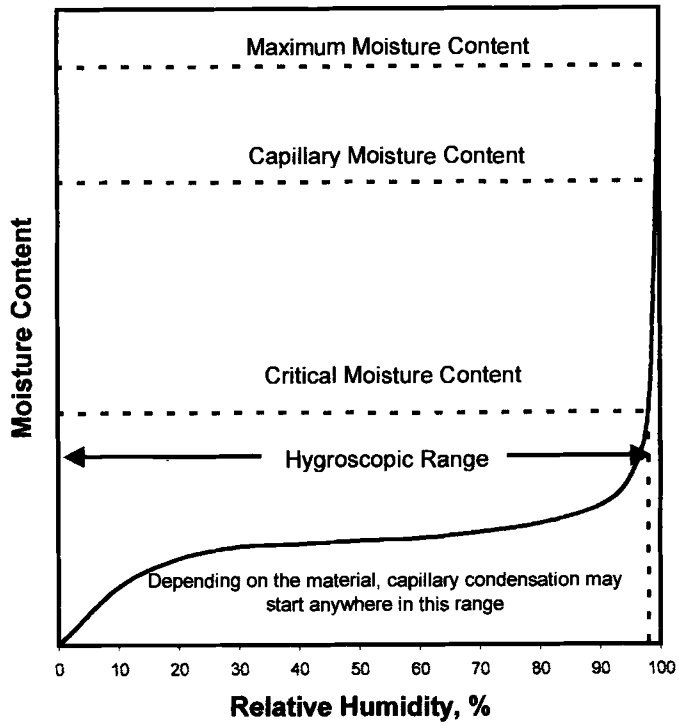

FIG. 1—Sorption Isotherm of a porous building material.

magnitude of the vapor pressure gradient in the direction of the flow.

The definition for vapor permeability stems from the transport equation:

$$\dot{m}_v = -\delta_p \cdot \text{grad } p_v \tag{5}$$

Among all the moisture transport properties, the vapor permeabilities of building materials are most readily measurable by use of the "cup method." Various data reported in the literature show that for most of the hygroscopic materials, the vapor permeability is a strong function of the mean relative humidity of the material.

For practical purposes a quantity called *vapor permeance* (Symbol: δ_1; unit: $kg \cdot m^{-2} \cdot Pa^{-1} \cdot s^{-1}$) of a specimen of a building material is useful. This quantity is defined as follows: The vapor permeance of a specimen of a material bound by two parallel surfaces is the ratio between the density of vapor flow rate and the magnitude of the vapor pressure difference across the bounding surfaces under steady state conditions.

The reciprocal of vapor permeability is *vapor resistivity* (Symbol: N; unit: $m \cdot Pa \cdot s \cdot kg^{-1}$) and that of vapor permeance is called *vapor resistance* (Symbol: Z_p; unit: $m^2 \cdot Pa \cdot s \cdot kg^{-1}$)

If the vapor transport equation is written as:

$$\dot{m}_v = -\delta_v \cdot \text{grad } \rho_v \tag{6}$$

The *vapor permeability* (Symbol: δ_v; unit: $m^2 \cdot s^{-1}$) at a point is defined as the ratio between the density of vapor flow rate at that point and the magnitude of the vapor concentration gradient in the direction of the flow.

Vapor resistance factor (Symbol: μ; unit: dimensionless)
The vapor resistance factor of a material is defined as the ratio between the vapor permeability of stagnant air, δ_a, and that of the material under identical thermodynamic conditions (same temperature and pressure). The vapor permeability of stagnant air can be calculated according to the equation given by Schirmer [3] in agreement with more Schirmer's equation is given below:

$$\delta_a = \frac{2.306 \times 10^{-5} P_0}{R_v T P} \left(\frac{T}{273.15}\right)^{1.81} \tag{7}$$

where

T = temperature, K,
P = ambient pressure, Pa,
P_0 = standard atmospheric pressure, i.e., 101 325 Pa, and
R_v = ideal gas constant for water, i.e., 461.5 $J \cdot K^{-1} \cdot kg^{-1}$.

The concept of vapor resistance factor introduces two physical quantities that describe the pore structure of the building material. By definition, μ for stagnant air is 1. If in a slab of dry material, the pores connect two parallel bounding surfaces of the material straight across and each pore is uniform with respect to the cross-sectional area, then:

$$\mu = 1/\psi_0 \tag{8}$$

where ψ_0 is called the *open porosity* (unit: $m^3 \cdot m^{-3}$), which refers to the volume of pores per unit volume of the material, accessible for water vapor.

If the pores are nonuniform and are directed randomly,

$$\mu = (\psi_\tau/\psi_0) \tag{9}$$

where ψ_τ is called the *tortuosity factor.*

Vapor diffusion thickness (Symbol: μd; unit: m)
Vapor diffusion thickness of a specimen is the product of its thickness and the vapor resistance factor of the material.

Water absorption coefficient (Symbol: A_w; unit: kg · m^{-2} · s$^{-1/2}$)
The property called water absorption coefficient quantifies the water entry into a building material due to absorption when its surface is just in contact with liquid water. It is defined as the ratio between the change of the amount of water entry across the unit area of the surface and the corresponding change in time expressed as the square root; in the early part of an absorption process, this ratio remains constant and that constant value is designated as the water absorption coefficient.

Moisture permeability (Symbol: k_m; unit: kg · m^{-1} · Pa^{-1} · s^{-1})
Moisture permeability of a material at a point in a direction is defined as the ratio between the density of moisture flow rate at that point and the magnitude of suction gradient in the direction of the flow. Suction includes capillarity, gravity, and external pressure. The definition for moisture permeability stems from the transport equation:

$$\dot{m}_m = k_m \cdot \text{grad } s \tag{10}$$

where s is the total suction (unit: Pa); then for capillarity suction, s includes the pore liquid pressure and for gravity includes the product of acceleration of free fall, density of water, and height. The sorption curve in the region above the critical moisture content includes the suction. But it is not particularly evident. Hence it is practical to construct a curve that represents the relation between moisture content and pore size distribution. Then the full moisture content range can be divided into two—the first range up to the critical moisture content in the form of a sorption curve and the second from critical moisture content up to maximum moisture content in the form of a suction curve.

Specific moisture capacity (Symbol: ξ; unit: kg · kg^{-1} · Pa^{-1})
Specific moisture capacity of a material is defined as the increase in the mass of moisture in unit mass of the material that follows the unit increase in vapor pressure or suction. If the vapor pressure is expressed in terms of relative humidity, the unit of this quantity changes to kg · kg^{-1} and then the symbol ξ_φ should be used.

Volumetric moisture capacity (Symbol: $\rho_0\xi$; unit: kg · m^{-3} · Pa^{-1})
The volumetric moisture capacity of a material is defined as the increase in the moisture content in unit volume of the material that follows the unit increase in the vapor pressure or suction.

For hygroscopic range, volumetric moisture capacity can be calculated from the slope of the sorption curve, and above critical moisture content it can be calculated as the slope of the suction curve.

Moisture diffusivity (Symbol: D_w; unit: m^2 · s^{-1})
The moisture diffusivity in the hygroscopic range is the ratio between vapor permeability and volumetric moisture capacity. Outside that range it is the ratio between moisture permeability and volumetric moisture capacity.

The above definition is analogous to that for thermal diffusivity. However, moisture diffusivity is currently used according to the following definition for the density of moisture flow rate:

$$\dot{m}_m = -\rho_0 D_w \cdot \text{grad } u \tag{11}$$

Thermal moisture permeability (Symbol: k_T; unit: kg · m^{-1} · K^{-1} · s^{-1})
The thermal moisture permeability of a material at a point is defined as the ratio between the density of moisture flow rate at that point and the magnitude of temperature gradient in the direction of the transport in the absence of any moisture content gradient.

The above definition for thermal moisture permeability stems from the transport equation:

$$\dot{m}_m = -k_T \cdot \text{grad } T \text{ (at uniform moisture content)} \tag{12}$$

Thermal moisture diffusion coefficient (Symbol: D_T; unit: m^2 · K^{-1} · s^{-1})
The ratio between the dry density and thermal moisture permeability is called the thermal moisture diffusion coefficient. Therefore, Eq 12 can also be written as:

$$\dot{m}_m = -\rho_0 D_T \cdot \text{grad } T \text{ (at uniform moisture content)} \tag{13}$$

Air permeability (Symbol: k_a; unit: kg · m^{-1} · Pa^{-1} · s^{-1})
The air permeability of a material at a point is defined as the ratio between the density of airflow rate at that point and the magnitude of the pressure gradient in the direction of the flow.

For practical purposes the quantity, *air permeance* (Symbol: K_a; unit: kg · m^{-2} · Pa^{-1} · s^{-1}) of a specimen of a building material is useful. This quantity is defined as follows: The air permeance of a specimen of a material bound by two parallel surfaces is the ratio between the density of airflow rate and the magnitude of the pressure difference across the bounding surfaces under steady-state conditions.

The current computer simulation models do not explicitly use all the material properties listed above. Only the following properties are generally used:

1. Thermal conductivity of the dry material as a function of temperature.
2. Thermal conductivity as a function of moisture content.
3. Water vapor permeability/permeance as a function of relative humidity.
4. Equilibrium moisture content as a function of relative humidity.
5. Moisture diffusivity as function of moisture content.
6. Water absorption coefficient.
7. Heat capacity of dry material (constant).
8. Heat capacity as a function of moisture content.
9. Air permeability/permeance as function of pressure differential.

Well-developed experimental procedures and international standard test procedures exist to determine the properties listed above except for the thermal conductivity and the heat capacity of moist materials. In the latter cases combining rules [6] are used to estimate the properties from that for the dry material and water. The principles of the experimental procedures currently used to determine the hygrothermal properties of building materials are given below.

Thermal Conductivity of Dry Materials

The heat conduction Eq 4 is directly used to determine the thermal conductivity of dry materials. Equipment that can maintain a known unidirectional steady state heat flux (under known constant boundary temperatures) across a flat slab of known thickness is used for the measurements. The most commonly used equipment is the guarded hot plate apparatus or the heat flow meter apparatus. ASTM Standards C 177, Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus, and C 518, Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus are widely used for this purpose. Similar standards are available from the International Standards Organization and the European Union. Other methods that may be used for the determination of thermal conductivity may be seen in ASTM STP 879 [7], Tye [8] and other more recent publications [9–11].

In the ASTM standards, the heat conduction equation is written for practical applications as:

$$\lambda = Q \cdot l/(A \cdot \Delta T) \tag{14}$$

where

Q = heat flow rate across an Area A,
l = thickness of test specimen, and
ΔT = hot surface temperature—cold surface temperature.

The thermal conductivity calculated according to Eq 15 is called apparent thermal conductivity. It is a function of the average temperature of the specimen.

Water Vapor Permeability/Permeance

The vapor diffusion equation (Eq 5) is used directly to determine the water vapor permeability of building materials [12]. The measurements are usually done under isothermal conditions. A specimen of known area and thickness separates two environments that differ in relative humidity (RH). Then the rate of vapor flow across the specimen, under steady-state conditions (known RH's as constant boundary conditions), is determined gravimetrically. From these data the water vapor permeability of the material is calculated as:

$$\delta_p = J_v \cdot l/(A \cdot \Delta p) \tag{15}$$

where

J_v = water vapor flow rate across an Area A,
l = thickness of the specimen, and
Δp = difference in water vapor pressure across the specimen surfaces.

Often, especially for membranes and composite materials, one calculates the water vapor permeance, δ_1, of a product at a given thickness from the above measurements as:

$$\delta_1 = J_v/(A \cdot \Delta p) \tag{16}$$

ASTM Standard E 96, Test Methods for Water Vapor Transmission of Materials, prescribes two specific cases of this procedure, a dry cup method that gives the permeance or permeability at a mean RH of 25% and a wet cup method that gives the permeance or permeability at a mean RH of 75%. A new CEN Standard 89 N 336 E is being developed in the European Union based on an ISO standard. More recently a number of technical papers that deal with various technical aspects, limitations, and analyses of the experimental data of these procedures have appeared in the literature [13–15].

For many hygroscopic materials, such as wood and wood products, the water vapor permeability/permeance is a strong function of the local relative humidity and increases with RH. ASTM Standard E 96 is being revised to address this behavior of building materials are quantitatively. For practical building applications, in addition to the traditional dry and wet cup conditions, it is desirable to determine the permeance or permeability of hygroscopic materials at a mean RH of 85%. This can be done using the wet cup method of E 96, but the RH in the humidity chamber shall be maintained at 70%.

Sorption/Desorption Isotherm

For sorption measurements, the specimen is dried at an appropriate drying temperature to constant mass. While maintaining a constant temperature, the dried specimen is placed consecutively in a series of test environments, with relative humidity increasing in stages, until equilibrium is reached in each environment. Equilibrium in each environment is confirmed by periodically weighing the specimen until constant mass is reached. From the measured mass changes, the equilibrium moisture content at each test condition can be calculated and the adsorption isotherm drawn.

The starting point for the desorption measurements is from an equilibrium condition very near 100% RH. While maintaining a constant temperature, the specimen is placed consecutively in a series of test environments, with relative humidity decreasing in stages, until equilibrium is reached in each environment. Equilibrium in each environment is confirmed by periodically weighing the specimen until constant mass is reached. Finally, the specimen is dried at the appropriate temperature to constant mass. From the measured mass changes, the equilibrium moisture content at each test condition can be calculated and the desorption isotherm drawn.

A new CEN standard 89 N 337 E is under development for the determination of "Hygroscopic Sorption Curve." ASTM C 16 Committee also is developing a standard.

Suction Isotherm

The specimens are saturated with water under vacuum. Those are then introduced in a pressure plate apparatus that can maintain pressures up to 100 bar for several days. The plates in perfect hygric contact with the specimens extract water out of the pore structure until an equilibrium state is established. The equilibrium values for moisture contents in the specimens and the corresponding pressures (measured as the excess over atmospheric pressure; the negative of this value is referred to as the pore pressure while the absolute value is the suction) are recorded. The equilibrium pressure, p_h, can be converted to a relative humidity, φ, using the following equation:

$$\ln\varphi = -\frac{M}{\rho RT} p_h \quad (17)$$

where

M = the molar mass of water,
R = the ideal gas constant,
T = the thermodynamic temperature, and
ρ = the density of water.

No standard procedure is yet developed for the determination of suction isotherm. A Nordtest technical report [*16*] briefly describes a procedure and reports the results from an interlaboratory comparison.

Moisture Diffusivity

Liquid water in contact with one surface of a specimen is allowed to diffuse into the specimen. The distribution of moisture within the specimen is determined as a function of time at various intervals until the moving moisture front advances to half of the specimen. The data are either analyzed through the direct application of moisture conservation equation (see introduction) or using the Boltzmann transformation [*17,18*] to derive the moisture diffusivity as function of moisture content.

There is no standard test procedure for the determination of moisture diffusivity. There are many publications in the literature that describe the technical and experimental details [*18–22*].

Water Absorption Coefficient

One major surface of each specimen is placed in contact with liquid water. The increase in mass as a result of moisture absorption is recorded as a function of time. Usually, during the initial part of the absorption process a plot of the mass increase against the square root of time is linear. The slope of the line divided by the area of the surface in contact with water is the water absorption coefficient.

A new CEN Standard 89 N 370 E on the determination of water absorption coefficient is under development.

Air Permeability/Permeance

Specimens with known areas and thickness are positioned to separate two regions that differ in air pressure, and the air flow rate at a steady state and the pressure differential across the specimen are recorded. From these data the air permeability, k_a is calculated as:

$$k_a = J_a \cdot l/(A \cdot \Delta p) \quad (18)$$

where

J_a = air flow rate across an Area A,
l = thickness of the specimen, and
Δp = difference in air pressure across the specimen surfaces.

Often, especially for membranes and composite materials, one calculates the air permeance, K_a, of a product at a given thickness from the above measurements as:

$$K_a = J_a/(A \cdot \Delta p) \quad (19)$$

ASTM Standard C 522, Test Method for Airflow Resistance of Acoustical Materials, prescribes a method based on this principle. Bomberg and Kumaran [*23*] have extended the method for general application to building materials.

During the past decade, building physicists from several research organizations have been systematically determining the hygrothermal properties of building materials. The results are compiled in a report [*24*] published from the activities of an International Energy Agency Annex. Some of these may be found in the Appendix to this chapter.

Building materials continuously evolve. As the manufacturing processes evolve and vary among different manufacturers of the same product, it is desirable to compile tables such as those given in the Appendix at least once in a decade. This will ensure that the hygrothermal models are using representative values and functional dependencies for the properties of each material. Such an effort is underway at the Institute for Research in Construction through two major research projects in which North American building materials are being systematically investigated.

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APPENDIX

The lists of material properties presented in this Appendix are compiled mainly from the data collected from all the 14 countries that participated in the International Energy Agency Annex 24 on "Heat, Air and Moisture Transfer in Insulated Envelope Parts." Special data sheets were developed for this purpose and distributed to all participating countries to make their input. Also, the "Catalogue of Material Properties" that resulted from the Annex 14 activities and a few technical publications, theses, and official reports from various organizations were used. The Annex 24 Report, Kumaran, M. K., "Heat, Air and Moisture Transfer in Insulated Envelope Parts," Volume 3, Task 3: Material Properties, International Energy Agency Annex 24, Laboratorium Bouwfysica, K. U.-Leuven, Belgium, p. 135, 1996, lists the sources, the experimental procedures, information on the building products and the primary data used in the present compilation. All properties are listed in SI units. Two examples of conversion to IP units are given below.

Thermal Conductivity and *R*-value:

Example: Calculation of *R*-value of glass fiber batt insulation with thickness 89 mm:

Glass fiber insulation has a thermal conductivity of 0.035 W $K^{-1} \cdot m^{-1}$.

Then the thermal resistivity is the reciprocal = 28.6 $K \cdot m \cdot W^{-1}$, and the thermal resistance, *RSI* = 28.6 K m $W^{-1} \times$ 0.089 m = 2.54 $K \cdot m^2 \cdot W^{-1}$.

The *R*-value = (2.54/0.176109) IP unit = 14.4 °F ft^2 h/BTU.

Water Vapor Permeability to Permeance and Perm rating:

Example: Calculation of the perm rating for 12.5 mm thick plywood at a mean RH = 90%.

Plywood has a permeability of 1.52×10^{-11} $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$ at 90% RH.

Then the permeance = (1.52×10^{-11} $kg \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1}$)/ 0.0125 m = 1.22×10^{-9} $kg \cdot m^{-2} \cdot s^{-1} \cdot Pa^{-1}$.

The corresponding Perm rating = (1.22×10^{-9})/(5.745×10^{-11}) Perm = 21 Perm.

HYGROTHERMAL PROPERTIES OF CONCRETE

Density: (2200 ± 100) kg m^{-3}

Heat Capacity): 840 J K^{-1} kg^{-1}

Thermal Conductivity: 1.2 W K^{-1} m^{-1} at 27.2 °C

Air Permeability: 3.3 E-07 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.018 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.0045	1.39E-12		
20	0.0070	1.41E-12		
30	0.0090	1.45E-12		
40	0.0108	1.52E-12		
50	0.0125	1.64E-12		
60	0.0143	1.85E-12		
70	0.0168	2.22E-12		
80	0.0215	2.88E-12		
90	0.0321	4.04E-12		
91	0.0338	4.20E-12		
92	0.0355	4.36E-12		
93	0.0375	4.54E-12		
94	0.0395	4.72E-12		
95	0.0419	4.92E-12		
96	0.0443	5.12E-12	5.46E-10	
97	0.0481	5.35E-12	8.54E-09	6.57E-14
98	0.0520	5.57E-12	1.08E-08	1.14E-13
99	0.0535	5.82E-12	1.08E-08	1.18E-13
99.1	0.0537	5.85E-12	1.08E-08	1.19E-13
99.2	0.0538	5.87E-12	1.08E-08	1.19E-13
99.3	0.0540	5.90E-12	1.08E-08	1.19E-13
99.4	0.0541	5.92E-12	1.08E-08	1.20E-13
99.5	0.0543	5.95E-12	1.08E-08	1.20E-13
99.6	0.0544	5.97E-12	1.08E-08	1.21E-13
99.7	0.0546	6.00E-12	1.08E-08	1.21E-13
99.8	0.0547	6.02E-12	1.08E-08	1.21E-13
99.9	0.0549	6.05E-12	1.08E-08	1.22E-13
100	0.0550	6.08E-12	1.08E-08	1.22E-13

HYGROTHERMAL PROPERTIES OF AERATED CONCRETE

Density: 550 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.138 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0E-08 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.1 kg m^{-2} $s^{-1/2}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.018	4.63E-11		
20	0.021	4.63E-11		
30	0.025	4.63E-11		
40	0.028	4.67E-11		
50	0.032	5.10E-11		
60	0.038	6.02E-11		
70	0.045	7.47E-11		
80	0.057	9.49E-11		
90	0.083	1.22E-10		
91	0.088	1.25E-10		
92	0.093	1.28E-10		
93	0.100	1.31E-10		
94	0.107	1.35E-10		
95	0.119	1.38E-10		
96	0.131	1.42E-10		
97	0.156	1.45E-10		
98	0.181	1.49E-10		
99	0.341	1.53E-10	2.59E-08	1.36E-12
99.1	0.356	1.53E-10	2.87E-08	1.55E-12
99.2	0.372	1.53E-10	3.21E-08	1.79E-12
99.3	0.388	1.54E-10	3.67E-08	2.09E-12
99.4	0.404	1.54E-10	4.29E-08	2.51E-12
99.5	0.420	1.55E-10	5.21E-08	3.13E-12
99.6	0.436	1.55E-10	6.66E-08	4.10E-12
99.7	0.452	1.55E-10	9.55E-08	6.02E-12
99.8	0.468	1.56E-10	1.65E-07	1.07E-11
99.9	0.484	1.56E-10	3.53E-07	2.33E-11
100	1.300	1.57E-10	3.53E-07	2.38E-11

HYGROTHERMAL PROPERTIES OF RED BRICK

Density: 1670 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.4 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-10 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.11 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.000	1.26E-11		
20	0.000	1.26E-11		
30	0.000	1.26E-11		
40	0.000	1.27E-11		
50	0.000	1.31E-11		
60	0.001	1.40E-11		
70	0.001	1.62E-11		
80	0.002	2.07E-11		
90	0.003	2.90E-11		
91	0.003	3.02E-11	2.23E-08	2.61E-15
92	0.003	3.13E-11	2.39E-08	3.35E-15
93	0.003	3.26E-11	2.80E-08	9.21E-15
94	0.003	3.39E-11	3.06E-08	1.59E-14
95	0.004	3.53E-11	4.11E-08	2.48E-13
96	0.004	3.68E-11	4.97E-08	5.74E-13
97	0.023	3.84E-11	2.57E-07	5.94E-12
98	0.042	4.00E-11	4.54E-07	1.58E-11
99	0.079	4.17E-11	8.81E-07	3.65E-11
99.1	0.083	4.19E-11	9.32E-07	3.92E-11
99.2	0.087	4.21E-11	9.85E-07	4.20E-11
99.3	0.091	4.23E-11	1.04E-06	4.51E-11
99.4	0.094	4.24E-11	1.10E-06	4.85E-11
99.5	0.098	4.26E-11	1.17E-06	5.23E-11
99.6	0.102	4.28E-11	1.25E-06	5.67E-11
99.7	0.106	4.30E-11	1.35E-06	6.21E-11
99.8	0.109	4.31E-11	1.51E-06	7.04E-11
99.9	0.113	4.33E-11	1.90E-06	8.97E-11
100	0.117	4.35E-11	2.50E-06	1.20E-10

HYGROTHERMAL PROPERTIES OF REHEATED RED BRICK

Density: 1800 kg m^{-3}

Heat Capacity: 870 J K^{-1} kg^{-1}

Thermal Conductivity: 0.75 W K^{-1} m^{-1} at 24 °C

Air Permeability: 6.5 E-09 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.0001 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.001	4.07E-12		
20	0.001	4.07E-12		
30	0.001	4.07E-12		
40	0.002	4.07E-12		
50	0.002	4.07E-12		
60	0.003	4.07E-12		
70	0.003	4.07E-12		
80	0.004	4.07E-12		
90	0.006	4.07E-12		
91	0.006	4.07E-12		
92	0.007	4.07E-12		
93	0.007	4.07E-12		
94	0.007	4.07E-12		
95	0.007	4.07E-12		
96	0.008	4.07E-12		
97	0.008	4.07E-12		
98	0.008	4.07E-12		
99	0.134	4.07E-12		
99.1	0.147	4.07E-12		
99.2	0.159	4.07E-12		
99.3	0.172	4.07E-12		
99.4	0.184	4.07E-12		
99.5	0.197	4.07E-12		
99.6	0.210	4.07E-12		
99.7	0.222	4.07E-12		
99.8	0.235	4.07E-12		
99.9	0.247	4.07E-12		
100	0.260	4.07E-12	1.00E-14	1.74E-16

HYGROTHERMAL PROPERTIES OF WHITE BRICK

Density: 1730 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.4 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-10 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.12 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.000	1.26E-11		
20	0.000	1.26E-11		
30	0.000	1.26E-11		
40	0.000	1.27E-11		
50	0.000	1.31E-11		
60	0.001	1.40E-11		
70	0.001	1.62E-11		
80	0.002	2.07E-11		
90	0.002	2.90E-11		
91	0.002	3.02E-11		
92	0.003	3.13E-11		
93	0.003	3.26E-11		
94	0.003	3.39E-11	1.00E-16	1.00E-16
95	0.004	3.53E-11	6.09E-09	3.63E-14
96	0.004	3.68E-11	5.95E-08	6.78E-13
97	0.022	3.84E-11	5.30E-07	1.21E-11
98	0.040	4.00E-11	8.14E-07	2.79E-11
99	0.076	4.17E-11	1.78E-06	7.26E-11
99.1	0.079	4.19E-11	2.15E-06	8.89E-11
99.2	0.083	4.21E-11	2.67E-06	1.12E-10
99.3	0.086	4.23E-11	3.43E-06	1.47E-10
99.4	0.090	4.24E-11	4.67E-06	2.03E-10
99.5	0.093	4.26E-11	5.99E-06	2.64E-10
99.6	0.097	4.28E-11	6.30E-06	2.81E-10
99.7	0.100	4.30E-11	6.30E-06	2.85E-10
99.8	0.104	4.31E-11	6.30E-06	2.90E-10
99.9	0.107	4.33E-11	6.30E-06	2.94E-10
100	0.111	4.35E-11	6.30E-06	2.98E-10

PROPERTIES OF DENSE CLAY BRICK

Density ≈2100 kg m^{-3}

Water Vapour Permeability:

RH, %	kg m^{-1} s^{-1} Pa^{-1}
10	2.15E-12
20	2.27E-12
30	2.39E-12
40	2.52E-12
50	2.66E-12
60	2.8E-12
70	2.95E-12
80	3.11E-12
90	3.28E-12
100	3.46E-12

Water Absorption Coefficient: 0.014 kg m^{-2} $s^{-½}$

Capillary Saturation: 104 kg m^{-3}

HYGROTHERMAL PROPERTIES OF MORTAR

Density: 1800 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.85 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-10 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.042 to 0.8 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.006	1.50E-11		
20	0.009	1.52E-11		
30	0.011	1.55E-11		
40	0.013	1.60E-11		
50	0.015	1.68E-11		
60	0.018	1.81E-11		
70	0.022	2.01E-11		
80	0.031	2.32E-11	2.66E-09	
90	0.046	2.80E-11	6.46E-09	
91	0.049	2.87E-11	7.24E-09	
92	0.051	2.93E-11	8.15E-09	
93	0.054	3.00E-11	9.27E-09	
94	0.056	3.07E-11	1.05E-08	
95	0.059	3.14E-11	1.22E-08	
96	0.062	3.22E-11	1.41E-08	9.77E-14
97	0.070	3.30E-11	2.09E-08	4.04E-13
98	0.078	3.39E-11	3.09E-08	9.81E-13
99	0.117	3.48E-11	5.04E-08	2.18E-12
99.1	0.121	3.48E-11	5.04E-08	2.24E-12
99.2	0.125	3.49E-11	5.04E-08	2.30E-12
99.3	0.129	3.50E-11	5.04E-08	2.36E-12
99.4	0.133	3.51E-11	5.04E-08	2.42E-12
99.5	0.137	3.52E-11	5.04E-08	2.47E-12
99.6	0.141	3.53E-11	5.04E-08	2.53E-12
99.7	0.145	3.54E-11	5.04E-08	2.59E-12
99.8	0.149	3.55E-11	5.04E-08	2.65E-12
99.9	0.153	3.56E-11	5.04E-08	2.71E-12
100	0.157	3.57E-11	5.04E-08	2.76E-12

HYGROTHERMAL PROPERTIES OF GYPSUM BOARD

Density: (640 ± 20) kg m^{-3}

Heat Capacity: 870 J K^{-1} kg^{-1}

Thermal Conductivity: 0.196 W K^{-1} m^{-1} at 24 °C

Air Permeability: 4.0 E-09 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.20 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.006	1.50E-11		
20	0.009	1.50E-11		
30	0.012	1.51E-11		
40	0.014	1.83E-11		
50	0.017	2.17E-11		
60	0.019	2.53E-11		
70	0.022	3.50E-11		
80	0.027	4.50E-11		
90	0.036	5.50E-11		
91	0.037	5.60E-11		
92	0.038	5.70E-11		
93	0.040	5.80E-11		
94	0.042	5.90E-11		
95	0.043	6.00E-11		
96	0.045	6.10E-11		
97	0.047	6.20E-11	1.50E-10	
98	0.049	6.30E-11	1.75E-10	1.53E-14
99	0.428	6.40E-11	3.44E-07	4.61E-11
99.1	0.466	6.41E-11	3.44E-07	4.77E-11
99.2	0.504	6.42E-11	3.44E-07	4.93E-11
99.3	0.541	6.43E-11	3.44E-07	5.09E-11
99.4	0.579	6.44E-11	3.44E-07	5.25E-11
99.5	0.617	6.45E-11	3.44E-07	5.41E-11
99.6	0.655	6.46E-11	3.44E-07	5.57E-11
99.7	0.693	6.47E-11	3.44E-07	5.73E-11
99.8	0.731	6.48E-11	3.44E-07	5.89E-11
99.9	0.769	6.49E-11	3.44E-07	6.05E-11
100	0.806	6.50E-11	3.44E-07	6.21E-11

HYGROTHERMAL PROPERTIES OF PLASTER

Density: 1380 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.6 W K^{-1} m^{-1} at 24 °C

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.011	2.55E-12		
20	0.013	2.55E-12		
30	0.015	2.55E-12		
40	0.017	2.55E-12		
50	0.019	2.55E-12		
60	0.022	2.55E-12		
70	0.026	2.55E-12		
80	0.032	2.55E-12		
90	0.043	2.55E-12		
91	0.045	2.55E-12		
92	0.047	2.55E-12		
93	0.050	2.55E-12		
94	0.053	2.55E-12		
95	0.057	2.55E-12		
96	0.060	2.55E-12		
97	0.066	2.55E-12		
98	0.072	2.55E-12		
99	0.089	2.55E-12		
99.1	0.091	2.55E-12		
99.2	0.093	2.55E-12		
99.3	0.094	2.55E-12		
99.4	0.096	2.55E-12		
99.5	0.098	2.55E-12		
99.6	0.099	2.55E-12		
99.7	0.101	2.55E-12		
99.8	0.103	2.55E-12		
99.9	0.104	2.55E-12		
100	0.106	2.55E-12	1.00E-14	1.00E-16

HYGROTHERMAL PROPERTIES OF SAND LIMESTONE

Density: 1685 to 1800 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.9 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-11 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.07 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.004	7.04E-12		
20	0.006	7.04E-12		
30	0.007	7.04E-12		
40	0.008	7.04E-12		
50	0.009	7.04E-12		
60	0.010	7.04E-12		
70	0.011	7.04E-12		
80	0.013	7.04E-12	1.00E-16	
90	0.026	7.04E-12	4.23E-10	
91	0.030	7.04E-12	5.76E-10	
92	0.034	7.04E-12	7.43E-10	4.89E-15
93	0.040	7.04E-12	1.04E-09	1.33E-14
94	0.047	7.04E-12	1.36E-09	2.57E-14
95	0.071	7.04E-12	2.57E-09	5.60E-14
96	0.095	7.04E-12	4.34E-09	1.07E-13
97	0.109	7.04E-12	7.05E-09	1.56E-13
98	0.124	7.04E-12	1.48E-08	2.89E-13
99	0.139	7.04E-12	4.36E-08	8.58E-13
99.1	0.140	7.04E-12	5.04E-08	9.93E-13
99.2	0.142	7.04E-12	5.73E-08	1.13E-12
99.3	0.143	7.04E-12	6.59E-08	1.30E-12
99.4	0.144	7.04E-12	7.66E-08	1.51E-12
99.5	0.146	7.04E-12	8.73E-08	1.73E-12
99.6	0.147	7.04E-12	1.04E-07	2.07E-12
99.7	0.149	7.04E-12	1.22E-07	2.42E-12
99.8	0.150	7.04E-12	1.45E-07	2.87E-12
99.9	0.152	7.04E-12	1.72E-07	3.42E-12
100	0.153	7.04E-12	2.00E-07	3.98E-12

HYGROTHERMAL PROPERTIES OF STUCCO

Density: 1700 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.39 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0E-11 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.0006 to 0.04 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.008	1.90E-13		
20	0.008	1.90E-13		
30	0.014	4.30E-13		
40	0.020	7.64E-13		
50	0.027	1.20E-12		
60	0.035	1.74E-12		
70	0.044	2.38E-12		
80	0.056	3.12E-12		
90	0.075	3.97E-12		
91	0.077	4.06E-12		
92	0.080	4.16E-12		
93	0.083	4.25E-12		
94	0.086	4.35E-12		
95	0.090	4.44E-12		
96	0.094	4.54E-12	1.47E-08	
97	0.100	4.64E-12	2.50E-08	
98	0.106	4.74E-12	2.50E-08	1.60E-13
99	0.147	4.84E-12	2.50E-08	6.10E-13
99.1	0.151	4.85E-12	2.50E-08	7.60E-13
99.2	0.155	4.86E-12	2.50E-08	9.90E-13
99.3	0.159	4.87E-12	2.50E-08	1.20E-12
99.4	0.163	4.88E-12	2.50E-08	1.40E-12
99.5	0.167	4.89E-12	2.50E-08	2.20E-12
99.6	0.172	4.90E-12	2.50E-08	2.80E-12
99.7	0.176	4.91E-12	2.50E-08	3.90E-12
99.8	0.180	4.92E-12	2.50E-08	5.80E-12
99.9	0.184	4.93E-12	2.50E-08	1.80E-11
100	0.188	4.94E-12	2.50E-08	2.70E-11

HYGROTHERMAL PROPERTIES OF EIFS(COMBINED BASE COAT AND FINISH)

Density: 1450 to 1730 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.59 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-12 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.00014 to 0.00032 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.011	1.85E-12		
20	0.013	2.03E-12		
30	0.015	2.35E-12		
40	0.017	2.35E-12		
50	0.019	2.35E-12		
60	0.022	2.35E-12		
70	0.026	2.35E-12		
80	0.032	2.44E-12		
90	0.043	2.79E-12		
91	0.045	2.82E-12		
92	0.047	2.86E-12		
93	0.050	2.89E-12		
94	0.053	2.93E-12		
95	0.057	2.96E-12		
96	0.060	3.00E-12		
97	0.066	3.03E-12		
98	0.072	3.07E-12		
99	0.089	3.10E-12		
99.1	0.091	3.10E-12		
99.2	0.093	3.11E-12		
99.3	0.094	3.11E-12		
99.4	0.096	3.11E-12		
99.5	0.098	3.12E-12		
99.6	0.099	3.12E-12		
99.7	0.101	3.13E-12		
99.8	0.103	3.13E-12		
99.9	0.104	3.13E-12		
100	0.106	3.14E-12	1.00E-14	1.78E-16

HYGROTHERMAL PROPERTIES OF CEMENT BOARD SHEATHING

Density: 1130 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1}

Thermal Conductivity: 0.25 W K^{-1} m^{-1} at 24 °C

Air Permeability: 2.5E-08 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.01 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.011	8.03E-12		
20	0.013	8.28E-12		
30	0.015	8.56E-12		
40	0.017	8.91E-12		
50	0.019	9.37E-12		
60	0.022	1.01E-11		
70	0.026	1.12E-11		
80	0.032	1.34E-11		
90	0.043	2.00E-11		
91	0.045	2.06E-11		
92	0.047	2.13E-11		
93	0.050	2.20E-11	1.00E-16	
94	0.053	2.27E-11	9.67E-11	
95	0.057	2.34E-11	6.59E-10	
96	0.060	2.41E-11	7.24E-10	
97	0.066	2.48E-11	8.61E-10	
98	0.072	2.54E-11	9.73E-10	1.32E-14
99	0.099	2.61E-11	1.76E-09	3.19E-14
99.1	0.101	2.62E-11	1.91E-09	3.56E-14
99.2	0.104	2.63E-11	2.09E-09	3.99E-14
99.3	0.107	2.63E-11	2.30E-09	4.51E-14
99.4	0.109	2.64E-11	2.57E-09	5.16E-14
99.5	0.112	2.65E-11	2.92E-09	5.98E-14
99.6	0.114	2.65E-11	3.37E-09	7.07E-14
99.7	0.117	2.66E-11	3.99E-09	8.56E-14
99.8	0.120	2.67E-11	4.91E-09	1.08E-13
99.9	0.122	2.67E-11	6.38E-09	1.43E-13
100	0.125	2.68E-11	9.13E-09	2.08E-13

HYGROTHERMAL PROPERTIES OF SPRUCE

Density: (400 ± 10) kg m^{-3}

Heat Capacity: 1880 J K^{-1} kg^{-1}

Thermal Conductivity: 0.1 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-12 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.0096 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.031	2.76E-12		
20	0.047	2.76E-12		
30	0.061	2.76E-12		
40	0.074	2.80E-12		
50	0.088	3.54E-12		
60	0.105	4.35E-12		
70	0.129	5.64E-12		
80	0.164	6.96E-12		
90	0.216	8.28E-12	1.00E-16	
91	0.222	8.41E-12	2.92E-13	
92	0.228	8.54E-12	5.82E-13	
93	0.235	8.68E-12	7.92E-13	
94	0.242	8.81E-12	1.05E-12	
95	0.250	8.94E-12	3.34E-11	
96	0.257	9.07E-12	4.79E-11	
97	0.294	9.20E-12	6.83E-11	
98	0.330	9.34E-12	6.68E-11	
99	0.540	9.47E-12	6.58E-11	
99.1	0.561	9.48E-12	6.86E-11	
99.2	0.582	9.49E-12	7.21E-11	
99.3	0.603	9.51E-12	7.68E-11	
99.4	0.624	9.52E-12	8.32E-11	
99.5	0.645	9.53E-12	9.18E-11	5.62E-15
99.6	0.666	9.55E-12	1.04E-10	6.51E-15
99.7	0.687	9.56E-12	1.21E-10	7.80E-15
99.8	0.708	9.57E-12	1.51E-10	9.89E-15
99.9	0.729	9.59E-12	2.02E-10	1.36E-14
100	0.750	9.60E-12	3.12E-10	2.15E-14

HYGROTHERMAL PROPERTIES OF PINE

Density: (400 ± 10) kg m^{-3}

Heat Capacity: 1880 J K^{-1} kg^{-1}

Thermal Conductivity: 0.1 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.0 E-12 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.004 to 0.016 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.031	2.76E-12		
20	0.047	2.76E-12		
30	0.061	2.76E-12		
40	0.074	2.80E-12		
50	0.088	3.54E-12		
60	0.105	4.35E-12		
70	0.129	5.64E-12		
80	0.164	6.96E-12		
90	0.216	8.28E-12		
91	0.222	8.41E-12		
92	0.228	8.54E-12		
93	0.235	8.68E-12		
94	0.242	8.81E-12		
95	0.250	8.94E-12		
96	0.257	9.07E-12		
97	0.294	9.20E-12		
98	0.330	9.34E-12	5.54E-12	
99	0.540	9.47E-12	6.64E-11	
99.1	0.561	9.48E-12	6.91E-11	
99.2	0.582	9.49E-12	7.27E-11	
99.3	0.603	9.51E-12	7.74E-11	
99.4	0.624	9.52E-12	8.37E-11	
99.5	0.645	9.53E-12	9.24E-11	
99.6	0.666	9.55E-12	1.04E-10	
99.7	0.687	9.56E-12	1.22E-10	
99.8	0.708	9.57E-12	1.51E-10	9.92E-15
99.9	0.729	9.59E-12	2.02E-10	1.36E-14
100	0.750	9.60E-12	3.13E-10	2.15E-14

HYGROTHERMAL PROPERTIES OF OSB

Density: 640 kg m^{-3}

Heat Capacity : 1880 J K^{-1} kg^{-1}

Thermal Conductivity: 0.12 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.9 E-09 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.002 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.016	8.40E-13		
20	0.029	9.44E-13		
30	0.042	9.27E-13		
40	0.054	8.95E-13		
50	0.067	9.55E-13		
60	0.081	1.21E-12		
70	0.100	1.78E-12		
80	0.128	2.76E-12		
90	0.174	4.25E-12		
91	0.181	4.44E-12		
92	0.187	4.62E-12		
93	0.194	4.82E-12		
94	0.201	5.02E-12		
95	0.208	5.23E-12		
96	0.216	5.44E-12	1.15E-12	
97	0.241	5.67E-12	1.04E-11	
98	0.266	5.89E-12	1.24E-11	
99	0.445	6.13E-12	2.13E-11	
99.1	0.463	6.16E-12	2.30E-11	
99.2	0.481	6.18E-12	2.49E-11	
99.3	0.499	6.21E-12	2.73E-11	
99.4	0.517	6.23E-12	3.02E-11	3.31E-15
99.5	0.535	6.25E-12	3.39E-11	3.79E-15
99.6	0.552	6.28E-12	3.90E-11	4.44E-15
99.7	0.570	6.30E-12	4.63E-11	5.37E-15
99.8	0.588	6.33E-12	5.80E-11	6.86E-15
99.9	0.606	6.35E-12	8.16E-11	9.82E-15
100	0.624	6.38E-12	1.39E-10	1.71E-14

HYGROTHERMAL PROPERTIES OF PLYWOOD

Density: 450 kg m^{-3}

Heat Capacity: 1880 J K^{-1} kg^{-1}

Thermal Conductivity: 0.11 W K^{-1} m^{-1} at 24 °C

Air Permeability: 8.0 E-10 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.02 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.024	6.89E-13		
20	0.038	1.01E-12		
30	0.051	1.49E-12		
40	0.062	2.20E-12		
50	0.074	3.24E-12		
60	0.087	4.76E-12		
70	0.105	7.01E-12		
80	0.131	1.03E-11		
90	0.169	1.52E-11		
91	0.174	1.58E-11		
92	0.179	1.64E-11		
93	0.185	1.71E-11		
94	0.190	1.77E-11		
95	0.196	1.84E-11		
96	0.202	1.91E-11		
97	0.208	1.99E-11		
98	0.215	2.07E-11		
99	0.592	2.15E-11	1.34E-11	1.30E-15
99.1	0.630	2.16E-11	1.86E-11	1.88E-15
99.2	0.668	2.17E-11	2.53E-11	2.63E-15
99.3	0.706	2.18E-11	3.37E-11	3.62E-15
99.4	0.743	2.18E-11	4.48E-11	4.96E-15
99.5	0.781	2.19E-11	5.90E-11	6.73E-15
99.6	0.819	2.20E-11	7.72E-11	9.07E-15
99.7	0.857	2.21E-11	1.01E-10	1.22E-14
99.8	0.894	2.22E-11	1.31E-10	1.63E-14
99.9	0.932	2.23E-11	1.70E-10	2.17E-14
100	0.970	2.23E-11	2.20E-10	2.88E-14

HYGROTHERMAL PROPERTIES OF WOOD FIBREBOARD

Density: 310 kg m^{-3}

Heat Capacity: 1880 J K^{-1} kg^{-1}

Thermal Conductivity: 0.055 W K^{-1} m^{-1} at 24 °C

Air Permeability: 1.5 E-07 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.03 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.020	1.65E-11		
20	0.029	1.65E-11		
30	0.036	1.65E-11		
40	0.043	1.67E-11		
50	0.049	2.10E-11		
60	0.058	2.57E-11		
70	0.072	3.45E-11		
80	0.096	4.35E-11	1.00E-16	
90	0.142	5.25E-11	1.32E-10	
91	0.148	5.34E-11	1.73E-10	
92	0.155	5.43E-11	2.10E-10	
93	0.162	5.52E-11	2.45E-10	
94	0.169	5.61E-11	2.82E-10	
95	0.177	5.70E-11	3.58E-10	
96	0.185	5.79E-11	4.23E-10	
97	0.196	5.88E-11	8.93E-10	3.47E-14
98	0.207	5.97E-11	9.31E-10	7.04E-14
99	0.853	6.06E-11	9.90E-10	1.14E-13
99.1	0.918	6.07E-11	9.90E-10	1.18E-13
99.2	0.983	6.08E-11	9.90E-10	1.22E-13
99.3	1.047	6.09E-11	9.91E-10	1.26E-13
99.4	1.112	6.10E-11	9.91E-10	1.30E-13
99.5	1.177	6.10E-11	9.91E-10	1.33E-13
99.6	1.241	6.11E-11	9.91E-10	1.37E-13
99.7	1.306	6.12E-11	9.92E-10	1.41E-13
99.8	1.371	6.13E-11	9.92E-10	1.45E-13
99.9	1.435	6.14E-11	9.92E-10	1.49E-13
100	1.500	6.15E-11	9.92E-10	1.53E-13

HYGROTHERMAL PROPERTIES OF CELLULOSE INSULATION

Density: 32 kg m^{-3}

Heat Capacity: 1880 J K^{-1} kg^{-1}

Thermal Conductivity:

Temperature °C	Conductivity W m^{-1} K^{-1}
-0.05	0.0339
12.10	0.0357
23.96	0.0376
32.03	0.0388
40.07	0.0402

Air Permeability: 5.5E-05 kg m^{-1} s^{-1} Pa^{-1}

Water Absorption Coefficient: 0.09 kg m^{-2} $s^{-½}$

RH, %	Moisture Content kg kg^{-1}	Water Vapour Permeability kg m^{-1} s^{-1} Pa^{-1}	Moisture Diffusivity m^2 s^{-1}	Liquid Permeability kg m^{-1} s^{-1} Pa^{-1}
10	0.001	4.43E-11		
20	0.006	5.12E-11		
30	0.017	5.91E-11		
40	0.035	6.82E-11		
50	0.062	7.87E-11		
60	0.098	9.09E-11		
70	0.147	1.05E-10		
80	0.222	1.21E-10		
90	0.407	1.40E-10		
91	0.443	1.42E-10		
92	0.480	1.44E-10		
93	0.528	1.46E-10		
94	0.576	1.48E-10		
95	0.639	1.51E-10		
96	0.703	1.53E-10		
97	1.047	1.55E-10		
98	1.391	1.57E-10		
99	6.616	1.59E-10	5.81E-12	
99.1	7.138	1.60E-10	6.14E-12	
99.2	7.660	1.60E-10	6.45E-12	
99.3	8.183	1.60E-10	6.74E-12	
99.4	8.705	1.60E-10	7.02E-12	
99.5	9.228	1.61E-10	7.28E-12	
99.6	9.750	1.61E-10	7.53E-12	
99.7	10.273	1.61E-10	7.76E-12	
99.8	10.795	1.61E-10	7.99E-12	
99.9	11.318	1.61E-10	8.20E-12	2.57E-15
100	11.840	1.62E-10	8.40E-12	2.70E-15

HYGROTHERMAL PROPERTIES OF GLASS FIBRE INSULATION

Dry density 8 to 180 kg m^{-3}

Heat capacity[2] 840 J K^{-1} kg^{-1}

Thermal conductivity of the dry material at 24 °C as a function of density

Density $kg \cdot m^{-3}$	Conductivity $W \cdot m^{-1} \cdot K^{-1}$	Density $kg \cdot m^{-3}$	Conductivity $W \cdot m^{-1} \cdot K^{-1}$
7.7	0.0483	38.1	0.0333
9.9	0.0473	44.4	0.0326
10.3	0.0455	53.4	0.0322
11.4	0.0450	60.7	0.0332
12.8	0.0427	68.6	0.0319
13.1	0.0424	71.0	0.0324
14.7	0.0412	135.0	0.0328

Temperature dependence of thermal conductivity:

Specimen Density = 8.3 kg m^{-3}

T,Hot surface °C	T, Cold surface °C	Temperature °C	λ W m^{-1} K^{-1}
12.68	-10.73	0.98	0.0472
22.61	1.20	11.90	0.0515
35.20	12.96	24.08	0.0552
45.89	25.21	35.55	0.0592
58.76	39.55	49.16	0.0662

Specimen Density = 53.7 kg m^{-3}

T,Hot surface °C	T, Cold surface °C	Temperature °C	Conductivity W m^{-1} K^{-1}
12.39	-11.13	0.63	0.0295
24.51	2.26	13.39	0.0311
35.20	13.36	24.28	0.0322
45.80	24.97	35.38	0.0338
57.60	37.01	47.31	0.0360

Specimen Density = 151 kg m^{-3}

T,Hot surface °C	T, Cold surface °C	Temperature °C	Conductivity W m^{-1} K^{-1}
24.11	-4.06	10.02	0.0320
37.06	9.02	23.04	0.0332
54.35	26.23	40.29	0.0351

Sorption/desorption curve:

Relative humidity %	Sorption moisture content kg kg^{-1}	Desorption moisture content kg kg^{-1}
20.4	0.0087	
43.4	0.012	
64.5	0.014	
84.9	0.017	
95.1	0.019	
98.0	0.026	
20.0		0.01
43.1		0.014
64.8		0.017
84.4		0.022
94.5		0.029
97.6		0.042

Water Vapour Permeability :

Specimen density kg m^{-3}	RH(1) %	Water vapour permeability Kg m^{-1} s^{-1} Pa^{-1}
16.8	27	1.32 E-10
16.8	27	1.41 E-10
35.2	25	1.65 E-10
37.3	25	1.35 E-10
35.0	25	1.22 E-10
72.0	25	1.15 E-10
74.3	27	1.15 E-10
67.3	27	1.16 E-10
119.8	26	1.27 E-10
108.9	26	1.23 E-10
119.1	26	1.35 E-10

Air permeability:

Specimen Density = 147.2 kg m^{-3}; flow ⊥ to fibre orientation

Pressure difference Pa	Permeability kg m^{-1} s^{-1} Pa^{-1}
0.1	2.49×10^{-5}
0.2	2.45×10^{-5}
0.3	2.43×10^{-5}
0.4	2.47×10^{-5}
0.5	2.40×10^{-5}
0.6	2.39×10^{-5}
0.7	2.38×10^{-5}

Specimen Density ≈ 20 kg m^{-3}

Pressure difference Pa	Permeability kg m^{-1} s^{-1} Pa^{-1}
25	9.5×10^{-5}
50	9.1×10^{-5}
75	8.9×10^{-5}
100	8.8×10^{-5}

HYGROTHERMAL PROPERTIES OF EXPANDED POLYSTYRENE INSULATION

Dry density[1] 11 to 40 kg m^{-3}

Heat capacity[1] 1470 J K^{-1} kg^{-1}

Thermal conductivity of the dry material as a function of density, ρ, (kg m^{-3}):

λ ($W \cdot m^{-1} \cdot K^{-1}$) = 0.0174 + 1.9 x$10^{-4}\rho$ + 0.258/ρ

Temperature dependence of thermal conductivity:

Specimen Density =23.2 kg m^{-3}

T,Hot surface °C	T, Cold surface °C	Temperature °C	Conductivity W $\cdot m^{-1}$ K^{-1}
13.09	-10.92	1.09	0.0324
22.23	-0.92	10.66	0.0336
30.14	7.28	18.71	0.0344
35.83	13.34	24.59	0.0352
47.28	25.58	36.43	0.0366
52.70	31.08	41.89	0.0371

Sorption/desorption curve:

Relative humidity %	Sorption moisture content kg kg^{-1}	Desorption moisture content kg kg^{-1}
20.3	0.030	
42.9	0.041	
65.0	0.040	
85.3	0.040	
94.4	0.050	
97.9	0.050	
20.0		0.020
44.5		0.040
65.1		0.048
84.5		0.056
95.1		0.070
97.9		0.080

Water Vapour Permeability

At a specimen density of 11.5 kg m^{-3} the permeability is 1.0 E-11 kg m^{-1} s^{-1} Pa^{-1}
At a specimen density of 15.8 kg m^{-3} the permeability is 3.4 E-12 kg m^{-1} s^{-1} Pa^{-1}

Air permeability:

Specimen Density = 16 kg m^{-3}

Pressure difference Pa	Permeability kg m^{-1} s^{-1} Pa^{-1}
25	5.6 E-06
50	5.2 E-06
75	5.0 E-06
100	4.9 E-06

Specimen Density = 25 kg·m^{-3}

Pressure difference Pa	Permeability kg·m^{-1}·s^{-1}·Pa^{-1}
25	4.9 E-08
50	4.9 E-08
75	4.9 E-08
100	4.9 E-08

HYGROTHERMAL PROPERTIES OF EXTRUDED POLYSTYRENE INSULATION

Dry density[1] 25 to 55 kg m^{-3}

Heat capacity[1] 1470 J K^{-1} kg^{-1}

Aging curve or time dependence of thermal conductivity at 24 °C

Specimen Density =24.5 kg m^{-3}, thickness = 50.5 mm

age day	Conductivity W m^{-1} K^{-1}
0	0.0219
45	0.0256
60	0.0261
91	0.0266
182	0.0273
270	0.0275
365	0.0274
451	0.0277
550	0.0279
673	0.0280
791	0.0280
911	0.0287
1031	0.0285

Specimen Density =28.6 kg m^{-3}, thickness = 50.1 mm

age day	Conductivity W m^{-1} K^{-1}
0	0.0220
55	0.0264
71	0.0268
99	0.0273
179	0.0280
270	0.0285
361	0.0283
452	0.0285
554	0.0286
677	0.0288
797	0.0288
994	0.0294

Temperature dependence of thermal conductivity:

Specimen Density =30.7 kg·m^{-3}

T,Hot surface °C	T, Cold surface °C	Temperature °C	Conductivity W m^{-1} K^{-1}
4.7	-4.8	-0.05	0.0266
14.6	5.6	10.1	0.0278
24.5	15.7	20.1	0.0292
34.4	25.6	30.0	0.0303

Sorption/desorption curve:

Relative humidity %	Sorption moisture content kg kg^{-1}
25	0.0007
50	0.0006
75	0.0013
90	0.0017

Water Vapour Permeability:

RH %	Water vapour permeability kg m^{-1} s^{-1} Pa^{-1}
25	0.95×10^{-12}
50	1.0×10^{-12}
75	1.2×10^{-12}
95	1.35×10^{-12}

For a product with density 27 kg m^{-3}, the water vapour permeability for the full range of RH was 1.75 E-12 kg m^{-1} s^{-1} Pa^{-1}.

Air permeability:

Density = 30.7 kg m^{-3}

Pressure difference Pa	Permeability kg m^{-1} s^{-1} Pa^{-1}
75	9.6×10^{-9}
150	9.3×10^{-9}
225	9.2×10^{-9}

HYGROTHERMAL PROPERTIES OF POLYURETHANE FOAM INSULATION

Dry density 20 to 55 kg m^{-3}

Heat capacity 1470 J K^{-1} kg^{-1}

Aging curve or time dependence of thermal conductivity at 24 °C :

Specimen Density =32 kg m^{-3} , thickness = 38 mm

age day	Conductivity W m^{-1} K^{-1}
0	0.0175
32	0.0188
61	0.0198
90	0.0208
185	0.0219
270	0.0227
360	0.0231
451	0.0236
567	0.0241
690	0.0243
810	0.0249
932	0.0247

Water Vapour Permeability of a sample with density 32 kg m^{-3} is 3.0E-12 kg m^{-1} s^{-1} Pa^{-1} for the full range of relative humidity.

HYGROTHERMAL PROPERTIES OF PERLITE BOARD

Density ≈250 kg m^{-3}

Thermal Conductivity: 0.0716 W m^{-1} K^{-1} at 24 °C

Water Vapour Permeability:

RH, %	kg m^{-1} s^{-1} Pa^{-1}
0 to 100	3.3E-11

Water Absorption Coefficient: **0.0065** kg m^{-2} $s^{-½}$

HYGROTHERMAL PROPERTIES OF CALCIUM SILICATE BOARD

Density ≈300 kg m^{-3}

Thermal Conductivity: 0.0811 W m^{-1} K^{-1} at 24 °C

Water Vapour Permeability:

RH, %	kg m^{-1} s^{-1} Pa^{-1}
50	3.6E-11
60	3.8E-11
70	4.2E-11
80	4.8E-11
90	5.6E-11
100	6.7E-11

Water Absorption Coefficient: **0.41** kg m^{-2} $s^{-½}$

Capillary Saturation: ≈ 800 kg m^{-3}

WATER VAPOUR PERMEANCE OF SHEATHING MEMBRANES

Membrane Thickness, mm	SBP 1 0.17	SBP 2 0.3	#15 Felt 0.84	60 minute 0.35	Building Paper 0.2
RH, %	Permeance kg m^{-2} s^{-1} Pa^{-1}				
30	3.1E-09	9.3E-10			1.9E-09
40	3.7E-09	9.3E-10			2.2E-09
50	4.2E-09	9.3E-10	7.1E-11	7.1E-10	2.5E-09
60	4.8E-09	9.3E-10	1.0E-10	7.8E-10	2.8E-09
70	5.3E-09	9.3E-10	1.6E-10	8.5E-10	3.2E-09
80	5.9E-09	9.3E-10	3.0E-10	9.2E-10	3.7E-09
90	6.4E-09	9.3E-10	7.2E-10	9.8E-10	4.3E-09
100	6.7E-09	9.3E-10	4.7E-09	1.0E-09	5.0E-09

AIR PERMEANCE OF SHEATHING MEMBRANES

Membrane Thickness, mm	SBP 1 0.17	SBP 2 0.3	#15 Felt 0.84	60 minute 0.35	Building Paper 0.2
	Permeance kg m^{-2} s^{-1} Pa^{-1}				
	1E-07	5E-05	3E-06	7E-06	4E-06

WATER VAPOUR PERMEANCE OF FINISHING MATERIALS

Wall Paper;

Type	Mass kg m^{-2}	Thickness mm	Permeance kg m^{-2} s^{-1} Pa^{-1} At 42.5 % RH	At 75 % RH
textile	0.291	0.425	7E-10	3.27E-08
textile	0.333	0.7	1.26E-09	1.03E-08
vinyl	0.212	0.45	2.18E-09	7.84E-09
vinyl	0.216	0.325	9.16E-11	1.09E-09
paper	0.168	0.28	5.6E-09	1.63E-08
paper	0.151	0.28	7.84E-09	2.45E-08

Primer + 2 Coat Paint as Applied on Gypsum:

Paint Type	Permeance at 86 % RH kg m^{-2} s^{-1} Pa^{-1}
Latex 1	1.15E-09
Latex 2	1.78E-10
Acrylic	4.26E-10
Synthetic	1.96E-10
Oil	2.58E-10

4

Failure Criteria

by Hannu Viitanen[1] *and Mikael Salonvaara*[2]

FAILURE OFTEN HAS a fatal effect on the service life and durability of materials. Durability of materials to different agents varies: weather, water, heat, biodeterioration (mold and decay fungi, bacteria). Performance requirements of materials and structure should be different for inside surface, inside structures (isolation layer), and outside surface or structures, and the effect of different organisms on the service life should be verified carefully.

Organisms can have permanent or temporary effects (esthetics or technical) and the requirements for repair of problems are varied. Performance requirements and quality of item vary for different targets. For example, mold growth on the inside surface of buildings can be more serious for the use of buildings than molds on the outside surface of buildings due to the eventual health risk of microbes. Mold growth also has different effect on the substrate itself; in some cases, mold destroys materials (e.g., wall papers and paints) or mold is only a superficial layer on the materials (e.g., tiled walls or facades). Mold or mildew is a general classification of organisms growing on the surface of materials (discoloring organisms or fungi). Blue-stain fungi are a special part of discoloring fungi. They can penetrate in to the sapwood of several wood species and cause color change in the wood material.

Damage classes are varied and have different effects on the durability and service life of materials. For example, mildew or mold fungi on the surface of different materials often cause indirect effects (color changes, health problems) and do not always change the properties of materials. Decay fungi are a general classification of fungi-decaying wood and other wood-based materials. Biocorrosion causes direct changes of materials, e.g., decay fungi and bacteria deteriorate different materials (wood-based materials, plastics, paints, metals, concrete, mortar). Biocorrosion is often connected with corrosion of metals.

DEFINITIONS FOR "FAILURE"

In order to predict failures we first have to define the term. Failure involves direct changes in the properties of materials or structures. The changes or deformations can be of various degrees: excess moisture can cause reversible or irreversible deformations or degradation in performance resulting from physical changes, chemical or biological processes. One type of failure is increased heat loss caused by high moisture contents in materials and airflow through building envelope systems. Other types are mold growth, rot damages, freeze-thaw cycles resulting in structural failures, dimensional changes, corrosion, emissions of volatile organic compounds (VOC), etc. Some of these failures affect only the appearance of the systems under consideration, but some may have severe consequences such as risk to the health of occupants (sick building syndrome caused by VOC and mold) or structural collapse of the whole building.

Some definitions for failure and related phenomena are presented mainly in the ISO Performance Standards in Building—Glossary of Terms (6707-1 1989) and in the references [*1*]. Here are some definitions mentioned:

Failure: Termination of the ability of an item to perform a specified function.

Decay: Damage of material and structures.

Service life: Period of time after installation during which all essential requirements of an item meet or exceed the performance requirements.

Durability: Capability of a building or its parts to perform its required function over a specified period of time under the influence of the agents anticipated in service.

Degradation mechanism: Chemical, mechanical, or physical changes that lead to changes in critical properties of a building product when exposed to degradation agents.

Degradation agents: e.g., water, heat, organisms, chemicals, wrong use of houses, construction defects, etc. They often have a synergistic effect (many agents are often needed for the development of damage).

Degradation or deterioration: Reduction in the performance over time of a component or material.

Biodeterioration: Any undesirable change in the properties of a material caused by the vital activities of organisms.

Biofilm: Layer on the surface of material consisting of inorganic and organic dust and organisms.

Biocorrosion: Reduction in the basic properties of materials over time caused by the decaying activity of organisms (e.g., decay fungi and bacteria).

EXISTING STANDARDS AND BUILDING CODE REQUIREMENTS

There are different standards and recommendations defining the service life or durability of materials, e.g., ISO Performance Standards in Building—Checklist for Briefing—Contents of Brief for Building Design Standards (9699-

[1]VTT Building and Transport, PB 1806, FIN-02044 VTT, Finland. e-mail: hannu-viitanen@vtt.fi
[2]VTT Building and Transport, PB 1804, FIN-02044 VTT, Finland. e-mail: mikael.salonvaara@vtt.fi.

1994), RILEM recommendations [2], CSA Guideline on Durability in Buildings. Draft Standard (S478-1995) standards. Calculations for life cycles, durability, and lifetime are presented in the ISO standard (ISO 9699-1994).

The methods for testing the resistance or durability of materials against mold and decay fungi or insects are different; several standards exist. There are many laboratory methods and field test methods for evaluating materials in ground contact or out of ground contact, e.g., ASTM Test Method for Wood Preservatives by Laboratory Soil-block Cultures (D 1413-99), ASTM Test Method of Evaluating Wood Preservatives by Field Tests with Stakes (D-1758-96), ASTM Test Method for Exterior Durability of Factory-Primed Wood Products (D 2830-96), or EN Standard Determination of Toxic Values of Wood Preservatives Against Wood Destroying Basidiomycetes Cultured on Agar Medium (EN 113, 1991). Problems with these test methods are the time schedule and severity of test conditions. The testing time should be as short as possible and the severity of conditions hazardous for the prediction of durability within the testing time used.

Results of a durability test are often relative, e.g., results are compared with reference material. In practice, conditions are often different and many factors are involved. Laboratory tests are needed for the development of new products, but the service life or durability of products should not be based only on these tests. Field tests in real conditions are also required. For field tests, test results are highly dependent on climate conditions. However, the situation is the same in real life, and the durability of building products or materials should be tested in different climatic zones or varied laboratory conditions.

In the building code requirements, moisture control is the main way to diminish the failure risk and to add the durability and expected lifetime of building products, e.g., BS Guide to Durability of Buildings and Building Elements, Products and Components (7543-1992) and (CSA S478-1995). The purpose of the instruction is to minimize the water and humidity stress of materials and structures. However, several decay and damage cases are faced every year; and the knowledge on building failures should be used for the evaluation of service life or durability of building materials or structures. The problems are that the information on the damage cases is often insufficient and the used materials, structures, and degradation agents are varied.

Building codes are often very different in various countries and they rarely present precise requirements with regard to durability and service life of building components. Most building codes require, for example, that nails and fasteners have to be corrosion resistant. Rather than giving direct requirements for durability or service life, performance building codes prefer requirements that allow for designing structures and buildings that do not experience conditions that would result in premature degradation of building components. The reason for the lack of code level requirements is quite obvious—even today we do not have reliable methods or models that would allow us to predict service life with satisfactory accuracy. The existing code requirements for durability are empirical without any explicit formulation in terms of performance or intended service life.

The external factors and degradation mechanisms affecting the performance of building materials and components are numerous and many are influenced by moisture and temperature. Various degradation factors can be divided into the following categories: weathering, biological, stress, incompatibility, and use factors. Weathering factors include radiation, temperature (elevated, depressed, cycles), water (solid, liquid, vapor), normal air constituents, air contaminants (gases, mists, particles), freeze-thaw, and wind. Biological factors include microorganisms, fungi and bacteria. Several guides for the durability of buildings have been proposed; however, these guides are not fully developed at a practical level [3].

In reality, the load and the conditions that the building components experience are random variables. The time of occurrence as well as the magnitude of the load can not be known a priori—just think of the accuracy of weather forecasts! In addition, the material properties of building components are not constants but instead may have wide ranges even between the parallel samples made from the same lot. Therefore, the realistic modeling of both load and resistance of building components requires the use of stochastic process theory [3]. The model that predicts the service life can be deterministic only if the randomness and time-dependence of the load and properties have been considered through appropriate probability distributions and partial safety factors. The service life is the period of time after installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained.

DIRECT AND INDIRECT MOISTURE PROBLEMS AND FAILURES IN BUILDINGS

Moisture causes direct or indirect failures in the buildings. In wood-based materials, the deformation in volume and shape of material is the direct effect. The creep deformation of wood beams is a slower process and caused by the load under fluctuating humidity and temperature conditions. The emollescense of gypsum board is a direct change of materials caused by water, but the mold growth on the material is a secondary effect of moisture. The effect of water on the emission of volatile organic compounds (VOC) from the materials is a direct effect, but the change of the materials' properties or the health effect caused by the VOCs is a secondary effect (Table 1).

The effect of moisture on the heat insulation capacity is a direct change. After lowering the temperature of the structure, this may lead to dust accumulation or mold growth in the interior surface due to moisture condensation of inside air. The shape deformation of wooden boards by moisture stress can cause more severe failure when water penetrates the structure due to open joints and edges of boards in the wash rooms [2,4].

Moisture damage in buildings is caused by moisture exceeding the tolerance of structures. This may lead to the growth of microbes or mold and decay fungi and insect damage of materials after a critical exposure time. Several causes of moisture damage of buildings have been detected. In most cases, water penetrates to the structure. Typical causes leading to moisture damage are water leakage, water penetration through joints and seams, the convection of damp air in the

TABLE 1—Critical level and failure effect of prolonged moisture exposure on different building materials (targeted in dry conditions).

Material	RH, %	Failures or Problems
Putty with organic additives (e.g., casein)	>75–85	Hydrolysis, formation of ammonia, amines, organic sulfur compounds
PVC—carpets or wallpapers in washrooms	>95	Color changes, decomposition, formation of 2-etyl-1-hexanol
Water-based glues	>85–95	Saponification, varied hydrolyze products
Products containing urea-formaldehydes: particle boards, lacquer, textiles, insulation	>60–70	Formation of formaldehyde and other VOC compounds
Paints, resins of injections agents, plastics	>65–96	Inhibition of hardening, emissions of VOC and monomeric compounds
Surfaces of different material exposed to organic and inorganic compounds, organic materials	−80–95	Microbial growth, VOC emissions

structure, insufficient ventilation of indoor air, moisture condensation, rising damp from ground, moisture accumulation in the structures, faults in structures, and absorption of water into structures.

The service life of untreated timber in structure depends primarily upon the humidity conditions of use, presence of wood-attacking organisms, the natural durability, and dimensions of the timber in use. The problems caused by fungi in buildings vary depending on the type of fungal attack. Problems caused by mold fungi are mainly discoloration, odor, and health disadvantages. Mold and decay problems are concentrated in the parts of the structures in which water can accumulate. Such parts are:

- The lower parts of floors and walls near the ground.
- The constructions affected by water leakage and condensation within walls.
- Poorly ventilated sub floors and attics.
- The joints, end grain, and lower parts of facades and windows.
- Bedroom closets or bathrooms on exterior walls.
- Poorly ventilated bathrooms.

Mold and decay problems can be very complicated in buildings. The major factors affecting the micro-climate are: moisture migration and accumulation, composition, texture and surface quality of the material, temperature, humidity, water condensation and air circulation.

COMPOSITION OF WOOD, CELLULOSE, AND GYPSUM-BASED MATERIAL

The susceptibility of different materials to failure and biodeterioration depends mainly upon the water activity, moisture balance or capacity, surface quality, and nutrient content of the substrate.

Wood Material

Wood is a porous varied material composed of different cells. Living cells are mainly in the phloem and cambium below the bark and in the most outside level of sapwood. The phloem produce a new layer of wood each year, a growth ring composed of early wood (spring wood) and late wood (summer wood) (Fig. 1). Early wood is characterized by cells having relatively large cavities and thin walls (Fig. 2). Late-wood cells contain smaller cavities and thicker walls. Within softwoods (coniferous trees like pine and spruce) wood fibers are mainly the cell type, but within hardwoods (like birch, oak, elm) wood is more varied, also containing vessels [5].

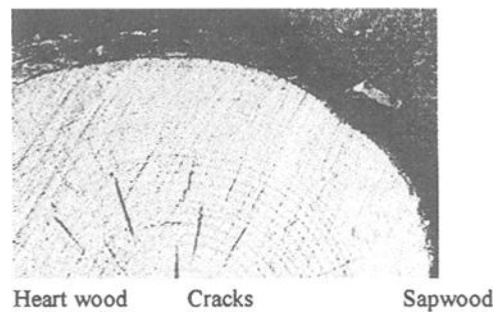

FIG. 1—End grain section of a green pine log. Some cracks are developed due to uncontrolled drying of wood.

The anisotropy composition of wood affects the moisture behavior of wood: the cell walls of late wood can take more water and swell more than the cell wall of late wood, resulting in an uneven dimensional change of wood. Most often more water can be transported in the cells of early wood, but the decay is often located in the walls of late wood.

Sapwood is the outer layer of wood in a living tree. The sapwood layer may vary in thickness and in the number of

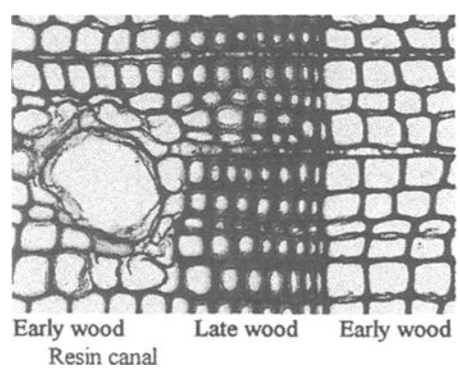

FIG. 2—Microscopic picture on end grain of pine.

growth rings. The moisture content of this part is much higher than that of the heartwood of a living tree. Sapwood contains both the living and dead cells, and its function is the transport of water and the storage of compounds. During the use of wood products, the sapwood is most sensitive to water, humidity, and the activity of decaying organisms.

Heartwood consists of inactive cells that are not supporting water transport. The cell wall and especially the pores between wood cells are penetrated by polymeric extractives, e.g., resins. In some species such as ashes, hickories, and certain oaks, the pores and vessels become plugged to a greater or lesser degree (tyloses). Heartwood having these plugged tyloses prevents the passage of liquid through the pores, and the permeability of wood is low. This is negative for the use of impregnation but in some circumstances can add to the natural durability of wood.

The density of wood is major factor for the mechanical properties of wood and also for the dimensional stability of wood as affected by moisture content changes. In general, low-density woods have less dimensional change than heavy woods. The density of wood varies between and within different wood species. For most species, the density falls between 320 and 720 kg/m^3, but the range of density extends from around 160 kg/m^3 (e.g., balsa) to over 1000 kg/m^3 for some tropical wood species [*5,6*].

As a hygroscopic, heterogeneous organic material wood as such is often a suitable growth medium and nutrient source for several types of organisms. Degradation of wood by microorganisms is affected by interaction of wood cells and the surrounding microclimate. The chemical and physical structure of the wood cell wall has a major effect on the decay type and also on the intensity of decay. Porosity, permeability, lignin content, and the extractive composition of wood are important factors for wood durability, but they are not always connected to density and annual growth ring width.

Cellulose, the main component of the cell wall, is a chemically simple but structurally complicated homopolysaccharide formed by insoluble fibers of b-1,4-glucane. Cellulose is located mainly in the secondary cell wall and covers about 40 to 45% of the dry weight of several wood species. Hemicellulose, another wood polysaccharide, is formed by branched chains of several sugars, e.g., mannanes, glucanes, and xylanes. The heteropolymeric substances are composed of glucose, xylose, galactose, mannose, arabinose, and 4-0-methylglucuronic acids of glucose and galactose. The third structural component of the wood cell wall, lignin, is an aromatic and amorphous polymer. The main role of lignin is to act as gluing material in the cell wall and to give sufficient rigidity to the cell wall. The content of lignin in coniferous wood species is lower (18 to 25%) than in wood from temperate angiospermous species (25 to 35%) [*6*].

The durability of wood material against biodeterioration is dependent on the amount and quality of primary metabolites, storage compounds, and the extractives of wood. The amount of primary metabolites such as sugars, lipids, peptides, and starch varies in pine and spruce sapwood. The extractives include waxes, fats, free fatty acids, and alcohols, steroids, higher carbon compounds, and resins [*6–8*]. The resins are mixtures of components such as terpenes, lignans, stilbenes, flavonoids, and other aromatics. Extractives are most characteristically found in large quantities in heartwood, where their presence often imparts a characteristic color. There is variation in extractives between different wood species and individual logs and also in their distribution over shorter distances. The durability of wood is classified or grouped in different ways in Europe and the United States (Table 2).

Gypsum Boards

Main compound in gypsum boards is hydrated calcium sulfate. Many different type of boards has been developed for use in different targets. Gypsum plasterboard has two layers of strong liner on both side of gypsum core. Normal plasterboards consist of 93% gypsum, 6% liner, and 1% moisture, starch, and other additives. The type of additives depends on the usage and target of boards. Gypsum material for boards comes from natural stones, recycled gypsum, or industrial gypsum [*9*].

The surface quality of gypsum boards is based mainly on the liner and additives in the liner and surface treatments. Gypsum and additives in the gypsum have a minor effect on the surface on normal humidity conditions, but in very wet conditions or in direct contact with water, gypsum has the main role on the performance of the board. In very wet conditions, the gypsum part can adsorb a high amount of water and drying is slower than that of the liner.

The weight of gypsum plasterboards varies between 5 and 15 kg/m^2 (1 lb/ft^2 and 3 lb/ft^2) depending on the target of use. Floorboards are the strongest and wall boards for renovation the lightest. Standard boards are most often between 7 and 12 kg/m^2 (1.4 lb/ft^2 and 2.5 lb/ft^2).

Wallpapers and Paints

Most often the inside surfaces of different building materials are sealed with wall papers or paints. Wallpapers ranging from woodchip to vinyl wallpapers usually contain cellulosic compounds, which like the organic compounds of adhesives may supply nutrients for fungi and bacteria [*1,10*].

Paint constituents are binders, solvents, emulsifiers, pigments, fillers, and additives. The waterborne paints are

TABLE 2—The durability or decay resistance of heartwood of different wood species.

Durability Class (Europe)	Durability Class (USA)	Examples
Very durable	Resistant or very resistant	Teak, iroko, aphzelia, bilinga, mesquite, junipers, redwood (Sequoia) natural, meranti
Durable	Resistant or very resistant	Western redcedar, white oak, american mahogany, meranti, redwood (Sequoia) plantations
Moderate durable	Moderately resistant	Larch, douglasfir, hickory, african mahogany, khaya, tamarack, scots pine, southern pine
Non durable	Slightly resistant or nonresistant	Pine, spruce, elm, hemlock, hickory, oaks (red and black species)
Perishable	Slightly resistant or nonresistant	Alder, aspen, beech, birch, maple, poplar, balsa, ramin

based on aqueous dispersions of synthetic acrylic polymers or vinyl-type binders like polyvinylacetate or polyvinylpropionate. Binders used for waterborne paints are generally highly resistant to microbial attack. The paint film of these paints, however, is porous, but porositivy and pore-size distribution vary. In very porous paint film, the effect of paint additives and the quality of the substrate, the leachates from the substrate, and the other compounds from the environment (organic and inorganic dust) have a main role on the performance of the paint film.

Humidity and Moisture Content

Moisture content (MC) of wood is measured as the ratio of weight of water in a given piece of wood to the weight of wood when it is completely dry. MC depends on ambient humidity, temperature, exposure time, dimensions, and the moisture absorption capacity of wood. Moisture absorption, and therefore the moisture content of wood, is affected by the size and proportion of wood pores (lumina and smaller voids in the cell wall) and the chemical composition of the wood structure itself (i.e., content of cellulose, hemicellulose, lignin, and extractive compounds) [*8,11*]. Water can exist in wood as free water in cavities or bound water within cell walls. The moisture content at which all free water from cell cavities has been lost, but when cell walls are still saturated with water, has been designated as the fiber saturation point (FSP). The moisture content is then around 30 to 35% in Scots pine. In green Scots pine sapwood, the moisture content is around 160 to 180% and in green heartwood around 50 to 65%.

At moisture content near the water saturation point and in green wood, the wood is swollen to its highest dimension. When wood is dried below FSP, the dimensions of wood start to diminish and the wood is shrinking. The shrinking of wood is unequal, caused by the anisotropy composition of wood: there is variation within the wood species and within the different direction of timber. Normally the shrinking is much higher (twice) in the tangential than in the radial direction.

Being a hygroscopic material, the equilibrium moisture content of wood and other wood-based materials is easily affected by the ambient humidity and water. Moisture (water and water vapor) is quickly transported in the direction of wood fibers (longitudinally) and at a much slower rate across the grain (radially and tangentially). Water vapor in the atmosphere is absorbed by the wood until an equilibrium condition is achieved.

Relative humidity (RH) is the ratio of the amount of moisture in the air (at a certain temperature) to the amount it would be able to hold at the temperature. For the growth of organisms in the wood, water availability is most often the critical factor [*10,11*]. Water activity (a_w) is, like water potential, related to actual availability of water and is determined by both matric and osmotic components. The a_w is defined as the equilibrium relative humidity (ERH) divided by 100, i.e., relative vapor pressure (p/p_0) of the atmosphere with which the substratum is in equilibrium. The balance of wood moisture content with ambient air humidity is called equilibrium moisture content (EMC). At RH 98 to 99%, the EMC of pine sapwood is close to FSP or around 28 to 30%. During the manufacturing of different wooden products, the EMC can be changed. However, for biological processes and also for other properties of wood and other building materials, the ERH is the more usable term.

BIODETERIORATION

Environmental Factors for Biological Processes

For the development of biodeterioration, different biotic and abiotic factors are needed. Bacteria and different fungi are the main group of microbes growing in the building materials. For practical means, the discoloring fungi (mold and blue-stain fungi) and decay fungi (soft-rot, brown-rot, and white-rot fungi) are often distinguished. The organisms can be in different stages of their life cycles: spores, germinated young hypha, matured mycelium, and sporangiophores (mycelium with new spores). Fungal spores can be dispersed by wind, water, insects, or other animals.

The abiotic factors like water, temperature and quality of substrate (nutrients, pH, water permeability) are the most significant for the growth of microbes [*9,11–13*]. In some cases, also radiation, air movements, and gases of air can have some effects. However, the effect of these factors is often indirect. Air circulation affects humidity conditions and the gas composition of air. As such, it does not have any significant effect on the development of mold and decay fungi, and air circulation is required primarily for spores. Dry spores are usually released more easily into dry air than into humid air. Within the moisture damage of buildings, the humidity, moisture content, and duration of exposure is the main factor for development of mold and decay (Fig. 3).

Failure Organisms

In building structures, materials can be damaged by different microorganisms: bacteria, mold (mildew), blue stain, and decay fungi and insects (Table 3). However, in decay damage, several organisms are often involved (Fig. 3).

Bacteria

Bacteria are small one-cell microbes living overall in the ecosystem. For example, in a human being, the bacteria content of the colon may be higher than the human population of the whole world. Many bacteria are harmless, but some cause different problems (biocorrosion, disease). In building materials, bacteria are often the first colonizers in wet conditions [*1*]. Some effects are not so dangerous, e.g., noncellulolytic bacteria can degrade pectin in the pore membranes of wood cells and the permeability of wood is increased. Pounding in water is sometimes used as a pretreatment of wood in order to improve the impregnability. Wood storing in water or with water spraying for a longer time (weeks or months) can increase the permeability of wood, and the staining or color of wood after surface treatments can be uneven [*12*].

Knowledge of the role of bacteria in wood degradation is still rather scarce. Bacteria are now known to be able to de-

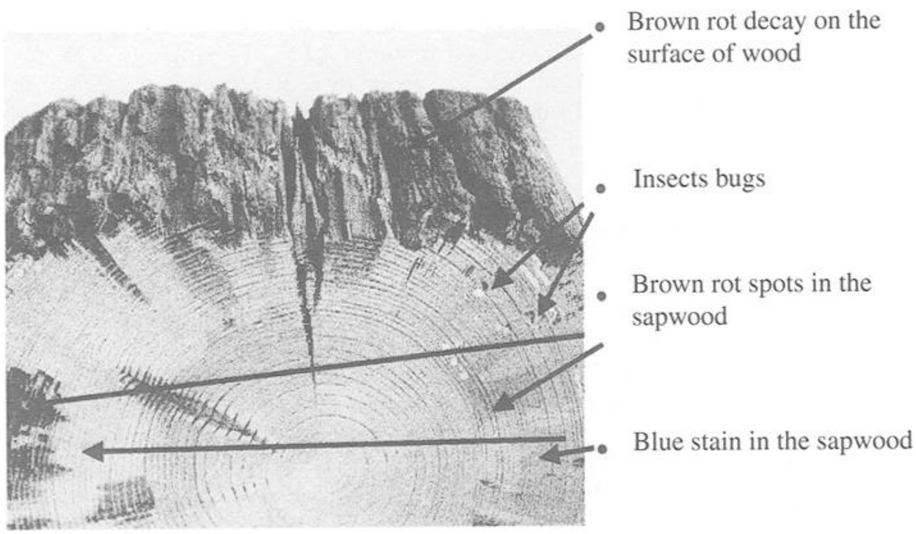

FIG. 3—Different types of bugs and decay in an old wooden beam.

TABLE 3—Organisms involving failures and damages of building components.

Organisms Type	Failure Type	Humidity or Moisture Range (RH or MC%)	Temperature Range °C (°F)
Bacteria	Biocorrosion of many different materials smell and health problems	Wet materials RH > 97%	Around −5 to +60 (23 to 140)
Mold fungi	Surface growth on different materials, smell and health problems	Ambient RH > 75%, depends on duration, temperature and mold species	Around 0 to +50 (32 to 122)
Blue-stain fungi	Blue-stain of wood permeability change of wood	Wood moisture content > 25–120% RH > 95%	Around −5 to +45 (23 to 113)
Decay fungi	Different type of decay in wood (soft rot, brown rot, or white rot), also many other materials can be deteriorated, strength loss of materials	Ambient RH > 95%, MC > 25–120%, depends on duration, temperature, fungus species and materials	Around 0 to +45 (32 to 113)
Lichen	Surface growth of different materials on outside or weathered material	Wet materials needs also nitrogen and low pH	Around 0 to +45 (32 to 113)
Insects	Different type of damages in organic materials; surface failures or strength loss of materials	Ambient RH > 65% depends on duration, temperature, insects species, and environment	Around 5 to +50 (41 to 122)

grade a wide range of untreated and treated timbers under diverse environmental conditions, including anaerobic situations. Bacteria may attack timbers resistant to fungal degradation due to preservation, high lignin content, or the presence of toxic extractives.

In very warm and wet conditions, some bacteria are also involved with the corrosion of many other materials, e.g., metals, plastics, concrete, and paints. Bacteria can cause corrosion of electric components, fuel oil tanks, surface of metals, and even concrete drain pipes [*1*]. In moisture damages of buildings, typical bacteria like Actinomycetes (e.g., *Streptomyces* spp) are involved. They are mycelium-forming bacteria and can cause a very powerful smell in wet materials [*14,15*].

Mold fungi

Mold and blue-stain fungi are often together called discoloring fungi. Discoloring fungi are often the initial microbial colonizers of materials. Blue-stain fungi invade the wood through the parenchyma and epithelial cells. Mold and blue-stain fungi assimilate available nutrients, low-molecular carbohydrates (sugars), lipids (fats), and proteins. Mold fungi can grow on the surface of many different materials, e.g., food, textiles, leather, coatings, paintings, paper, wood, wooden boards, gypsum boards, some plastics, facing, brickwork, concrete [*1,9,13–18*].

Mold fungi is a heterogeneous and not a particularly well-defined group of fungi. Most of the mold fungi, as also the blue-stain and soft rot fungi, belong to *Ascomycotina* (Ascomycetes) fungi. Also many *Myxomycota, Mastigomycotina,* and *Zygomycotina* fungi are considered as mold fungi.

In wooden materials, both mold and blue-stain fungi may cause problems in different stages of the industrial production of wood-based products. Logs can be infected by fungi in forests and in storage, sawn goods can be contaminated before and during drying and storage or at the building site if the conditions for fungal growth are favorable. In buildings, mold fungi cause problems in different structures and materials: roofs, basements, floors, and walls.

Many building materials can support growth of microbes, and mold problems are more common than decay damages. Typical mold fungi found in damaged buildings are, e.g., *Acremonium*, Aspergillus species (e.g., *fumigatus*), *Aureobasidium pullullans*, *Alternaria alternata*, *Cladosporium* species (e.g., *herbarum*, *sphaerospermum*), *Mucor* species, *Penicillium* species (e.g., *brevicompactum*) and *Stachybotrus* species (e.g., *atra*). Often these fungi are also found in nature (soils, decaying materials, and waste).

Decay fungi

Different classifications are used for the decay fungi in practice. Often three different decay types are classified: brown rot, soft rot, and white rot. Most of the brown rot and white rot fungi belong to *Basidiomycetes*, but some belong to *Ascomycetes*. Most of the soft rot fungi belong to *Ascomycetes* and *Fungi Imperfecti*. Soft rot fungi cause cavities in the cell wall and the strength of wood is rapidly affected (the color or structure of wood is less changed).

In buildings suffering from excessive moisture loading, brown rot is the most common decay type. Brown rot develops rapidly and will change the color, form, and strength of wood if conditions are suitable for the development of fungi. Among the typical brown rot fungi that cause the most serious damage in buildings in temperate climates are *Serpula lacrymans* (dry rot fungus), other *Serpula* and *Leucogyrophana* spp., *Coniophora puteana* (cellar fungus), different *Antrodia/Poria* species, *Gloeophyllum sepiarium*, *Gloeophyllum trabeum*, *Paxillus panuoides*, and *Lentinus lepideus* [*21*]. The dry rot fungus and the cellar fungus cause damage, especially in floor construction. In roofs and walls, the damage is more often caused by mold fungi or other brown rot fungi. A typical soft rot fungus is *Chaetomium globosum*. White rot fungi are not so often connected to moisture damages of buildings. They are the main cause of damage in growing trees, wood storage, and in very wet conditions.

Insects

Insects can deteriorate different types of materials even though they don't use them as food [*1*]. However, wood-destroying insects usually utilize material as a foodstuff, either directly or indirectly. Some insects are only boring materials to make nests without feeding on them. Termites (*Isoptera*) are the most important wood destroyers in the tropics, and subterranean termites are economically the most important wood-destroying insects. The termite colonies are usually housed in nests called termitaries. All termites live almost exclusively in total darkness. Subterranean termites build shelter tubes from the ground to wood, often over building foundations. Some termites can also attack dry wood. Dampwood termites attack wet and decaying timber. Harvester termites feed on leaves and plants and do not damage wood.

Many thousands species of beetles (*Coleoptera*) can attack materials [*20*]. The problems in materials are most often caused by larvae. *Lyctidae* (e.g., *Lyctus brunneus*) often infest hardwoods with wide vessels. *Anobium punctatum*, the common furniture beetle, is common in most parts of the temperate world. It can not tolerate the cold winter of cold climate regions and the minimum ERH for the development of *A. punctatum* is at around 65 to 70%. The death watch beetle, *Xestobium rufovillosum* and *Hadrobregmus pertinax*, requires higher moisture content in wood and usually attacks decaying timber (Fig. 3). They are typical beetles in old wooden houses that are attacked by rot fungi. *Anobium punctatum* has become more uncommon when the relative humidity of inside air is lowered due to better heating and ventilation systems in buildings. Long horn beetles, *Cerambycidae*, are mostly forest insects with few species attacking timber in constructions. *Hylotrupes bajulus* is widespread in Europe. The large larvae tunnel usually in softwood for 3 to 6 years. In many cases, *Buprestis haemorhoidalis* causes local damage in wood constructions and is not as harmful as *H. bajulus*. Some insects live only in the bark of trees or in the outer part of sapwood, e.g., bark borer beetle, pinhole borer beetle. Many insects cause problems with foods, textiles, and other materials in buildings.

Critical Conditions for Mold Development

Mold fungi can grow on many different materials. They need nutrients from the medium, high humidity, or water. In order to avoid mold and decay damage in structures, the lowest (threshold) conditions were fungal growth is possible are critical. However, the duration of conditions is also significant. There are certain minimum and maximum levels for moisture content of material (or water activity) or temperature between which fungi can grow in wood. Between these threshold levels, the growth and development of damage may start and proceed at different rates depending on the interrelationship between humidity and temperature and upon other factors such as the organisms and the properties of the materials (Fig. 4).

Ambient relative humidity (RH) above 75 to 80% (a_w above 0.75 to 0.80) are critical for the development of mold fungi in the surface of building materials (Table 4). Also, lower water activity limits for growth of mold fungi have been presented, but these studies have not been concerned with building materials [*15,17*]. The temperature range required for the growth of mold fungi is most often between 0 and +50°C (32 and 122°F). Some mold fungi have been found to grow at very low temperature, between 0 and −7°C (32 and 20°F) and some thermotolerant species like *Aspergillus fumigatus* can grow at +55°C (130°F) [*10,14,21*]. The mold fungi grow rapidly at higher humidity (ERH > 95% or a_w > 0.95) at temperatures between +20 and +40°C (68 and 104°F). At low temperatures, below +5°C (41°F), the growth of mold fungi is slower even at high RH (Fig. 5). The wood moisture content is not a very valuable measure for mold development, since mold fungi are growing on the surface of wood. For mold development, the moisture content close to the wood surface is the most critical. However, the wood moisture content also affects the humidity condition close to

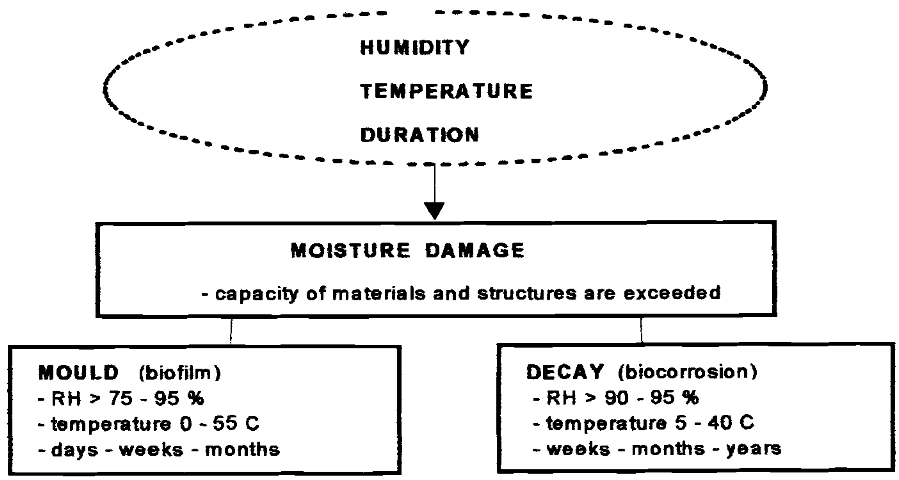

FIG. 4—Humidity, temperature, and exposure time affect moisture damage and subsequent potential mold and decay problems.

TABLE 4—Critical humidity (RH%) level for mold growth and decay failure on different materials.

Material	Mold Growth	Decay
Pine sapwood	>80–95	>95
Pine heartwood	>80–95	>95
Particle board	>80–95	>90
Gypsum board	>80–95	>95
Fiber board	>80–95	>95
Wallpapers	>75–95	>90
Putties	>90–95	
Different coatings	>75–95	
Concrete	>95–98	

the surface. If materials are wet, the humidity of the microclimate of the surface can be higher for a long time and can promote the fungal growth on the surface.

For fungal growth on gypsum board, an RH between 86 and 92% is critical [*9,11*]. In high-humidity conditions (RH 97%) the growth of fungi is faster. According to Grant et al. [*10*], the growth of mold fungi on emulsion painted woodchip paper was found after three weeks' exposure at 25°C (77°F) and RH 79%, and the nature of substrate affected fungal growth on the painted surface [*13*]. According to Pasanen et al. [*15*] the minimum RH required for fungal growth on wallpaper, plywood, gypsum board, and acoustical fiber board was between 83 and 96%, depending on the fungal species involved.

A certain duration of suitable exposure conditions is required before fungal growth will start or the damage will reach a certain grade. In the work of Viitanen [*21,22*], particular emphasis is focused on this time period, the so-called response time or response duration. The response times proved to be short (from a few days to a few weeks) in conditions favorable to the growth of microorganisms and long (from a few months to a year) in conditions close to the minimum and maximum moisture or temperature levels.

Within fluctuating humidity conditions, the period of low-humidity conditions preventing mold growth is especially critical for mold growth when the period at high RH (above the limit for the growth of mold fungi) is shorter than 24 h [*23,24*]. When the period at high RH is longer than 24 h, the effect of cumulative time at high humidity is more linear, and the cumulative sum of periods with favorable conditions for the growth of mold fungi can be used as a measure to predict their development. An exposure period at low RH prevents growth and has a direct effect on the total response time required for mold growth. In practical cases it means that the short high humidity causes no risk for mold if the moisture of structures is not increased to a longer time. For example, RH 95% for 2 h/day causes no harm if the continuous ERH of materials is below RH 75% (Fig. 6). Temperature fluctuation can cause condensation of water or high RH near the surface if the RH of the inside air is high (e.g., above 50% during the winter). In fluctuating temperature conditions at a high RH, a fall in temperature will add or even condense moisture on the wood surface and drastically enhance the available moisture for microbial growth.

Adan [*9*] used a non-linear regression technique to model sigmoidal curves describing vegetative fungal growth of *Penicillium chrysogenum* on gypsum board material. He introduced the time-of-wetness (TOW) as an overall measure of water availability for fungal growth under fluctuating humidity conditions. The TOW is defined by the ratio of the cyclic wet period (RH $\geqq$ 80%) and the cyclic period. The preliminary experiments indicated that growth of *P. chrysogenum* on the gypsum-based finishes is only weakly affected for a TOW $\leqq$0.5, whereas it accelerates strongly with increasing values >0.5.

Critical Humidity and Moisture Level for Rot Decay

The moisture required for spore germination and mycelial growth is higher for the brown rot fungi than for the mold fungi. It has been shown by many authors that a brown rot attack on wood has no practical significance if the wood moisture content is less than 30%. However, a slight growth and activity of *C. puteana* and *S. lacrymans* has been recorded even at RH 97% and 20°C (68°F) when the moisture

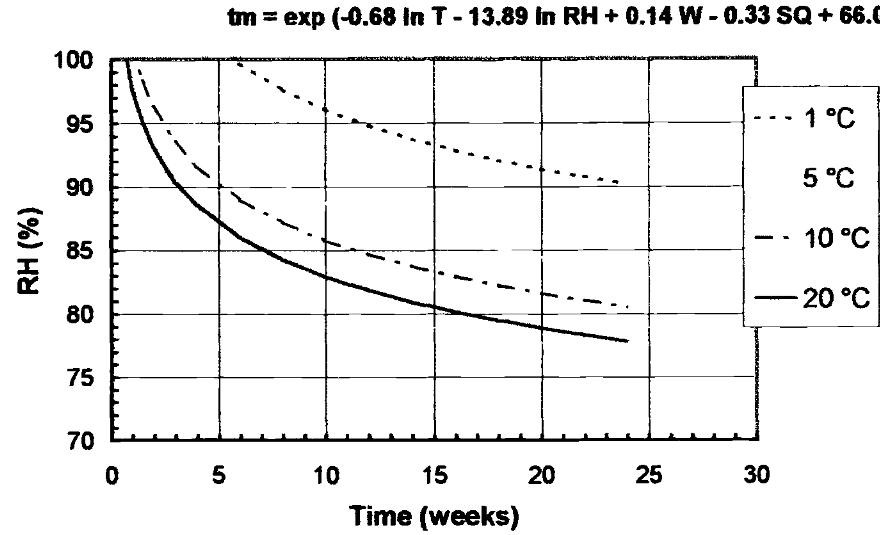

FIG. 5—Prediction of risk for mold development on pine sapwood at prevalent ambient temperatures (1, 5, 10, and 20°C) and prevalent ambient relative humidity (RH). After Viitanen [21].

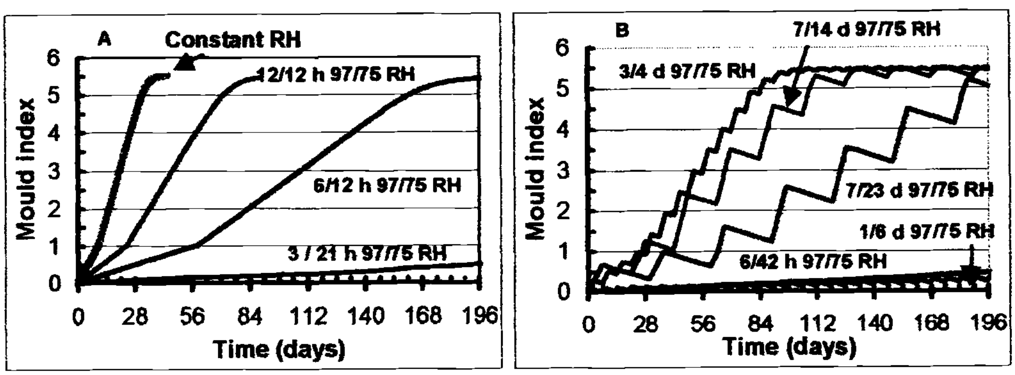

FIG. 6—Prediction of mold development on pine sapwood in fast (hours) fluctuated (A) and slow (days) fluctuated (B) humidity conditions at 20°C (68°F). High humidity is RH 97% and low humidity RH 75%. After Viitanen et al. [24].

content of unsterile pine and spruce sapwood was on average 25.6 to 26.5% [21]. The brown rot fungi are growing best, however, at wood moisture contents between 30 and 70% (Table 5).

The dry rot fungus has caused serious damages in buildings due to effective water transport system of its mycelium. Fungus can transport water from moisture sources towards dry wood, if no evaporation is possible. In airtight or low permeable structures, fungus can spread in the construction and cause large damage.

The critical response time period required for decay development is strongly dependent on water activity and temperature (Fig. 7). The minimum water activity level for decay development is around 0.95 to 0.98 (ERH 95 to 98%). The temperature limits for the growth of rot fungi has been reported to vary between −5 and +45°C (23 and 113°F). However, below 0 to 5°C the development of decay is very slow and the lethal temperatures vary between 35 and 80°C (95 and 176°F) [25,26,27].

Effects of Materials on the Development of Mold and Decay

The susceptibility of different materials to mold and decay fungi depends mainly upon the water activity and nutrient content of the substrate. According to Block [17], the materials that are most hygroscopic and have sufficient nutrients are most susceptible to mold growth. However, the nutrient content level has no significant effect on the ultimate humidity limit for mold growth on materials.

During the manufacturing of different wooden products, the properties of materials and also the equilibrium moisture content (EMC) can be changed. For example, the EMC of particle board is lower than the EMC of solid wood [18,21]. However, for biological processes and also for other properties of wood, the water activity, RH, or equilibrium relative humidity (ERH) is a more usable term. ERH or ambient RH or water activity should be used as the critical measure for mold and decay problems. However, for rot development, the

TABLE 5—The temperature and moisture content levels for the development of decay caused by different brown rot fungi found in building damages.

	Temperature °C (°F)		
Fungus Species	Min.	Opt.	Max.[a]
Serpula lacrymans	0 to 5 (32 to 41)	15 to 22 (59 to 72)	30 to 40 (86 to 104)
Coniophora puteana	0 to 5 (31 to 41)	20 to 25 (68 to 77)	40 to 46 (104 to 115)
Antrodia/Poria spp.	3 to 5 (37 to 41)	25 to 30 (77 to 86)	50 to 70 (122 to 158)
Gloeophyllum trabeum	5 to 10 (41 to 50)	30 to 50 (86 to 122)	55 to 80 (131 to 176)
G. sepiarium	0 to 5 (32 to 41)	30 to 45 (86 to 113)	40 to 60 (104 to 140)
	Moisture Content, MC %		
Fungus Species	Min.	Opt.	Max.[b]
Serpula lacrymans	17 to 25[c]	20 to 55	60 to 90
Coniophora puteana	25 to 30[d]	30 to 70	60 to 100
Antrodia/Poria spp.	25 to 30	35 to 55	60 to 100
Gloeophyllum trabeum	25 to 30	40 to 60	80 to 180
G. sepiarium	25 to 30	40 to 60	80 to 120

[a] Fungi can tolerate this higher temperature for limited periods only.
[b] In decayed wood, moisture content can be higher due to increased porosity of wood caused by decay (especially within *Gloeophyllum trabeum*).
[c] Mycelium of Serpula lacrymans (dry rot fungus) can transport water and the fungus can spread from a moisture source towards wood with about 17 to 20% moisture content. Normally the growth of dry rot fungus can be started at RH > 95% (wood moisture content around 25%).
[d] According to some laboratory and field tests, lower levels were also obtained. However, the moisture content of wood depends on the quality of wooden products and in some cases the EMC is lower at the same RH. Normally the growth of cellar fungus can be started at RH > 95% (moisture content of pine sapwood around 25%).

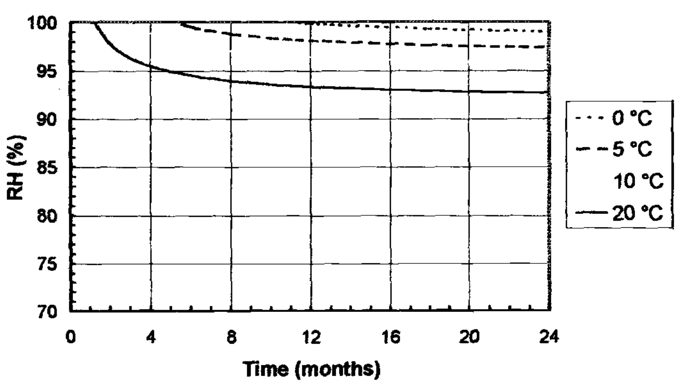

FIG. 7—Critical response time in constant humidity and temperature conditions for brown rot decay development (early stage decay, mass loss below 5%). After Viitanen [27].

humidity conditions needed are so high that the use of ERH is difficult. For decay development, the moisture content is often above the fiber saturation point (MC > 30%).

Norway spruce sapwood has often proved to be less susceptible to mold than Scots pine sapwood. In conditions favorable for decay, however, the decay rate in spruce can be higher than in pine. The heartwood of several wood species is often more resistant than sapwood. However, the effect of surface quality can be more significant than the effect of wood species for growth of mold fungi. It has been shown that after fast kiln drying, the amounts of nitrogen and low-molecular hydrocarbon compounds on the surface layers of sawn timber can be higher than inside the wood [*12,16,28,29*] and this may promote the mold growth.

Logs are often wet-stored or water-stored at the sawmill. Water spraying is routinely applied to protect timber from fungal and insect attack during storage, especially to decrease economical losses caused by blue stain fungi. However, prolonged wet storage has been shown to lead to increased permeability and chemical changes with unfavorable effects on several properties or subsequent use of the wood. In very wet conditions, water-stored wood can absorb higher amounts of water than non-wet-stored wood. In some circumstances, this will retard the start of growth and activity of mold and rot fungi [*21,27*].

In buildings, the material is most often coated, treated, or painted with different products and treatments. In such cases, the surface treatment has an important role for the durability and lifetime of substrate. Degradation of the surface by micro-organisms is affected by the interaction of material, surfaces, and the surrounding environment and microclimate. The chemical and physical structure of the substrate as well as the surface treatments has a significant effect on the quality and service life of the treated system, e.g., several factors affect mold and decay resistance of painted wood [*13,21,30,31*]:

- Wood material and nutrient content on the wood surface.
- Type of the exposed structure (wall height, eaves, joint, end grains, fastenings).
- Paint type, fungicides, and their concentration in the paint.
- Application of fungicides in the pretreatments, primers, and paints.
- Exposure conditions (humidity, temperature) and exposure time.
- Colonies of microbes and fungi.

CORROSION

Electrochemical corrosion of metal components such as structural framing, reinforcing bars, masonry anchors, ties, flashings, etc.

Mechanisms

The nature and rate of the atmospheric corrosion depends upon the properties of surface-formed electrolytes, particularly with regard to the level and type of gaseous and particulate pollutants in the atmosphere and to the duration of their action on the metallic surface. Thus, not only the hygrothermal performance of the building structure but also the corrosivity of the exterior (or interior) environment determine the vulnerability of the materials to corrosion. The corrosivity categories may be assessed in terms of the most significant atmospheric factors influencing the corrosion of metals and alloys, i.e., time of wetness and pollution level. The corrosivity category is a technical characteristic that provides a basis for the selection of materials and protective measures in atmospheric environments subject to the demands of the specific application, particularly with regard to service life.

Affected Materials

Corrosion affects mainly metals, alloys, and metallic coatings—in a broader sense other materials may also be considered susceptible to corrosion. Corrosion does not require water in liquid form—chemical attack may occur at, for example, relative humidities as low as 80% ISO Standard Corrosion of Metals and Alloys—Classification of Corrosivity of Atmospheres (9223). Some materials may not suffer from corrosion at all in some structures even though the thermal and moisture conditions are favorable to corrosion—some chemical catalyst is required. This may happen, for example, when fire-retarding chemicals used in thermal insulation materials are transported by water movement onto the metal surface [*32*].

Chemical incompatibility may cause corrosion when two dissimilar metals are in contact. Joined materials may require (but not always) liquid water to be present in order to suffer from corrosion or chemical damage. Corrosion of metal in reinforced concrete can be slowed down by the slow diffusion of oxygen from the atmosphere into the concrete at high moisture contents (pore space filled with water-resisting oxygen diffusion). The corrosion rate of concrete has been found to be at its highest at a relative humidity of 95% in the concrete because of the reduced diffusion effect.

Small details in structures—e.g., nails in wood, joints between sheets—may be exposed to different conditions than for example the clear wall surface. Moisture condensation on the surface of a steel frame may be driven by gravity or capillary forces and be found between two sheets of metal. The wetting of this joint occurs fast, whereas drying may take extremely long because of a very small surface area for evaporation to allow drying.

Corrosivity Categories

Corrosivity of the atmosphere is defined as the ability of the atmosphere to cause corrosion in a given corrosion system (e.g., atmospheric corrosion of a given metal or alloy). The corrosivity categories in the ISO Standard (9223) are classified for time of wetness, pollution by SO_2, and airborne salinity. Different metals and materials may be susceptible to corrosion caused by various other chemicals, too, such as NO_x, Cl_2, H_2S, organic acids, etc. For the purpose of the International Standard, SO_2 and chloride have been selected as the key corrosion factors. Thus, degradation factors that need to be taken into account must be individually determined for each case under consideration. The time of wetness is defined as the period during which a metallic surface is covered by adsorptive and/or phase films of electrolyte that are capable of causing atmospheric corrosion. The time of wetness can be determined either by using calculation methods or measured directly.

Calculation of Time of Wetness

The time of wetness can be calculated by summing up the length of time over one year when the relative humidity RH is above 80% at the same time when the temperature is above 0°C (32°F). The atmosphere can be characterized in relation to its corrosivity by calculating the time of wetness using the temperature and the relative humidity of the ambient air. The time of wetness in the building envelope parts, however, does not necessarily correspond with the time of wetness in the exterior climate. The time of wetness may be high in the building structure even in cold and dry climates if the moisture performance of the structure is poor. Within the time of wetness categories the pollution level by sulfur dioxide and chlorides are the most important factors. The corrosivity of the atmosphere is divided into five categories, each corresponding to a corrosion rate. The category of corrosivity for a given location is determined as a function of (a) time of wetness, (b) the deposition rate of chloride, and (c) the deposition rate of sulfur (sheltered structures can be considered to have no deposition of pollutants).

CALCULATION METHODS TO PREDICT FAILURES

Heat, air, and moisture transfer simulation models can be used to predict the hygrothermal performance of building envelope components. The results from the simulations in turn can be analyzed to predict failures. The failure analyses can be carried out by postprocessing the primary output data from the hygrothermal simulations, or the numerical simulation model can be modified to calculate additional parameters that assist us in determining whether a risk for damage exists. Various levels of accuracy can be obtained by using not only different numerical methods but also different levels of input data. Even the most sophisticated models that exist today rely vastly on the input that the users are able to insert to the programs.

A very simple method to evaluate the failure risk in materials and structure is to measure and calculate the moisture or humidity level of materials for a longer period. Unfortunately, this method can be used only for limited targets since the moisture and humidity level, as well as the temperature and their duration time, are changed. The minimum moisture requirement for the growth of fungi, about 20% in wood corresponding to about 80 to 90% RH, is often quoted in the literature [*7*]. Accordingly, it is often given in building instructions as the maximum allowable moisture condition for wooden structures in order to avoid biological damages. In Fig. 8, some aspects of humidity, temperature,

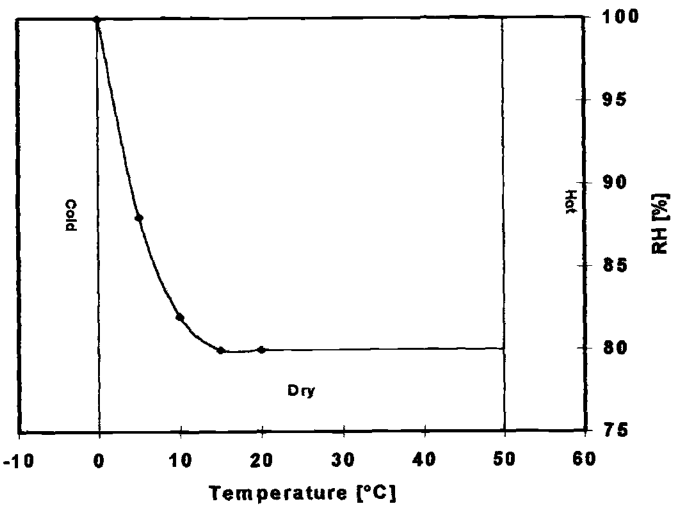

FIG. 8—Conditions favorable for initiation of mold growth on wooden material as a mathematical model. After Hukka and Viitanen [33].

and the mold index are presented [32]. Then the duration of the condition or the temperature has not been taken into account. According to experience, the ambient humidity in active mold damages have been above 75 to 80% and in decay damages above 90 to 95%.

In buildings, moisture transport and accumulation and interactions of different materials affect local moisture conditions and complicate the evaluation of moisture risks. The growth of fungi also changes the moisture conditions, as water is produced in the decay process and certain fungi like the dry rot fungus can efficiently transport water from a moisture source to dry structures. This will change the concept of calculations.

Manual Methods

The dew point method, or its modifications in the Glaser or Kieper methods, may be used to roughly estimate the likelihood of condensation or high relative humidities within the building structures (see Chapter 7). Surface condensation on windows or wall frames may be estimated simply by looking at the wall/window surface temperature, the corresponding saturation vapor pressure, and the vapor pressure of indoor air. The simple hygrothermal calculation methods have such shortcomings that they can not be used to predict failures or damage in building components except in structures with excessively poor moisture performance. The manual calculation methods ignore many of the processes and properties that are relevant in order to perform accurate analysis. Some of these are moisture or thermal capacity of materials, moisture-dependent transport properties, airflow, capillary transport, latent heat of evaporation, or melting just to mention a few. Even the most sophisticated methods still lack a lot of information and submodels of moisture transfer.

Advanced Numerical Tools

Advanced heat, air, and moisture transfer models, such as those described in other chapters, may provide us with the relevant parameters required to perform damage or failure prediction. Such parameters include temperature, relative humidity, and moisture content. Additional parameters that have to be embedded into the models or extracted from the saved results include: time of wetness, freeze-thaw cycles (as a function of moisture content or saturation), and mold growth estimating index. The models should separate vapor and liquid flows—liquid flow of moisture may transport chemicals to the surfaces of materials that are not resistant to them. Moisture-driven salts on the surface of brick walls might not damage the brickwork, but nevertheless damage has occurred in the form of lost esthetic quality.

Current damage models that use hygrothermal simulation results as input should be used primarily for comparing the performances of building components and for carrying out sensitivity analyses. The reason for this is the combined accuracy and uncertainty of the calculations. The accuracy of the models is discussed later.

Currently only deterministic models are used for hygrothermal performance predictions. Some stochastic or probabilistic models have been used for research purposes, but even today with quite powerful computers, e.g., the Monte Carlo simulation method requires in most cases too much effort to be practical for everyday use for designers. Stochastic modeling is needed if proper damage or risk analysis is going to be carried out. Most of the input parameters in a hygrothermal simulation have statistical distributions—they are not single valued [3].

The most important types of parameters are exterior and interior climate, material properties, geometry of the structure, and initial conditions and finally and most importantly the degradation processes, i.e., the performance criteria. In order to carry out meaningful simulations for the purpose of designing durable structures with long service life we need to use, for example, the moisture design reference year (MDRY) as exterior climate instead of weather data meant for energy calculations. MDRY should be more severe than the long-term average climate conventionally used for energy calculations—we do not want our buildings to fail every second year. Here we have to make a clear distinction: we will have to decide whether we are going to carry out simulations in order to predict the performance in the future with the known environmental conditions or whether we want to design the structures in order to make them last and serve as intended as long as possible. When designing building structures with deterministic models we will have to set safety factors in the input data, i.e., the boundary conditions and material properties or in the failure criteria.

Failure Criteria

In order to assess the material and system performance we first have to identify the mechanisms that lead to damage and loss of performance. In the design phase of buildings we should (1) establish appropriate levels of performance for building and components (i.e., the limit states), (2) prescribe performance criteria for materials, components, and assemblies, and (3) confirm acceptability and achievement of performance [4]. The performance criteria can be divided into two main categories: qualitative criteria and quantitative criteria.

Qualitative criteria have to be used when we do not know the degradation processes in detail. For example, we could know that the rate of degradation increases as the moisture content increases. With qualitative criteria it is not possible to assess the risk for moisture damage. The examples of the qualitative criteria could be, e.g., not to allow net yearly moisture accumulation or condensation to occur at any time of the year. Conventional methods have been to set critical moisture content levels, critical relative humidity, or critical cumulative exposure to certain conditions. We may require, for example, that the moisture content of the material may not rise above 80% RH or 90% of saturation moisture content or that no freeze-thaw cycles (or a certain number of them) are allowed when moisture content is above the set limit.

Quantitative criteria can be used only if performance limit states are known. Statistical data about degradation for considered materials with known conditions have to exist. Quantitative criteria can ultimately be used to assess degradation or risk for moisture damage.

Mold Growth Estimation

Recently, Viitanen [*22*] has published comprehensive regression models for mold growth in constant humidity and temperature conditions for pure pine and spruce sapwood. Those regression models along with the experiments in fluctuating conditions are the basis for the new mathematical model [*33*]. It is a material model describing the response of pure wooden material to arbitrary temperature and humidity conditions and will form an essential part of a more complete structural model simulating the moisture behavior of building structures in actual measured weather conditions. Adan [*9*] has developed a model for the mold growth and moisture properties of gypsum boards and other gypsum materials.

The regression models describe the development of mold and decay in relation to humidity, temperature, and the duration of exposure (see Figs. 5 and 7). The critical minimum level of humidity and temperature and their critical duration for the initial stages of mold and decay or for the development of mold and decay in pine and spruce sapwood can be predicted from these models.

Mold growth in the structures can be estimated by using a model equation that employs temperature, relative humidity, and exposure time as input [*4,33*]. A short introduction to the mold growth model and involved mathematical equations is given here.

Quantification of mold growth in the model is based on the mold index used in the experiments for visual inspection (Table 6). The mold growth model is based on mathematical relations for growth rate of mold index in different conditions including the effects of exposure time, temperature, relative humidity, and dry periods. The model is purely mathematical in nature and, as mold growth is investigated only with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also, the mold index resulting from computation with the model does not reflect the visual appearance of the surface under study, because traces of mold growth remain on wood surfaces for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface.

TABLE 6—Mold index values and their description for mold growth.

Index	Descriptive Meaning
0	No growth
1	Growth starts, some growth detected only with microscope
2	Moderate growth detected with microscope
3	Some growth detected visually, new spore formation
4	Visually detected coverage more than 10%
5	Visually detected coverage more than 50%
6	Visually detected coverage 100%

The model makes it possible to calculate the development of mold growth on the surface of small wood samples exposed to fluctuating temperature and humidity conditions including dry periods (see Fig. 6). The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

The calculation method is briefly as follows. The critical relative humidity above which mold growth is possible is a function of temperature. At temperature below 0°C and above 50°C (122°F), mold growth is in most cases not possible. The critical relative humidity lies between 100% RH (at 0°C (32°F)) and 80% RH (at 20°C (68°F)). The growth rate of mold increases as temperature and relative humidity increase and is also dependent on the mold index itself: higher mold index enables faster mold growth. During dry periods when relative humidity is below the critical humidity or when temperature is outside the range of temperature enabling mold growth, the mold index decreases at a constant rate.

After having mathematical models in mold growth or mold index, we can connect the model with building physics simulation model like TCCC2D [*4*]. In this way, we can estimate if the conditions in different simulated structures offer a risk for mold growth. We can also simulate if the mold risk is a significance risk and in which part of a simulated envelope structure the risk can exist. Currently, the mold growth estimation model is used mainly for comparison of different structures with different air leakages. We can ask: should we allow any mold growth at all in various parts of the building envelope or can we allow growth to occur in the exterior parts not directly in contact with the interior air? These are the questions that have yet to be answered. In the current situation the mold growth estimation model is used mainly for comparison purposes for which it is a powerful tool. An example of this is given in Fig. 9, which shows the calculated mold index in the exterior sheathing when different cavity ventilation rates have been used in the exterior wall cavity between the siding and exterior sheathing. For this specific exterior wall case, a minimum ventilation rate could be found to minimize the potential for mold growth.

Uncertainty and Errors of the Failure Predictions

The results of hygrothermal performance simulations accommodate vast uncertainty even if the numerical and physical equations are very accurate in comparison to analytical solutions. We know, for example, that the material properties may have large scatter (e.g., ±40%) [*34*] and the boundary conditions and the microclimate around the building envelope part can not always be known with satisfactory accuracy. Degradation mechanisms have their own statistical behavior and furthermore degradation relies on the results of the hygrothermal simulations. Owing to this we have con-

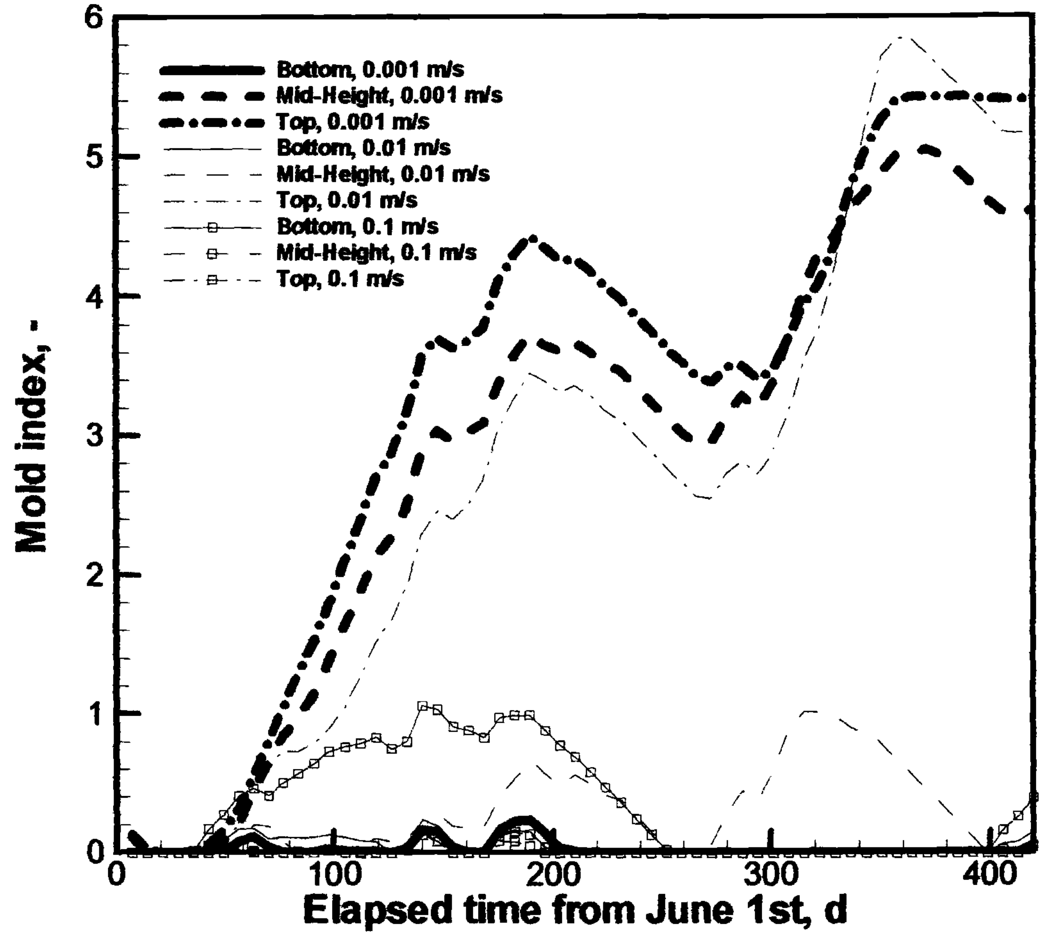

FIG. 9—Mold index on the exterior surface of exterior sheathing (porous wood fiber board) at different heights of the wall as a function of different cavity ventilation rates. Results for a wall with building paper.

founding factors that make the estimation of failures quite uncertain with the use of deterministic models. Because of these uncertainties that can not be taken care of with the deterministic methods, we will have to set safety factors and carry out sensitivity analyses in order to find material properties, systems, and practices that lead to more durable, hygrothermally well-behaving building systems with long (design) service life.

FUTURE PROSPECTS

New models are developed further, and the fluctuation of humidity and temperature are included in the models and these new models are connected with the LATENITE programs [*4*]. The mathematical models developed can be utilized in building design and maintenance to evaluate and eliminate the risk of biological damage in timber structures. These models can be used to predict the critical duration of different humidity and temperature conditions for the development of mold in wood materials.

It has to be noted that the models thus far are based on a limited range of materials and conditions and may not apply outside the limits of this study. The model makes it possible to calculate the development of mold growth on the surface of small wood samples exposed to arbitrary fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

When applying the models, the great natural variability of materials and different treatments should also be taken into consideration. More information is needed on the effects of wood properties in order to include the properties as true variables in the models. Further studies are also needed on the effects of alternating conditions on the development of damages. With further research, the models could in the future serve as a basis for improvement of design and dimensioning of timber structures in order to avoid biological damages.

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5

Overview of Hygrothermal (HAM) Analysis Methods

by John Straube[1] *and Eric Burnett*[2]

IN THE DESIGN of modern engineered buildings it is customary to use a variety of mathematical models to simulate the performance of the structural system and the service (HVAC) systems. Structural, mechanical, and electrical engineers use various different mathematical models to analyze the response of the modeled system or subsystem and then improve, adjust, or revise the system as needed until a final design is arrived at. Analysis, even crude analysis and, perhaps, with more than one model, is necessary to design a new facility or subsystem as well as to assess an existing building or part thereof.

The building industry is moving toward a similar situation with building enclosures. However, we in North America still have some way to go in developing a professional consensus on which models are to be preferred, what analysis procedures are cost and qualitatively effective, and how to develop the necessary experience to use these models properly. Rapidly changing technologies, e.g., materials and interior building environments, combined with higher expectations of performance for both the enclosure and the building, have created a very real need for the development and use of practical hygrothermal analysis methods.

This chapter will provide some background and a brief overview of the various building hygrothermal analysis methods. The objective is to provide a framework to identify the different needs, to list and compare analytical procedures and models, and to give some direction to those who would like to match need and HAM (heat, air, and moisture) analysis methods. The intent and limitations of the various hygrothermal analysis procedures, the factors that affect the value of the results, and the nature and amount of information required are also outlined.

The intent of this chapter is not to reproduce the excellent and detailed state-of-the-art report authored by Hugo Hens as part of the IEA Annex 24 project. This document should be referred to for more detailed information on heat, air, and moisture physics and for a more comprehensive listing of models.

THE NEED FOR ANALYSIS

The general goal of hygrothermal analysis is the evaluation of the temperature and moisture conditions that might prevail across and within a portion of any building enclosure over time. Different individuals or groups may have different needs for HAM analysis. Three general needs for analysis can be identified: design, assessment, and study (Fig. 1). Design professionals such as architects and engineers generate the first two needs. Researchers and students have a need to study enclosure performance.

Probably the most important and also the most basic need is to learn how to conduct a HAM analysis and thereby to develop the experience necessary to undertake design and then to utilize the more sophisticated analysis tools. Research is an extension of this basic need in that, for the purposes of research, development, or demonstration, more accurate and more complex mathematical models may be necessary. The need for assessment of an enclosure whether for the purpose of a condition assessment, forensic investigation, conversion, or space conditioning energy calculation usually involves an existing building. Of course the process of design involves choices, repetition, and judgment and requires much more than analysis. Figure 2 is an attempt to demonstrate the procedural and other differences between design needs and assessment or study needs. Note that one important decision that has to be made is whether a formal analysis is even necessary; prior experience may obviate any need for an analysis.

The purpose of most hygrothermal analysis is usually to provide sufficient and appropriate information needed for decision-making. The three most common reasons for conducting of a hygrothermal analysis can be listed as:

1. Develop an appropriate level of understanding of enclosure response, e.g., does condensation occur and how much; is thermal bridging significant; where and when will decay occur?
2. Identification and/or avoidance of a performance problem, e.g., excessive condensation; stud ghosting; decay.
3. Quantify energy flow through the enclosure as well as its impact on comfort and mechanical systems.

Depending on the need, an appropriate analysis technique should be chosen. The quality and quantity of information required must be consistent with the analysis technique chosen. For example, consider the case where one needs to avoid a specific enclosure problem. This problem may require only a one-dimensional, steady-state analysis of one extreme set of climatic data and material properties. Although a simple analysis technique may provide neither absolutely correct or accurate results, so long as a satisfactory decision can be made (i.e., a safe design) with this information, the technique fills the need. Consider also the situ-

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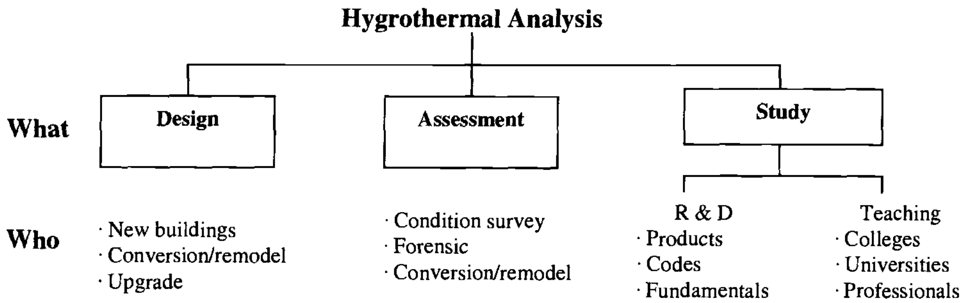

FIG. 1—General need for hygrothermal analysis and user groups.

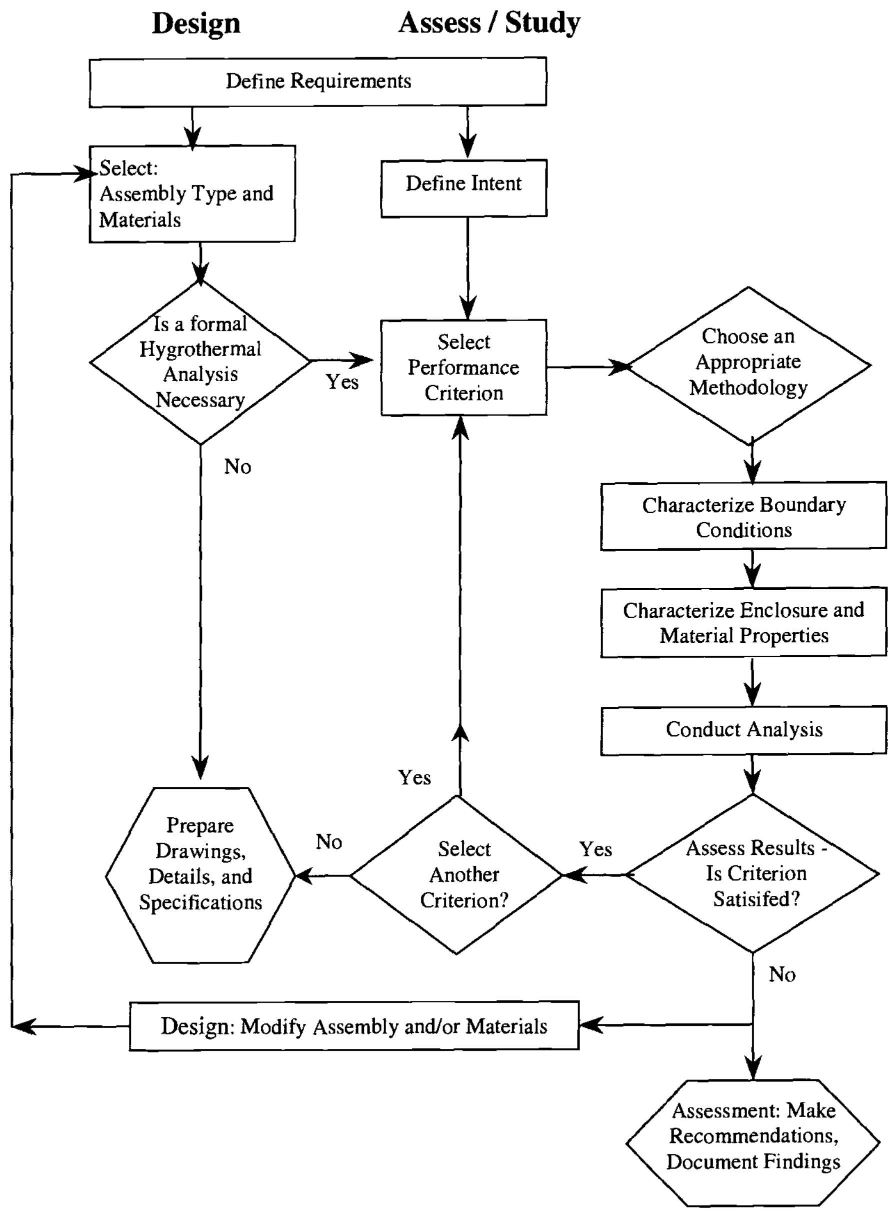

FIG. 2—General hygrothermal enclosure design or assessment procedure.

ation when conducting a parametric analysis where the accuracy of the difference between results (relative results) may be much more accurate than the absolute value of any particular result. Indeed, in many buildings no analysis is required because of long and successful experience with that specific assembly in that specific climate.

More detailed, and more accurate, analysis is often required when the potential cost of a problem is high, a new and untried product is to be used, or to demonstrate conformance to regulatory bodies. A detailed analysis, however, requires a much higher level of experience on the part of the analyst, more and more detailed material and boundary condition information, more powerful computers, and above all, more time.

MODELING HYGROTHERMAL PERFORMANCE

Although the physics of moisture storage and transport are reasonably well understood, predicting the moisture and temperature conditions inside building enclosures is seldom a simple task. The prediction of the hygrothermal performance of the building enclosure typically requires some knowledge of:

1. *Geometry of the enclosure*—including all macro building details (e.g., building shape and height), enclosure assembly details, and micro-details (e.g., cracks) (as shown in Fig. 3, the building enclosure is usually discretized into smaller representative elements).
2. Boundary Conditions
   (i) interior environment, including the interaction of the enclosure with the interior environment, and
   (ii) exterior environment, including the interaction of the building with the exterior environment.
   (iii) boundary conditions between elements (Fig. 3).
3. Material properties and their variation with temperature, moisture content, and age, as well as their chemical interaction with other materials.
4. Physics, chemistry, thermodynamics, and mathematics of combined heat, air, and moisture transport.

These four categories are sufficient to conduct an analysis. However, analysis cannot or should not be done in a vacuum; there must be both context and limitations. In any enclosure problem, one must know the general performance conditions as well as the important performance thresholds. This could constitute the fifth category of information required for a hygrothermal analysis:

5. Performance thresholds (that is, the conditions under which a material or assembly will cease to perform as intended).

Five major categories of required knowledge and information have been listed above. Each of these five categories involves some mathematical representation. Representation requires assumptions and approximations. Therefore, whatever the model used (no matter how complex), it will, to some degree, be incorrect. At present, one is often forced to make gross assumptions because of a lack of information and knowledge. In practical situations, such as a design

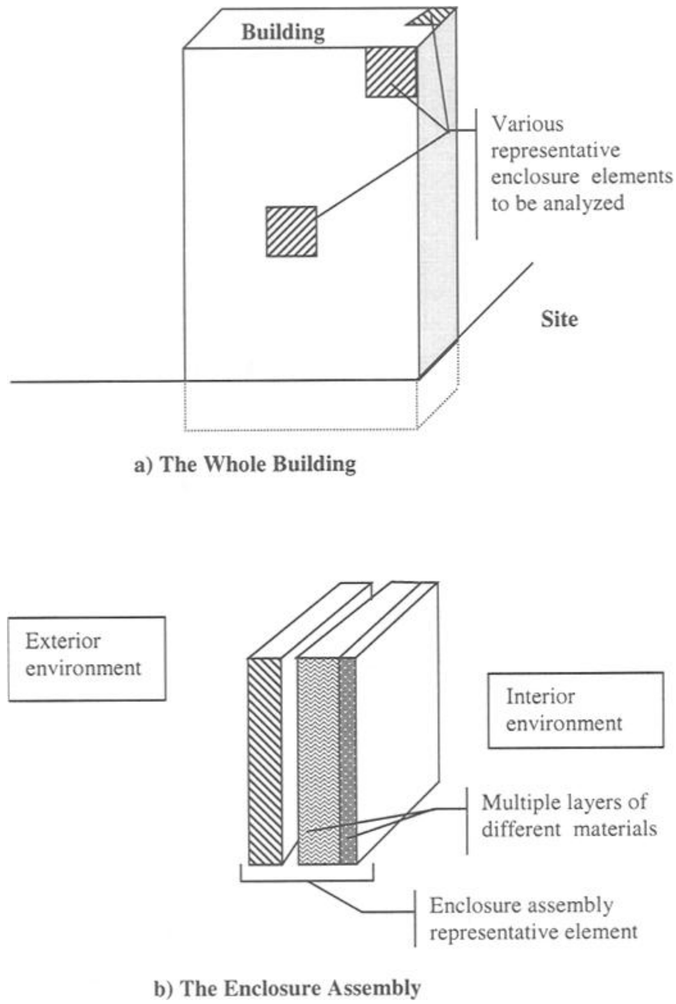

FIG. 3—Aspects of the enclosure.

problem, the constraints of time and money will also have an impact on which approximations and assumptions are made.

Most champions of complex HAM models emphasize the accuracy of the modeling of the building physics or the number of dimensions, etc. For example, in the recent Annex 24 review of HAM models [1], the models were differentiated on the basis of how well the physics was modeled. The ability of a model to match real performance, however, depends on the collective, possibly accumulative, influence of all the other aspects as well.

To illustrate the scale and complexity of the problem of accurately modeling HAM, consider that each one of the five required categories of information listed above is also dependent on the consideration of:

1. Dimension—one, two, or three dimensional.
2. Time—steady-state, quasi-static, or dynamic.
3. Quality and availability of information.
4. Stochastic nature of each data set (e.g., material properties, weather, construction quality).

The degree to which these factors are taken into account is usually considered to be the measure of the sophistication of the model. For example, a three-dimensional, dynamic model that uses measured material and boundary condition data and accounts for their variation with time could be considered to be a reasonably comprehensive and therefore sophisticated model. However, regardless of the sophistication, the accuracy of other input data (boundary conditions, material properties, and geometry) and the performance thresholds will limit the accuracy and utility of the results. Furthermore, from a practical point of view, the value of the results should be consistent with the effort, time, computational resources, and cost entailed.

INFORMATION REQUIRED FOR ANALYSIS

Each of the five categories of information required for a HAM analysis is briefly reviewed below. It should be emphasized that the study of each of these topics is a significant undertaking in itself and only the most important points can be discussed.

Enclosure Geometry

The actual enclosure geometry must be modeled before any hygrothermal analysis can begin. In simple methods the geometry is almost always reduced to a series of one-dimensional layers. Note that it is rare to ever have a detailed and comprehensive knowledge of the three-dimensional enclosure. Gaps and discontinuities are important as they usually create a contact resistance or break for capillary flow, cracks, and punctures allow airflow, etc. In fact, most analyses are conducted on ideal walls. The reason for most performance problems is unknown or unpredictable imperfections in the enclosure. The ability to model the actual enclosure geometry, including the inevitable imperfections, may in fact often be the most important factor for the accurate prediction of true, three-dimensional hygrothermal enclosure performance. The shape of the enclosure may change with time, for example due to wind pressures, shrinkage, etc.

Boundary Conditions

The boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modeling of the moisture physics. In general, both the internal and external environments need to be known (see Chapter 2). For instance, both driving rain and solar radiation must be properly accounted for. Few of the models deal with driving rain, partly because there are little data available. There are some practical situations where driving rain need not be accounted for, namely enclosures with functional fully sealed perfect barrier or non-absorbent claddings systems. However, the practical value of models that do not account for driving rain deposition is curtailed, especially if the tolerance of an assembly to imperfections in construction is to be assessed.

For models that include air flow, accurate and detailed knowledge of wind pressure variations and building stack effect pressures is required, but are only very rarely available. Interior and exterior temperatures are known with a much greater degree of accuracy than any of the other boundary conditions, but their precise knowledge is usually not that important to the results. The magnitude and variation of interior humidity, which can be critical to the success or failure of a given enclosure in service, is more poorly known, although recent research has improved the quality and quantity of the information available.

The time-domain is also important. Almost all computer models employ hourly time steps, since most weather data are available in this form. Simple analysis methods employ monthly averages, binned data, or even seasonal averages. The choice of time step is not critical for most models: a 15-min time step provides no increase in accuracy over a 1 h time step that is not overwhelmed by the uncertainties of the input data.

Material Properties

The material properties required for hygrothermal analysis depend on the type of problem that needs to be solved and the analysis tool chosen to assist in the solution. Simple models often require only a single value for the vapor permeability and thermal conductivity. Such data are tabulated in various references for many materials (see Chapter 3), but it is sometimes difficult to find and is often inaccurate and out of date.

More detailed analysis requires more detailed and higher quality material property data. Detailed models will require air and vapor permeability, moisture diffusivity, and thermal conductivity values, all as a function of temperature, moisture content (RH), and age. Such complete detailed material property data sets are exceedingly rare. While this detailed information exists for a limited number of material samples [*2*], almost no studies have been conducted to quantify the variability of ostensibly similar materials. It is known that some materials (e.g., wood, concrete) can exhibit very wide variations in properties depending on source, manufacturing technique, etc. (See also Chapter 3.)

Modeling the Physics

Several comprehensive and informative review papers from chemical engineering [*3*] and soil science [*4*] appear to provide a more comprehensive view of moisture transport physics than the building science literature. Some of the more recent mathematical models proposed [*5,6*] improve upon the more limited models of Philip and de Vries [*7*] and Luikov [*8*], which have often been used as the basis for building enclosure hygrothermal performance models. The work of Imakoma et al. [*9*] also suggests that great improvements can be made. Building science applications, however, are more dynamic than soil problems, boundary conditions are less accurately known than in chemical process engineering, and, unlike most other disciplines, multi-layer assemblies must be dealt with.

Despite the difficulties, many models have been developed, ranging from the very simple to the most complex practical with the computer resources and knowledge available.

Each detailed model is based on a particular means of modeling the moisture physics. One approach is to choose a driving potential and lump all mechanisms into one total moisture diffusivity function. Another approach is to separate vapor diffusion from liquid transport. In the latter case, one can model the flow as either a parallel process (vapor diffusion and capillary transport) or series (i.e., vapor diffusion functions to a certain moisture content, then capillary conduction takes over). In reality the flow is parallel, although the series approach may be sufficiently accurate in some cases.

Almost all models use an average moisture storage function that does not exhibit hysteresis. Some models only deal with the hygroscopic region.

There is a range of possible moisture driving potentials: vapor pressure, relative humidity, capillary suction stress, or moisture content. (Chemical potential is another little used potential). The argument against vapor pressure is that it drives only vapor diffusion, and hence is not typically used alone. The disadvantage of using moisture content, while physically valid, is that it is discontinuous at material interfaces and hence its use adds mathematical difficulties to the calculations. Capillary suction is likewise a discontinuous function. Relative humidity does not actually drive liquid or vapor flow but is continuous across an assembly. All of the potentials can be related to one another and can be used with the proper transformations (i.e., via Kelvin's equation and the sorption isotherm/moisture storage function).

Vapor diffusion is supposedly a well-understood transport mechanism, although the measurement and understanding of different vapor flow enhancement mechanisms requires more work before a consensus can be reached. Knudsen diffusion (effusion) is explicitly ignored by all building models, but is usually implicitly included in the vapor permeability. Few computer models account for the different temperature dependencies of Fickian and Knudsen diffusion, likely because the differences are small in comparison to the variability of the measured vapor permeability.

Surface diffusion is discussed as a transport mechanism in many of the model developments. Few models explicitly deal with the fact that the adsorbed moisture density gradient is the driving force. Surface diffusion may be implicitly included in models that use measured total moisture diffusivities, but temperature effects must be accounted for and many models use material properties that include only capillary flow driven by suction. In fact, it is important to understand that moisture flow cannot simply be driven by vapor diffusion or capillary suction, but that surface diffusion also acts and all three mechanisms may be acting at some times.

Liquid conductivity is included in most of the detailed models described later, although some of the earlier and simple models use constant diffusivity (even though it usually varies by several orders of magnitude with changing moisture content). One model includes different functions for wetting, drying, and redistribution, although this may be possible to implement in models with multiple sets of data for each material. This is worrying since Karagiozis et al. [*10*] have shown, through parametric modeling, that the use of the proper liquid diffusivity is very important for accurate predictions in some applications. If water content is used as a driving potential, it must be coupled to the suction curve to avoid the erroneous calculation of liquid flow in the supersaturated region (a fictitious liquid diffusivity might also be used).

Gravity-driven liquid flow (i.e., drainage) may be important for the accurate modeling of some types of walls and some conditions (rain penetration). Liquid water not absorbed in the pores of capillary active materials will cling to surfaces until gravity forces overcome surface tension and drainage flow begins. The amount of moisture that clings is a function of the surface on which it is deposited. This surface water can be modeled by assuming a surface material layer with certain moisture storage properties. Most of the models that consider drainage assume perfect drainage (e.g., the water is removed from the enclosure) after a certain amount of moisture is deposited on a surface. Note, however, that liquid water transport is similar to air leakage in that both occur at unknown locations with unknown intensity.

Convective vapor transport, i.e., air leakage, is accounted for in some of the most comprehensive models. The proper modeling of convective airflow and its moisture transport is important to some types of buildings (especially lightweight framed enclosures with incorrectly installed or low-density insulation). Unfortunately, convection is even more difficult to model than diffusive and capillary moisture transport. In practice, most building enclosures are designed as if they are perfect air barriers; in reality, they are not. In order to model air leakage, one must have some knowledge of the flaws. Any models that do include air leakage effects must deal with the fact that the results are only as accurate as the estimate of the flaw in the air barrier. With these limitations in mind, several of the models that do include air leakage have been shown to be quite useful as research tools.

Performance Thresholds

The temperature and moisture conditions at which performance is lost are covered in much greater depth in Chapter 4 of this manual.

The threshold moisture content level that corresponds to most moisture-related damage mechanisms is often equivalent to that material's moisture content when that material is in equilibrium with an environment of approximately 80% RH [*11–13*]. At this relative humidity, both fungal growth and corrosion can be sustained, provided temperature conditions are favorable. This is a first-order estimate, since wood may require higher RH levels for decay fungi to act, and steel may corrode at lower RH levels. Although it may be reasonable and conservative to use the moisture content of a material at 80% RH as a threshold level for performance problems, the actual performance threshold varies with time, temperature, type of deterioration, etc. Liquid water is required for freeze thaw damage and high rates of deterioration. Much more work is required to define the conditions under which most materials will deteriorate.

AVAILABLE ANALYSIS TOOLS

Since all models are simplifications of real behavior, it is difficult to define a demarcation point between simple and detailed models based on their modeling parameters alone. It may instead be more useful to differentiate between models based on the need they are intended to fill. This chapter assumes that the differentiation is based on the intent of the model: detailed models aim to predict actual performance, while the purpose of simplified models is primarily to provide sufficient information to allow designers and analysts to make decisions.

In many design or assessment situations, the results of an analysis must provide sufficient information to accept or reject a particular assembly or material. The relative performance of several assemblies is far more important to a designer with a choice to make than the actual performance of each. A great deal can be learned from "what-if" analysis, especially when tracking the influence of a single variable. In any case, the designer often does not have the resources (time, knowledge, material properties, etc.) to conduct a more detailed analysis. Simple models have been developed to fill this need.

Simple models are not necessarily intended to predict performance accurately, but to provide predictions of sufficient accuracy for the purpose of decision making. Such models must include information from all five of the basic data sets, but simplifying the data significantly. For example, monthly average conditions can be used to represent boundary conditions; three-dimensional airflow can be simplified to one-dimensional steady state; material properties are assumed to be constant, etc.

It is often useful or necessary to conduct a detailed analysis for research, product development, litigation, and historic renovation work. Detailed models have undergone dramatic development in recent years. They are briefly reviewed below.

Heat Flow Models

Heat and moisture flow through building enclosures are inextricably coupled. However, knowledge of only the temperature conditions in an enclosure can still be very useful to the analyst. Numerous computer models exist for the prediction of heat flow through buildings. These programs can be differentiated by the number of dimensions that can be modeled, whether dynamic analysis is possible, and on how they handle radiation and convection at surfaces and in cavities. The most widely used programs in North America, FRAME 4.0 and Therm 2.0, are two-dimensional steady-state models that are especially useful for assessing the thermal performance of windows and other lightweight assemblies. Both of these programs allow for fast analysis of the temperature conditions in an existing or proposed enclosure. The Swedish programs HEAT2 and HEAT3 provide even more information by allowing for the dynamic analysis of two- and three-dimensional structures. All four of these programs are commercially available. HEAT7.2, developed at Oak Ridge National Laboratory (ORNL), has been used widely to solve complex three-dimensional thermal bridging and dynamic heat loss problems [*14*].

Simplified HAM Models

One of the first, and most widely referenced, simple models is Glaser's method [*15,16*], originally published in 1958–59 as a graphical method. This model assumes the building enclosure is one-dimensional and that all moisture transport is driven by vapor diffusion. The *ASHRAE Handbook of Fundamentals* has included a cursory example of this method since the 1981 version. Typically Glaser analysis assumes steady-state boundary conditions for periods ranging from a few days to a few months, and invariant material properties. (See also Chapter 7.)

Several European codes accept the use of Glaser's method for supporting an enclosure design. The German moisture standard, DIN 4108 [*17*], for example, provides the thermal conductivity and vapor permeance of a range of materials, defines the boundary conditions and period of time to be used for both wetting and drying, and even recommends acceptable performance thresholds (e.g., by giving maximum safe moisture contents for various materials). Most North American publications describing Glaser's method assume only one set of boundary conditions (wetting) and even consider any condensation as failure.

While diffusion may be an important moisture transport mechanism in enclosures made of solid, capillary active materials (such as the plaster-finished masonry walls often used in Europe), exfiltration condensation is more important for both energy consumption and moisture tolerance of the lightweight framed assemblies used widely in North America. A simple extension of Glaser's diffusion method can be made that adds simple convection in parallel with diffusion. Such a model considers air leakage to be a diffusive process, uncoupled from heat flow, with no account for latent heat effects. By the further expedient of ignoring hygroscopic adsorption and convective heat flow, several simple models have been developed.

Stewart [*18*] was probably the first to develop such a model. His model used hourly weather data and included solar radiation effects, but it did not gain acceptance likely because it was proprietary. TenWolde [*19*] reported the development of a computer model based on one-dimensional convection and diffusion with no capillary transport but using monthly average temperature and humidity values.

Handegord [*20,21*] developed EMPTIED, Envelope Moisture Performance Through Infiltration Exfiltration and Diffusion for Canada Mortgage and Housing Corporation. It uses monthly bin temperature data (e.g., it does not consider heat storage) and outputs plots of the monthly amount of condensation, drainage, and evaporation. EMPTIED is available free from CMHC, is very easy to operate, and provides fast, generally conservative, results.

DeGraauw [*22*] documented a Simplified Hygrothermal Analysis Method (SHAM) that extended EMPTIED's simple diffusion/convection model by adding guidance for assessing the impact of driving rain, solar radiation, built-in moisture, coupling of convective heat and vapor flow, etc. Although the method typically uses computer spreadsheets and can be easily implemented in a simple computer program, it was developed for use as a pedagogical tool and for designers with an understanding of building science.

Review of Detailed Computer Models

A comprehensive review of available heat, air, and moisture models can be found in the Task 1 Report of the International Energy Agency's Annex 24 [*1*]. This review emphasizes the models that are either available to North American practitioners or have been used in important research.

The models that are discussed below have each been implemented in computer programs that use various finite-element or finite-volume schemes. The numerical virtues and difficulties of each approach are not the primary interest here (although this topic is critical for practical computer models).

Cunningham [*23*] took a simplified approach and used vapor pressure as the only driving potential, as vapor diffusion and convection are assumed to be the only moisture-transport mechanisms in this model. The model used the sorption isotherm to couple moisture content to vapor pressure and a linearly varying vapor diffusion coefficient. Despite the extensive simplifications, the model was validated by simple lab tests [*24*] and extensive in-service monitoring [*25*] of wood-framed roof structures. The limitations of the model are that it cannot deal with rain absorption, situations where capillary active materials are above the critical moisture content, or complex airflows.

WALLDRY [*26,27*] is a simple model that attempts to model the drying of framed wall assemblies by decoupling heat, moisture, and airflow. Moisture transport is considered to be exclusively by vapor diffusion, since capillary transport in wood is a rather slow process. In field validation trials, the model was unable to capture finer details of the drying process, although in some situations it was able to model some features of the moisture transport process. It is a public-domain package available from the Canada Mortgage and Housing Corporation. It is presently being upgraded to better model the drying of walls, especially those that incorporate ventilation behind the cladding.

TRATMO (Transient Analysis Code for Thermal and Moisture Physical Behaviours of Constructions), developed by Kohonen [*28*], was one of the first relatively complete and useful computerized building enclosure models. It used vapor pressure (calculated from the moisture isotherm) and temperature as driving potentials. However, as initially implemented, the moisture diffusivity and vapor permeability were constant, and surface diffusion was included as part of the vapor diffusion term.

Carsten Rode (formerly Pedersen) [*29,30*] used both the sorption and suction curves to define the moisture storage function in his one-dimensional model, MATCH. In the hygroscopic regime the sorption isotherm (defined by an equation that allows hysteresis) is used, and moisture transport is assumed to be by vapor flow only, driven by vapor pressure differences and defined by the vapor permeability of the material. In the capillary regime the suction curve is used together with the hydraulic conductivity to model moisture transport. The more recent research-only version accounts for diffuse air leakage, enthalpy flow, and latent heat. Some validation has been carried out through the use of his own [*31*] and other researcher's [*32*] lab results, although none of the work has involved driving rain deposition or similar natural exposure. MATCH, like the similar MOIST, can probably be used successfully for the approximate analysis and design of protected membrane roofs and walls with non-absorbent cladding.

Burch's MOIST model [*33*] (see Chapter 8) is similar in many respects to Rode's earliest MATCH model. Moisture transport is modeled as vapor flow driven by vapor pressure gradients and capillary transport driven by capillary pressure gradients. The vapor permeability and hydraulic conductivity are both given as functions of moisture content. The latent heat of phase changes is accounted for, as is the increased heat capacity provided by wet materials. Fibrous insulations are assumed to have no moisture storage capacity. No attempt is made to model air leakage, but a useful indoor climate model aids the development of realistic indoor climate data. Simple lab validation tests have been conducted in the hygroscopic range [*34*], with good results, and field comparisons [*35*] (without solar exposure, although it can calculate solar effects) have shown reasonable comparison, so long as the moisture content remained in the hygroscopic range and rain deposition was not involved. It is a public-domain package.

Ojanen et al. built on Kohonen's work to produce TCCD2, (Transient Coupled Convection and Diffusion 2 Dimensional) [*36–38*], a two-dimensional program developed primarily for the analysis of framed building walls. The model uses the same basic physics and mathematical formulation as used in Kohonen's model. A major improvement made over Kohonen's model is the use of moisture content dependent diffusivity. Convection airflow is accounted for as well as condensation (and frost formation) and evaporation, but capillary transport and surface diffusion must be lumped into the vapor diffusion process. It has been validated with laboratory experiments and has been shown to provide useful information regarding the impact of convective flows on hygrothermal performance [*39*].

Kerestecioglu et al. [*40,41*] have produced a comprehensive and flexible program called FSEC, which contains a library of differential equations, different finite elements, and various functional relationships for materials properties. This commercially available program can account for all of the moisture transport mechanisms, including convection, but in the implementation liquid and vapor flow are described by different sets of equations. Vapor is driven by vapor pressure differences, and liquid flow is driven by capillary suction. Surface diffusion is not explicitly handled. A great deal of user knowledge is required to operate the program.

The Windows-based WUFI [*42*] (see Chapter 9) was developed by Hartwig Kuenzel but is supported by the comprehensive work of Kiessl, Krus, and other workers at the Fraunhofer Institut fuer Bauphysik. This model uses a full moisture retention function, from the sorption isotherm and suction curve. Surface diffusion and liquid transport are driven by RH (and capillary suction via Kelvin's equation) and governed by a combined moisture diffusivity. Vapor diffusion is considered separately. All of the material properties can be defined arbitrarily as a function of moisture content (or RH) by entering a series of points (from, for example, measurements) or approximated from several important behavioral markers, like the absorption coefficient, capillary saturation, and dry-cup vapor permeance. Important features of this model are its ability to incorporate driving rain deposition as part of its boundary conditions, the use of different liquid moisture diffusivities for wetting and drying/redistribution processes, the ease of use, stability of the calculations, and the degree of field validation. The close fit between model predictions and many full-scale field validation exercises of a variety of walls and roofs over several years demonstrates the quality and robustness of this model. Its major limitations are its inability to handle air leakage and the associated energy and moisture flow. A two-dimensional version, WUFIZ, exists but has to date only been used as a research tool [43]. A version of WUFI ORNL/IBP for North America is enclosed in this manual.

LATENITE developed by Karagiozis and Salonvaara [44–46] is likely the most comprehensive heat, air, and moisture model available. Using a complete moisture storage function (e.g., sorption isotherm and suction curve), the model considers vapor and liquid transport separately, driven by vapor pressure and suction, respectively. The vapor permeability and liquid diffusivity vary with moisture content (surface diffusion is included in the liquid diffusivity) in an arbitrary way (defined by the user). Airflow, gravity drainage, driving rain deposition, moisture sources (e.g., leaks), wind, and stack pressures can all be incorporated into a simulation of up to three dimensions if desired. Driving rain can be comprehensively modeled through the use of a sophisticated commercially available CFD package as a pre-processor. Stochastic modeling can be used to assess the influence of inaccurate or variable material properties and boundary conditions. One, two, or three dimensions can be modeled, but only one- and two-dimensional calculation results [47] have been presented. Although this model has not been field verified, it was found to be reliable in the recent IEA Annex 24 comparison project.

CONCLUSIONS

In this chapter we have attempted to provide a general overview of a major technical field, namely, the building enclosure and its analysis and thus its design and performance. What is perhaps unique in this overview is the fact that need is used as the basis for assessment, i.e., whose need (designer, student, or researcher) and the nature of this need (money and time available, accuracy, intent, etc.). Implicit in this approach is the consideration of the experience and competence of the analyst—in fact, the critical element in the process is the ability of the analyst to define the problem correctly and to choose the appropriate methodology, data, and tool to resolve the problem. Furthermore, there is the fundamental need to learn and thus, conversely, to teach, and then gain experience. It follows that there is no single software or model that is best nor only one way to do things.

At the entry or most fundamental level, an essentially manual, relatively simple approach incorporating heat, water vapor, and airflow is recommended. With some experience this procedure can readily be adapted to a standard spreadsheet and thus computerized. At the next level, the analyst might want to learn to use software packages such as MOIST, and EMPTIED, which is useful in wetter and cooler climates, and WUFI ORNL/IBP. At the next level, one might wish to purchase a proprietary software package, such as the original WUFI, in order to expand one's capabilities. Beyond this level, the issue becomes problematic. At this time, programs such as Latenite are not available for general use. It is likely to be some time before this level of modeling is available or even needed for general design office use. First, the software has to be user friendly; second, the analyst has to be capable of making proper use of this level of analytical capability.

This brief overview of heat, air, and moisture analysis methods has emphasized the analysis needs of various groups. The review has shown that there are numerous computer models with a range of capabilities. More attention should be paid to developing a consensus about a simplified, manual methodology.

Wider use of hygrothermal analysis would foster the design and production of better buildings and building products. However, the largest user group, designers, are hampered more by the need for both education and training on how to conduct and interpret HAM analysis rather than the availability of sophisticated and accurate computer models. Researchers, code writers, and building product manufacturers often require better analysis tools than are presently available, preferably analysis tools with field and experimental validation.

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6

Advanced Numerical Models for Hygrothermal Research

by Achilles N. Karagiozis [1]

Today, complex, three-dimensional (3-D), transient thermal performance of building systems can be investigated using either experimental or numerical modeling approaches with a high degree of confidence. The thermal performance of building envelopes without effects of moisture is understood for some envelope systems, and relevant information exists in various handbooks such as the ASHRAE handbook and ASTM manuals. A large body of scientific work is also available in research papers by Kosny et al. [*1*], Christian et al. [*2*], Petrie et al. [*3*], and others.

In contrast, 3-D advanced hygrothermal (combined heat, air, and moisture or HAM) analysis of complete building envelope systems does not exist. Quantitative analysis of any hygrothermal performance of envelope systems or subsystems, originating either from experiments or modeling, is also limited. Many field forensic investigations are available that describe problematic failures due to moisture intrusion, but these investigations are primarily qualitative in nature.

Design tools and simplified models as presented in the previous chapter provide valuable guidance in making building envelope design decisions in a more or less qualitative manner. However, simplified tools are useful only as long as they comply with guidelines of good practice and conform to past demonstrated performance. Decision-making must still rely heavily on expert advice and judgment. Simplified models incorporate more limiting assumptions with respect to the physics, environmental loads, geometries, and material property inputs than advanced hygrothermal models. As a consequence, these design tools cannot be applied to all building envelopes of interest for research.

Development of hygrothermal design guidelines that define quantitatively the performance of building envelopes requires the use of advanced hygrothermal performance models (moisture engineering models). It is the general consensus among experts in the building science field that the fundamental transport of heat, air, and moisture flow through building envelopes must be understood before envelope performance, degradation, and service life can be characterized. Advanced hygrothermal models allows significant advancement of our fundamental knowledge of combined heat, air, and moisture transport. In addition, advanced hygrothermal models incorporate capabilities to allow the assessment of the effectiveness of various moisture control design strategies.

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A serious need exists to develop design guidelines to characterize the performance of the following elements of any building envelope:

- Define role of thermal insulation, quantify system effects, location, and amount.
- Define role of the vapor retarder, quantify its performance and application.
- Define role of the air barrier, quantify its performance attributes, and define properties.
- Define the role of ventilation drying, quantify performance and geometry.
- Define the role of water management, quantify the magnitude of wind-driven rain, and water penetration.
- Define the extent of the interface/joint between wall components, characterize performance.
- Define aging and degradation factor of key wall components and characterize adverse effect on moisture management, especially to predict deterioration rates.
- Define/characterize material properties in terms of HAM performance.
- Define the performance of the wall sub-systems and systems effects.
- Define chemical compatibility of material assembly.

The predictions of the driving forces/potentials may then be processed/displayed in either a graphical or numerical way to represent the complexities of the transport mechanisms. Results are usually further analyzed to determine the moisture tolerance of an envelope system. Ultimately, the goal is to develop a characterization of whole wall performance. In this chapter, this newly applied moisture engineering approach and a subsequent holistic moisture engineering approach will be described. Both approaches require extensive use of advanced hygrothermal research models to analyze various moisture strategies. The purpose of this chapter is to introduce the reader to the concepts of moisture engineering, holistic moisture engineering, and to review the requirements of current advanced models.

MOISTURE ENGINEERING

Many recent moisture-induced failures in low-rise residential and high-rise residential/commercial buildings have exerted a significant pressure to change construction codes in North America and Europe. However, solutions to moisture-induced problems may be difficult when several interacting mechanisms of moisture transport are present. Recently, a new approach to building envelope durability assessment has been introduced in North America, an approach termed "moisture engineering." It requires system information about the wall systems as constructed and aging characteristics (how the thermal-hygric-mechanical-chemical properties of a weather-resistive barrier change with exposure and time). Through advanced modeling, it predicts long-term performance of building envelope systems [4,5]. This permits the comparison and ranking of individual building envelope systems with respect to total hygrothermal performance. Moisture engineering analysis integrates experimental and analytical approaches to develop performance indexes of a building envelope system and sub-systems for specific interior and exterior environmental loads. This analysis is needed to establish the design life-span and durability requirements of a particular building envelope component.

Moisture engineering is a relatively new area of building research that is rapidly evolving. It requires multidisciplinary expertise—mechanical, civil, and chemical engineering—and inputs to correlate structural analysis/loading, chemical reactions, and biological growth and decay processes with the transport of heat, air, and moisture. To date, limited work is available that encompasses this spectrum of multi-disciplinary activity. Moisture engineering has concentrated mainly on the one-to-one interactions between a specific building envelope component and interior and exterior thermal and moisture loads.

HOLISTIC MOISTURE ENGINEERING

While critical information can be obtained by investigating the interactions between a building envelope component and the interior and exterior environments affecting it, the total behavior of the whole building is not addressed. Moisture engineering to date is usually concerned with the response of a building envelope to a particular load or series of loads (thermal, moisture, and pressure). A holistic analysis would go one step further, by integrating the individual hygrothermal performances of all walls, the roof, the floor, the indoor environment, and the mechanical systems. This would be accomplished by the direct and indirect coupling of the building envelope components and indoor environment with the HVAC system. The full house hygrothermal performance of various building envelope systems could then be examined for any type of climate. Moisture control strategies could be identified for the whole house building, and holistic moisture engineering assessments could be performed. Only a very few current models have this capability for holistic analysis [6–8].

In this chapter, the current state-of-the-art advanced moisture engineering models will be discussed and reviewed. These advanced models will be classified with respect to the different levels of sophistication they encompass. A few of the most relevant advanced hygrothermal models will be presented with sample application cases.

BACKGROUND

The physics involved in the transport of heat, air, and moisture is complex. Heat and mass transport occurs simultaneously in each porous construction material. The solid matrix phase of the porous media may interact with one or more of the three phases of moisture: vapor, liquid, and solid ice phases, if present. Phase change phenomenon, such as evaporation, condensation, heat of absorption, freezing, and thawing, are some of the physical phenomena that can occur during the transport of moisture. To further complicate matters, construction materials have transport coefficients that are strong functions of the dependent variables. In many cases, materials may incorporate elements of memory (past history), and material properties may also change as a function of time (aging materials). In certain instances, as when moisture accumulation reaches a critical level, material dimensional and structural changes may occur that drastically alter the material performance. Micro and macro accumulative damage may also occur within the structure of the material due the presence of moisture, thermal, and pressure loads.

Over the past 20 years, almost all construction materials have been evolving and improving. New manufacturing processes have been introduced. Different raw materials and additives have been employed. All of these have contributed to changes in the heat, air, and moisture transport properties. As a result, building envelope designers, especially in historical retrofit applications, face a significant challenge to account for the historical changes for each element of the envelope when new retrofit strategies must be implemented.

Moisture engineering, a recently emerging field of building envelope analysis, has accepted the challenge of characterizing the response of the building system subjected to heat, air, and moisture excitations. As discussed previously in Chapter 5, moisture engineering has not yet fully matured as an engineering field, but a significant amount of new knowledge has been gained by it. More than 15 Ph.D. dissertations on the subject have been published in the last five years. This significant amount of new research has just begun to be incorporated into advanced models that predict the transport of moisture and subsequent effects of moisture.

The potential beneficial impact that advanced moisture engineering could have in the optimization of building energy use, comfort, and durability is enormous, and realizable in the near future. Activities in the area of moisture engineering have already been introduced, in the past five years, in a number of simplified design models that predict the moisture performance of building envelope components. However, none of the advanced multi-dimensional models are publicly or commercially available [9].

The International Energy Agency IEA Annex 24 on Heat, Air, and Moisture Transport through insulated building envelope systems introduced important concepts for moisture transport theories, environmental loads, material properties, and durability assessment. Within the activities of the IEA Annex 24, a critical review of the existing hygrothermal models was presented [10]. This led to a classification scheme that ranked each model with respect to complexity of the transport physics it entailed. This classification system was the first attempt to evaluate the model's predictive capability with respect to hygrothermal performance. This classification system was extended by introducing the concepts of "real envelope system and sub-system effects" and durability assessment by Karagiozis [*11*]. Figures 1 and 2 present the two classifications of hygrothermal models. Figure 1 has the essential features of the IEA Annex 24 review. Figure 2 addresses system and sub-system and durability capabilities. The main difference between Fig. 1 and Fig. 2 is that the latter considers an advanced hygrothermal model to be one which captures "real features of the envelope." As depicted in Fig. 2, models are first characterized as steady state or transient. Models are then classified as deterministic or stochastic by their inherent dimensionality and then by their ability to incorporate envelope system and sub-system attributes, such as water penetration through cracks, interfaces, and so on. As the complexity of the model increases with additional features, the classification of Fig. 2 provides a better distinction between advanced hygrothermal models and design tools as described in Chapter 5.

The development of an advanced moisture engineering model requires particular attention to:

- Heat and mass transfer physics.
- Definition of the environmental loads.
- Definition of the construction entity (workmanship, defects, system and sub-system effects, aging-degradation).
- Hygrothermal (structural-biological-mechanical) material properties.

Significant differences exist among these advanced hygrothermal models. The additional level of complexity and interactions incorporated in these models have required that

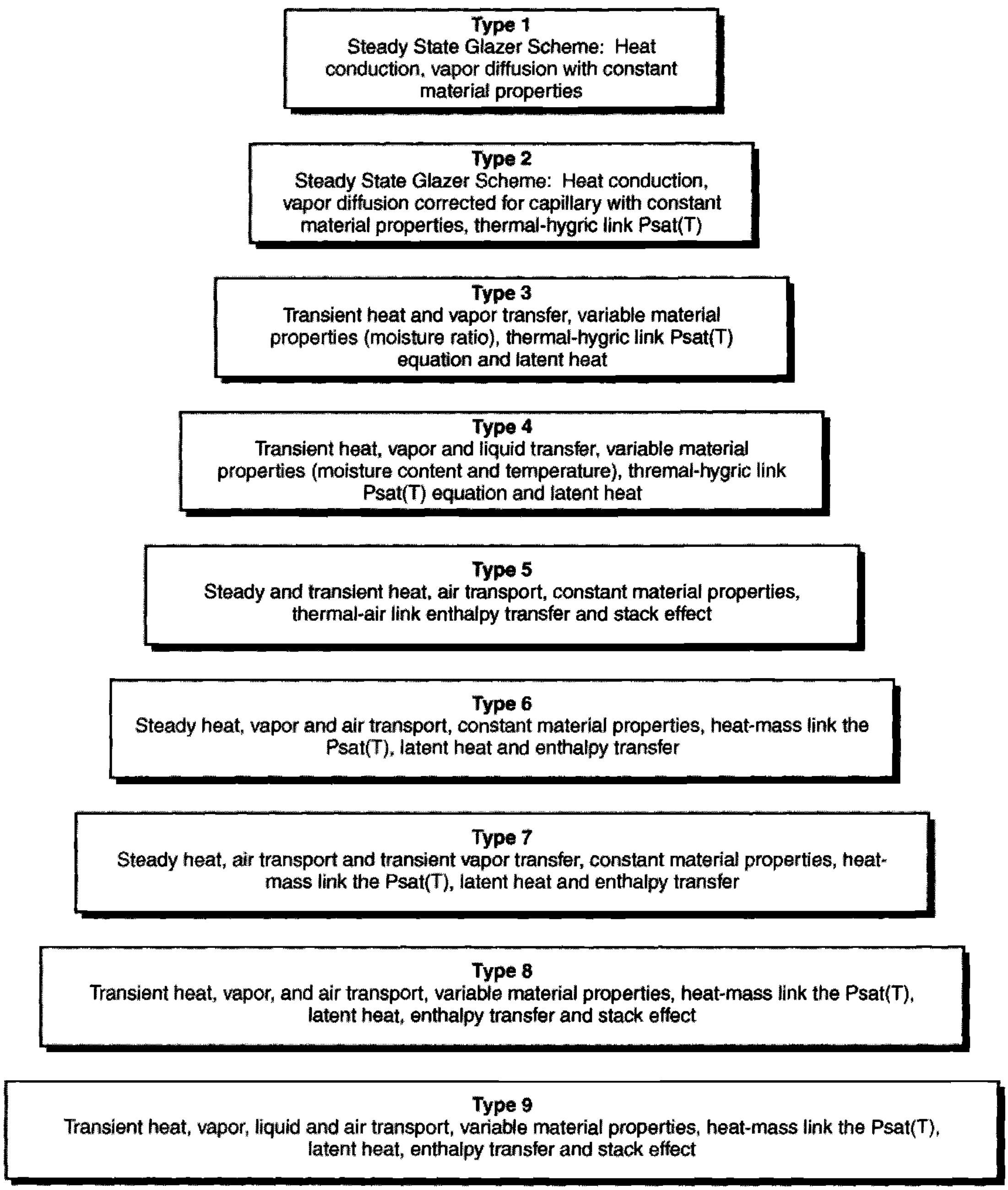


FIG. 1—IEA Annex 24 Classification of Hygrothermal Models by Hens [*10*].

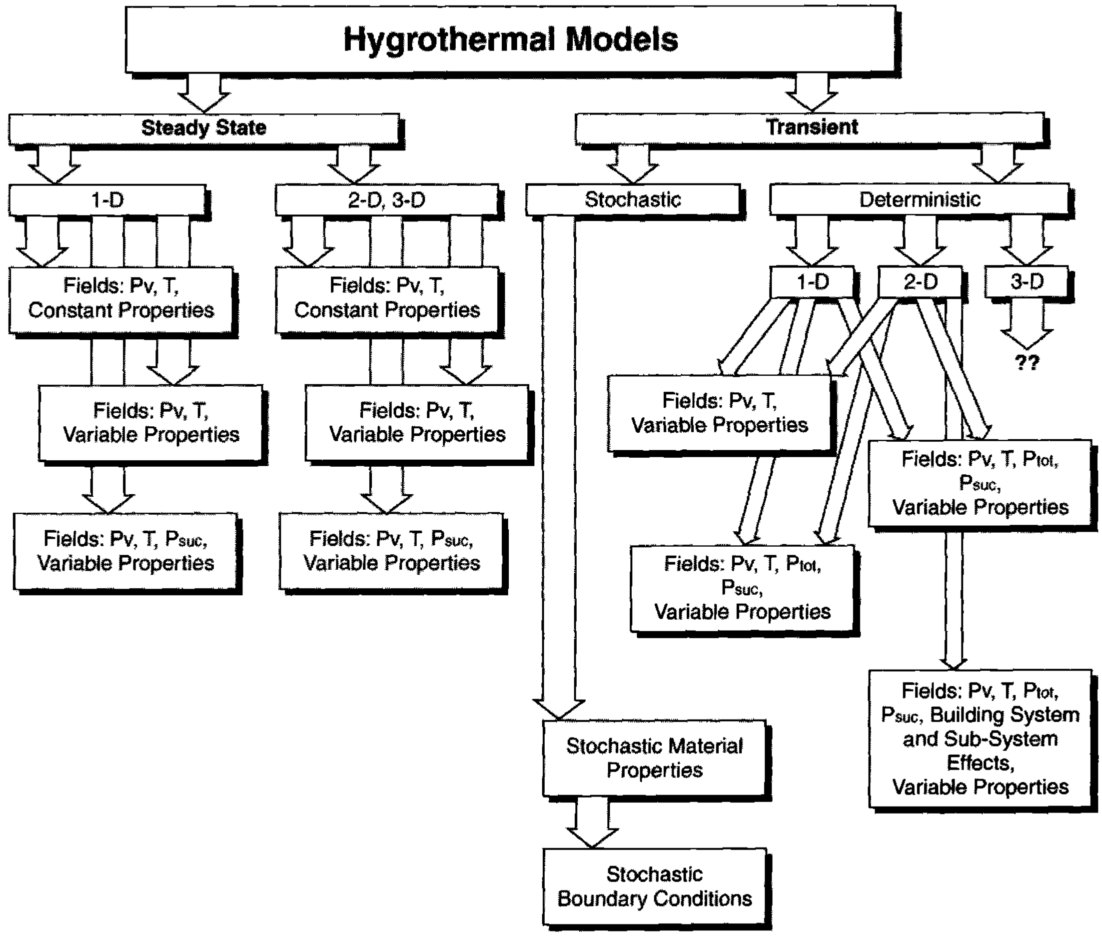


FIG. 2—Classification including sub-system and system effects and durability.

the authors only correctly apply the model in applications. In some instances, the preparation period for initiating even a simple 2-D simulation may require several days or even months if additional material property data, laboratory system, or sub-system characterization of the envelope is needed. These models require not only a higher level of expertise in preparing a simulation, but also significantly more sophisticated computational as well as experimental facilities. The computational time increases very non-linear as one goes from 1-D to 2-D, and from 2-D to 3-D simulations. As of early 2001, the simulation of the 3-D transient moisture performance of a building envelope system does not exist; a model is not available. In some instances, the numerical requirements of an advanced moisture engineering model are difficult to acquire even with the more sophisticated commercial computational fluid dynamic (CFD) models.

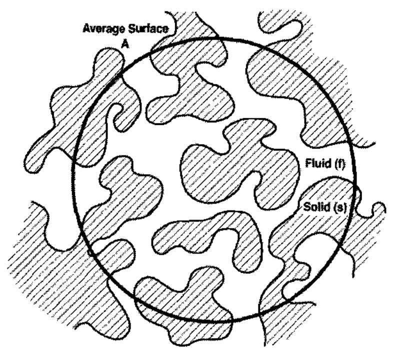
The following section will give details on the current status of advanced hygrothermal numerical models, the essential attributes, the inputs, concerns, and outputs. Authors of some advanced hygrothermal models were contacted and invited to include relevant information on their models. Illustrative examples are presented in Appendix 1 (Appendices A–K) at the end of the book.

Theoretical Background

Porous Medium

A porous construction material (medium) may contain a multi-phase assembly of solids, liquids, and gas. Heat and mass transfer essentially occurs at the microscopic level for each phase. To resolve the transport mechanisms at the microscopic level, a detailed description of geometry and topology of the porous medium is required. The description of the porous medium and the associated transport processes at the microscopic level is difficult and complex. A continuum approach is commonly employed to avoid analysis at the molecular level and to permit analysis at the macroscopic level. The continuum approach resorts to phenomenologically determining the mass/thermal transport coefficients from mass/thermal fluxes imposed experimentally on a representative elementary volume (REV) (see Fig. 3).

Employing this basic assumption allows the development of differential balance equations for mass, momentum, and energy transfer. The porous medium may then be described by three distinct phases, the solid, s, the liquid water, l, and the gas phase, g. According to Whittaker [12], by employing the spatial average of a microscopic property P at a point m, the microscopic property P over an elementary volume can be defined as an average of:



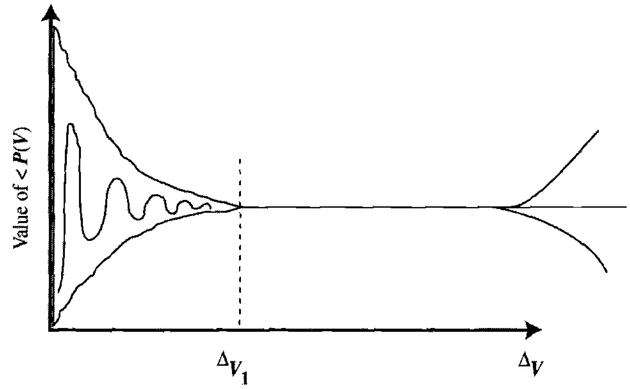


FIG. 3—A schematic of a representative elementary volume (REV) (left). The fluid volume is continuous. The density depends on the size of volume (ΔV) (right).

$$\langle P \rangle = \frac{1}{V}\int_V P dV$$

The phase average over a microscopic property P_i is given by:

$$\langle P_i \rangle = \frac{1}{V}\int_V P_i dV = \frac{1}{V}\int_{V_i} P_i dV \quad i = s,\, l,\, g$$

This definition implies that for a constant microscopic property, P_i, the value of the phase average $\langle P_i \rangle$ is different from the local value of the microscopic property P_i. The macroscopic value of the property must be independent of the size, the shape, and the orientation of the elementary volume V that is employed in the conceptualization [13]. The smallest elementary volume that satisfies this condition [14] is the representative elementary volume (REV).

$$\langle P \rangle = \lim_{V \to V_{\mathrm{REV}}} \frac{1}{V}\int_V P dV$$

Whitaker [15] limits the validity of the averaging process as long as:

$$d \ll l \ll L$$

where d is a microscopic characteristic length over which significant variations in the mathematical point properties occur, l is a characteristic length of the representative elementary volume V_{REV}, and L is a macroscopic characteristic length. The use of the REV is convenient to describe the averaging procedure to obtain a field of macroscopic properties for each phase. The macroscopic properties of many rigid and homogenous geometrical and topological porous materials are single-valued functions of time and space. The REV averaging concept is an important assumption in any modeling of mass transfer in porous media, as it provides upper and lower bounds of length scales in the modeling domain.

LOCAL THERMODYNAMIC EQUILIBRIUM

In the representative elementary volume of Fig. 3, temperature differences may exist between the fluids in the pores and the solid material. The assumption of local thermodynamic equilibrium imposes negligibly small temperature differences between the various phases at any particular location, relative to the applied temperature differences of the system. This assumption is used by almost all advanced hygrothermal models.

In the cases where large latent heat transfer occurs, such as during phase change of vapor to liquid or vice versa, the assumption of thermodynamic equilibrium does not hold exactly. Similarly, when the boundary conditions at the faces of the building envelope change significantly over a short time, or when the thermal properties of the solid and fluid phases are significantly different, serious deviations from thermodynamic equilibrium may be present. Adopting the thermodynamic equilibrium assumption in hygrothermal models allows the lumping of all phases with respect to thermal transport and reduces the number of governing differential equations and interphase couplings. This limiting assumption of thermodynamic equilibrium is employed throughout this chapter and reflected in the presentation of the governing equations for heat and mass transfer.

TRANSPORT MECHANISMS

The objective of this section is to provide a sample set, but not an exhaustive theoretical review of the definition of the transport mechanisms present in hygrothermal processes in porous media. Works by Kuenzel [16], Krus [17], Kohonen [18], Janssens [19], and Luikov [20] provide details on the theoretical development of various transport potentials. The choice of moisture transport potential was made based on what was familiar to the author. Transport mechanisms may also be defined for moisture flow using chemical potential μ^*, or even concentration gradient X, and a similar theoretical development is required.

In the past, many moisture transport models were developed based on discontinuous potentials such as moisture content [20,21]. The moisture content at an interface between two materials is discontinuous. This requires an elaborate flux analysis developed at each inhomogeneous material intersection, and an iterative treatment is required to satisfy mass conservation. The main advantage in employing moisture content as a mathematical transport potential is that the liquid diffusivity is directly measured as a function of moisture content. LATENITE [22] and TRATMO2 [23] employ this approach in their formulation. Recently, continuous driving potentials have been employed successfully [*16,24,25*]. Examples are vapor pressure, suction pressure, relative humidity, and chemical potential. They appear to be more efficient in both formulating the governing equations and execution time. The issue of flux splitting, the separation of the quantity of mass that is transported in vapor or liquid phase, becomes a focal point for differences among all advanced hygrothermal moisture models. Apparently, a straightforward approach has not yet been recognized and each model employs some limiting assumptions.

Mass Transfer

An excellent description of the transport mechanism in porous media is described by Kerestecioglu et al. [*26*] and Kaviany [*27*]. It is important to recognize that the transport coefficients may not only be strong functions of the independent variable, but may change as a function of time and exposure. Some of the more important modes by which moisture may be transported are:

Molecular vapor diffusion, by partial vapor pressure gradients.

Molecular liquid diffusion, movement of the liquid phase due to liquid filled pores.

Capillary liquid flow, movement of the liquid phase due to capillary suction pressures.

Knudsen vapor diffusion, movement of the vapor phase in small pores and at low pressures; the mean free path is greater than the pore diameter and collisions of molecules with the pore walls occur more frequently than collisions with other diffusing molecules.

Evaporation-condensation vapor flow, movement occurs in conjunction with heat transfer, moisture evaporates and recondenses in a similar fashion to a heat pipe.

Gravity-assisted diffusion liquid flow, movement occurs due to gravity and occurs mostly in macroporous materials.

Vapor Transport

The diffusion of water vapor under isothermal conditions may be described by Fick's first law for unimpeded flow in still air:

$$q_v = -D_v \nabla X$$

where q_v is the mass flux rate of vapor flow (kg/m^2 · s), D_v the diffusion coefficient of vapor in air m^2/s, and X the vapor concentration (kg/m^3).

$$q_v = -D_v \frac{M}{RT} \nabla P_v$$

where R is the universal gas constant (8.314 J/(mol · K)), P_v is the partial vapor pressure, T is temperature (K), and M is the molar weight of water (0.018 kg/mol).

In a porous material, diffusion is reduced in comparison to that in still air by a resistance that corresponds to the volume fraction of air-filled open pores a and a tortuosity factor α. This is expressed as:

$$q_v = -\alpha\, a\, D_v \frac{M}{RT} \nabla P_v$$

In most European countries a resistance factor is introduced as $\mu = (1/\alpha\, a)$ leading to the following flux equation for vapor flow:

$$q_v = -\frac{D_v}{\mu}\frac{M}{RT} \nabla P_v$$

In the measurement of the water vapor permeance using the ASTM E 96 standard or the EN 12086:1997, the factor δ_p is used, and that is equivalent to $\frac{D_v}{\mu}\frac{M}{RT}$. This transport coefficient is termed as the water vapor permeability and has units of kg/Pa · m · s.

Liquid Transport

Liquid flow is defined in two ways since it is transported differently within the two regions of interest in building materials. The first region is defined as the capillary water region. It follows the hygroscopic sorption region and extends until free water saturation. This region can be characterized by states of equilibrium. Liquid transport occurs under the influence of a suction pressure or force in the capillary regime, and moisture liquid transport occurs mainly in this region. The second region, the supersaturated capillary region, follows the capillary water region. Normal suction processes are not physically plausible in it. Liquid flow in this region occurs through diffusion under a temperature gradient or by external pressure under suction. In this region, there are no states of equilibrium.

In 1856, Darcy [*28*] developed the theory of laminar transport in capillary tubes, which applies directly to suction flow through building materials. Extending the original formulation, to account for gravity forces, the transport of liquid in the capillary regime is given by

$$q_w = -\left(D_\phi \nabla \phi + \frac{D_\phi \frac{\partial \phi}{\partial u}}{\frac{\partial P_h}{\partial u}} \rho_w \vec{g} \right)$$

where q_w is the mass flux of liquid (kg/m^2 · s), D_ϕ is the liquid coefficient (kg/m · s), g is the gravitational acceleration (m/s^2), and ρ_w is the density of water (kg/m^3). The suction pressure is usually described by employing a cylinder capillary model and can be presented as:

$$P_h = \frac{2\,\sigma \cos\theta}{r}$$

where σ is the surface tension of water (72.75 10^{-3} N/m at 20°C), r the capillary radius (m), and θ the contact angle or wetting angle (°).

Using thermodynamic equilibrium conditions for a cylinder capillary model, the relationship between relative humidity ϕ over a concavely curved water surface and the capillary pressure P_h is defined by Kelvin's equation:

$$\phi = \exp\left(\frac{-P_h}{\rho_w R_v T}\right)$$

where ρ_w is the density of water (kg/m^3), P_h is the capillary pressure (Pa), R_v is the gas constant for water vapor (J/kg K), temperature T is in Kelvin (K) and ϕ is relative humidity (−).

Heat Transfer

Within construction envelopes, heat transfer may occur by conduction, convection, and radiation transfer. Table 1 lists the governing equations of state for these modes of heat transfer. The thermal conductivity k is a function of the content of ice and liquid present in the porous material and may be strongly influenced by temperature. In addition, the thermal conductivity may also be directionally dependent.

Phase Change

The phase change conversion enthalpies contribute a local source of heat that is stored or released in a porous material when moisture accumulation or drying is present. If one considers that the amount of moisture I_{ij} of phase i is converted to j the control volume receives the following amount of heat:

$$q_l = \Delta h_{ij} \cdot I_{ij}$$

where Δh_{ij} is the change in enthalpy, $3.34 \cdot 10^5$ J/kg for conversion of ice to water and $2.45 \cdot 10^6$ J/kg at 20°C for water to vapor.

This quantity of heat may be significant when drying or accumulation is present in porous media. A modeling challenge exists to properly accommodate this latent heat term in the governing equation of energy.

Air Transport

Airflow is driven by a difference of air pressure. The mass flux of air through a porous material may be expressed as:

$$m_a = -k_a \nabla P_a$$

where m_a is the air mass flux (kg/m²s), k_a is the air permeability (kg/m · s Pa), and P_a is the air pressure (Pa).

Governing Equations for Mass, Momentum, and Energy Transfer in a Porous Medium

Advanced models require the simultaneous solution of the heat, mass, and momentum transfer equations. The governing equations are written for a hygroscopic-capillary porous medium. The conservation equations for the porous medium will provide moisture content and temperature as a function of space and time of the material. The macroscopic or volume average equations are derived with respect to averaging volumes large enough for a continuum approach.

Assumptions

Several assumptions are necessary for this development and must be acknowledged as the limitations of existing advanced models:

1. The material is macroscopically homogeneous.
2. The solid phase is a rigid matrix, and thermophysical properties are constants with space.
3. Enthalpy of each phase is a function of temperature and moisture.
4. Compressional work and viscous dissipation are negligible for each phase.
5. Diffusional body force work and kinetic energy are small.
6. The gas phase is a binary mixture of ideal gases.
7. The three-phase system is in local thermodynamic equilibrium (solid-vapor-liquid).
8. Gravity terms are important for the liquid phase mass transfer but not the gas phase mass transfer.
9. Fluids are Newtonian and inertial effects are small.
10. The transport processes are modeled in a phenomenological way.

According to the manner the axioms of conservation for transport process, the rate of storage of any entity within a control volume at any given time equals the rate of this entity entering the control volume through the surrounding surfaces plus the rate of generation of the entity within the volume.

Mass Conservation

Conservation of mass of air and moisture can be expressed as:

Air

$$\frac{\partial \rho_a}{\partial t} = -\nabla m_a$$

Moisture

$$\frac{\partial (U\rho_a)}{\partial t} = -\nabla q_v - \nabla q_w - \nabla(\rho_v u)$$

Energy Conservation

Conservation of energy can be expressed as:

$$\frac{\partial (\rho C T)}{\partial t} = -\nabla q_c - \nabla q_a - h_v \nabla q_v + q_s$$

where q_s is the rate of heat generation per volume W/m³ and includes the latent heat due to freezing, and other heat sinks or sources.

TABLE 1—Energy transport.

Conduction	Convection	Radiation
$q_c = -k \nabla T$ where k = thermal conductivity (W/m K) T = Temperature (°C)	$q_a = \nabla \rho_a v C_a T$ where ρ_a = Density of air (kg/m³), v = velocity (m/s), C_a = volumetric heat capacity (J/m³ K).	$q_r = \varepsilon \sigma F(T_b^4 - T_\infty^4)$ where ε = emissivity of gray surface (−), σ = Stefan Boltzmann constant = (5.67 × 10⁻⁸ W/m² K⁴), F = view factor (−), T_b = surface temperature (K), and T_∞ = surrounding temperature (K).

$$\sum(\rho_i h_i) = (\rho C_d + C_w \rho U)T$$

where ρ is the density of the porous medium, ρ_a is the density of air, ρ_v is the density of vapor, C_d is the specific heat capacity of the dry material, C_w is the specific heat capacity of liquid water, and U is the moisture content (kg_d/kg_w).

Momentum Conservation

The rate of change of momentum of a fluid is balanced by the sum of impact and reaction forces associated with the flow of momentum and the internal and external forces acting on the fluid element. The Navier-Stokes equation encompass all possible theoretical combinations.

$$\frac{\partial(\rho u)}{\partial t} = -\nabla\ \rho u \cdot u - \nabla P + \eta\ \nabla^2 u + F$$

where u is the velocity vector (m/s), P is pressure (Pa), η is the dynamic viscosity (s · Pa), and F is the body force per unit volume (N/m^3).

When the airflow rate is small and the inertia effects small enough to be neglected [17], Darcy's law can be substituted in the mass conservation equation and this is expressed as:

$$v_P = -\frac{k_a}{\mu}(\nabla P + \rho_a g)$$

where v_p is the air flow velocity (m/s), and k_a is the air permeability tensor (m^2), and μ = fluid viscosity (Pa · s).

The above equation is then substituted in the conservation of mass and an equation in terms of pressure is developed. This equation is used by the advanced hygrothermal models such as LATENITE [29,30], 2DHAV [19], and TCCC2D [31] model with the exception of DIM [32], TRATMO2 [33], SIMPLE-FULUV [34], and the newly developed state-of-the-art model by the Oak Ridge National Laboratory, MOISTURE-EXPERT. Solving Darcy's equation for pressure and air movement, however, is restrictive, as slip effects, acceleration terms, and friction forces are not accounted for. As a consequence, the airflow patterns developed by LATENITE, and TCCC2D are not correct when simulating air gaps and interfacial discontinuities, 2DHAV incorporates the effects of heat and mass transfer in air channels by indirectly accounting for these effects. In the more advanced airflow models, TRAMO2, SIMPLE-FULUV, and the MOISTURE-EXPERT model, the full Navier Stokes equations can be solved that incorporate accurate description of physics of the transport of air and moisture in air spaces. However, at present, none of these models account for turbulent effects that may be present in exterior ventilated cavities.

DETERMINISTIC AND STOCHASTIC APPROACH

Both deterministic and stochastic analyses have been developed. Some of the advanced hygrothermal models have incorporated both of these features (LATENITE, WUFI-ORNL/IBP,2D [34] FRET) [36], and MOISTURE-EXPERT [25]. Most hygrothermal building envelope simulation models are strictly deterministic. Deterministic processes are defined in both space and time by a single and defined quantity. This means that a physical quantity (e.g., temperature) has a defined distribution in time for any space relation. Deterministic analysis has been employed extensively in building envelope thermal analysis.

In most hygrothermal analysis, as well as in construction design and implementation, material properties and exterior and interior environmental loading are a subset to influences of many other factors. For many of these, a large number of factors are random and sometimes not clearly defined. Some exhibit a probabilistic or statistical nature, such as the material properties of construction materials. Two bricks or two wood studs are unlikely to have the same unique hygrothermal properties. In a similar manner, the environmental loads will never be exactly the same for the same day in different years. Stochastic models incorporate the uncertainty of a process, variable, or event happening. The use of stochastic models such as a Monte Carlo model, allow the input of variability in material properties, environmental potentials, and loads in hygrothermal analysis [35,36]. Probability distribution functions for each random factor are required as inputs to the model. Successive simulations of the same occurrence, using the randomness in the inputted parameter, e.g., water vapor permeability material property, allow predictions of a range of possible values in terms of time and space. The ranges in terms of moisture content or relative humidity and time give better indications of possible moisture tolerances in a given construction design. An example of this is depicted in Fig. 4. Results show the relative differences between deterministic and stochastic relative humidities, as a function of time. A value of +0.1 signifies that 10% positive variations may be present. Here it is assumed that a uniform normal distribution is present for material properties. In most cases this may be valid, but in some other cases not. It is expected that as better definitions of material properties, environmental loads, and construction practices and implementation are developed in the future, moisture engineering will incorporate more elements of stochastic analysis in design.

Features of Advanced Moisture Engineering Models

So far, we have discussed the individual elements that are required for developing an advanced hygrothermal model. An advanced hygrothermal model must incorporate some key features that will allow the models a higher level of confidence in simulations. Depending on the construction type, certain elements may be more important than others. For example airflow through masonry walls is not as important as through lightweight wood frame constructions. Understanding the application limits of each model is an important part of applying advanced models to develop design guidelines. See Table 1 for a list with features of the current advanced hygrothermal models.

Advanced moisture engineering models require (see Fig. 5):

(a) Transient heat, air, and moisture transport formulation (as a minimum).
(b) Two-dimensional spatial formulation (as a minimum).
(c) Variable material properties, e.g., as functions of space (x,y,z), moisture content and temperature.

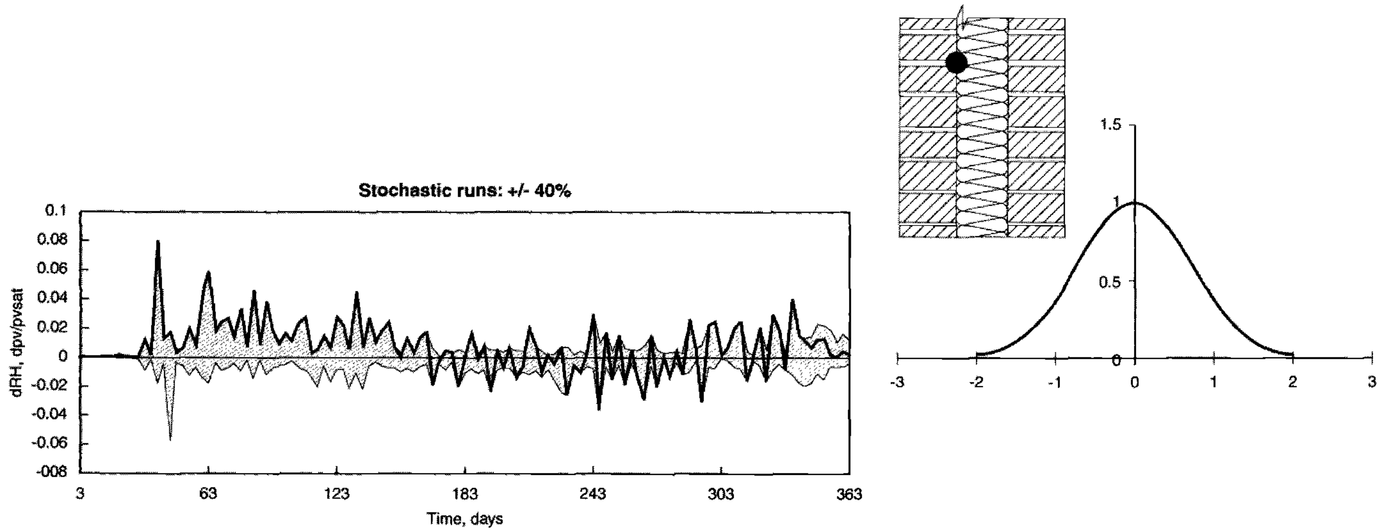


FIG. 4—Moisture engineering stochastic design: Relative humidity difference (daily averages) of the internal surface of brick layer [37].

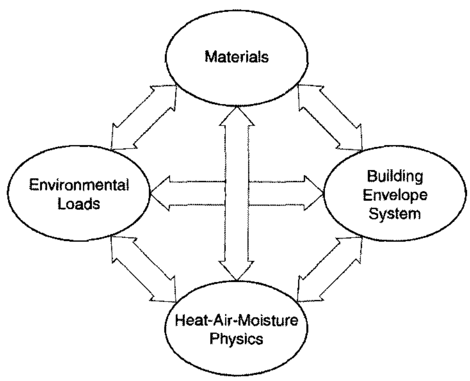


FIG. 5—Interactions that must be accounted for in advanced hygrothermal models.

(d) Incorporating physics of:
- vapor transport
- liquid transport
- airflow
- hydraulic transport
- moisture capacity of the materials
- condensation and evaporation processes
- freezing and thawing process

(e) Incorporating boundary conditions
- incident solar radiation and sky radiation
- wind-driven rain at exterior surfaces
- wind pressure
- interior and exterior temperature and relative humidity
- interior moisture sources
- fog conditions

(f) Incorporate building systems and sub-system effects
- water penetration rates through sub-systems (joints, cracks, etc.)
- air leakage (cracks, joints, e.g., around a window)
- additional sources of moisture
- drainage and gravity effects

An additional feature that may be required in some applications where moisture flow is through unintentional cracks and intentional openings. To accurately model these cracks and openings, supplementary experiments may be used to define the sub-system performance of these wall elements under various possible loads. In feature (f), inputs to the model are provided by controlled laboratory tests that provide performance data specific to each sub-system, e.g., water entry through a crack. In most cases it is preferable to take performance measurements of system and sub-system effects in field situations, as only then all exterior loads and influences are captured.

The mathematical formulations of these advanced models are at least in two dimensions and require special attention in both the pre- and post-processing. During the preprocessing the surface heat and mass transfer coefficients must be specified along with the initial or starting conditions. Depending on the numerical method and time linearization (Newton Raphson or standard linearization), the initial conditions must be specified in a realistic manner or stable solutions may be difficult to achieve.

The validation, verification, and benchmarking of advanced hygrothermal models is a formidable task. Currently, internationally accepted experimental data do not exist to benchmark hygrothermal models, but efforts are underway at NTUU by Geving et al. [42] and at the ORNL-Energy Center of Wisconsin by Desjarlais [43]. It is difficult to measure moisture flows and moisture transport potentials even in controlled laboratory conditions. Each of the advance models have some level of validation, but again this varies significantly depending on the model. With a few exceptions (WUFI, [16]), limited validation of advanced models has been conducted using field investigations.

INTERIOR AND EXTERIOR ENVIRONMENTAL CONDITIONS

Exterior and interior environments are important factors that influence the hygrothermal performance of envelope systems. The importance of environmental conditions depends on the hygrothermal model employed and the envelope system used in the simulation. One or more climatic conditions may be ignored if the influence of that parameter to both thermal and moisture transport is negligible. An example would be fog in desert-like climates.

In general, advanced hygrothermal models require boundary inputs of the following parameters as boundary and initial conditions:

- inclination of structure (horizontal, vertical, or inclined)
- orientation of the structure (south, north, west, or east)
- interior and exterior air temperature, (°C)
- interior and exterior relative humidity, (%)
- solar radiation, (W/m^2)
- absorptivity of exterior surface (−)
- emissivity of exterior surface (−)
- convective heat transfer coefficients (W/m^2 (°C))
- mass transfer coefficients (kg/m^2 Pa)
- water resistant substances (kg/m^2 Pa)
- rain fall on exterior surface (kg/m^2 h)
- fog (kg/m^3)
- interior moisture generation rates, kg_w/m^3

Additional input conditions needed when considering airflow are:

- ventilation values (ACH, air changes per hour)
- wind speed (m/s)
- wind orientation (degrees)
- stack pressure (Pa)
- stratification (°C)
- neutral pressure level (m)
- interior pressurization (Pa)

In the more advanced models, the heat and mass transfer coefficients are a function of the wind speed and orientation of the envelope. The boundary conditions are provided mainly on an hourly basis. Recent evidence, not conclusive yet, indicates that this may not capture correctly the contributions of wind-driven rain. Time step intervals smaller than 1 h require more detailed boundary conditions that in most cases are not available. Rainfall constitutes an important source of moisture to walls of high-rise buildings with capillary-type facades or envelopes that permit water intrusion. At present only three models (WUFI, MOISTURE-EXPERT and LATENITE) have demonstrated capability to handle the effects of wind-driven rain. The main reason for the lack of wind-driven rain capability is the complexity in the mathematical and numerical procedures to handle rain flow at the exterior boundary surface, and the lack of information regarding the amount of rain striking the exterior surfaces of buildings. In addition, there is recent evidence that the use of weather years for energy calculations is not appropriate for moisture analysis. This practice underpredicts the critical moisture behavior because an average year does not give sufficient information for peak moisture transport. The reader is encouraged to review Chapter 2 for more information.

MATERIAL PROPERTIES FOR ADVANCED HYGROTHERMAL MODELS

Advanced hygrothermal models are extremely difficult to assess or compare because many of the basic input material properties used by each of them is different, dependent on selection of the transport potentials for heat and moisture flow. In Chapter 3 of this manual a set of thermal and moisture properties is given. In this section some additional information is given on the particular moisture properties that are needed in advanced hygrothermal models:

Sorption Isotherms

Most building materials are hygroscopic, which means that they absorb water vapor from the environment until equilibrium conditions are achieved. This behavior can be described by sorption curves over a humidity range between 0 and 95% RH. For some materials the equilibrium water content is not very sensitive to changes in temperature; the sorption curves are called sorption isotherms. Sorption curves and sorption isotherms for these materials from 95% RH up to the capillary saturation at 100% RH are difficult to measure. In this range the equilibrium water content of a material is still a function of relative humidity. However, this function can no longer be determined by sorption tests in climatic chambers. Here, a pressure plate apparatus is necessary in order to complete the sorption curve in the high humidity range. The resulting water retention curve is a prerequisite for simulations including liquid transport. Figure 6 of this paper, Kuenzel and Holm (*54*), shows an example of the sorption and suction isotherm and the water content versus capillary pressure for autoclave aerated concrete.

The sorption isotherms are the equilibrium moisture content states in a porous material as a function of relative humidity at a particular temperature. Families of sorption isotherms that encompass both the hygroscopic and capillary regimes are:

- Absorption isotherm
- Desorption isotherm
- Hysteresis isotherms (the equilibrium moisture content curves that span the complete spectrum of moisture equilibrium during both absorption or desorption)
- Temperature-dependent sorption curves (the equilibrium moisture content curves dependent on temperature)

The units for moisture content employed in the sorption isotherms are:

- water content (kg/m^3)
- moisture content by mass (kg/kg)
- moisture content by volume (m^3/m^3)

The hysteresis between absorption and desorption isotherms is usually not very pronounced. Rode (1990) approximated the effect of hysteresis and found that the effect on the calculated water content results was not large. Most models do not incorporate hysteresis and use the absorption isotherm or, where necessary, an average function of absorption and desorption. Neglecting the hysteresis might not have a great influence on the water content but it dampens the fluctuations in relative humidity within the building assembly. In order to avoid this effect seperate absorption and desorption isotherms and a validated method to interpolate between both curves must be employed.

Nearly all advanced hygrothermal models, with the exception of MOISTURE-EXPERT, use a single curve to represent the absorption/desorption equilibrium isotherm. MOISTURE-EXPERT uses a set of sorption isotherms at different equilibrium temperatures. This may be important when simulating wood-based material elements, and is probably less important for mineral-based materials.

Vapor Permeability

The vapor permeability (kg/m Pa s) is defined as the transport coefficient for vapor diffusion in a porous material subjected to a vapor pressure gradient. In most technical publications, vapor permeance is used to characterize the vapor transmission coefficient. Vapor permeance ((kg/m^2 Pa s) is defined as the ratio between the vapor flow rate and the magnitude of vapor pressure difference across a slab in steady state conditions. Other expressions for vapor permeability exist, as the transport coefficient under a vapor concentration gradient (m^2/s) or as a vapor resistance factor μ.

To determine the vapor permeability of a porous material, ASTM Standard E 96 for water vapor transmission of materials may be used. It is important to recognize that the full dependency of the vapor transport coefficient as a function of temperature and relative humidity must be included in the model. Assuming constant values may introduce higher errors in the simulation results than is the case when one includes the correct function curve but higher uncertainties around these values. Also, as advanced hygrothermal models incorporate both vapor and liquid transport, correctly splitting the transport coefficients is critical for properly simulating hygrothermal performance.

Liquid Transport Properties

The coefficient that describes the liquid flow is defined as the liquid transport coefficient. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on liquid transport coefficients. Most of the time a moisture diffusivity is used, which is the total diffusivity measured. The main reason moisture diffusivity is used is due to the difficulty in determining what part is pure liquid flow and what is enhanced vapor flow. Different moisture dependent liquid transport coefficients exist according to the transport potentials of the advanced models, and some are:

- Moisture diffusivity, D_w (m^2/s)
- Liquid conduction coefficient, D_φ (kg/ms)
- Hydraulic Conductivity, D_p (kg/m s Pa)

The transport coefficient for liquid flow can change dramatically from one time step to the other. Several orders of magnitude changes occur in the transport coefficients when rain first strikes buildings the exterior façade due to the steep increase of the diffusivity with water content. These large changes may cause numerical stability or convergence problems, and special numerical solution methods are required.

In Chapter 9, Kuenzel et al. (2001), provide an explanation for the differences in diffusivity employed for the wetting and drying (liquid redistribution) process. Indeed, depending on the material a factor of up to 10 or more may exist between these transport coefficients for the same water content. Only two of the advanced hygrothermal models include this discrimination for the liquid transport process by employing two distinct coefficients, WUFI and WUFI-ORNL/IBP and recently MOISTURE-EXPERT. In Figure 7 the moisture diffusivities are displayed for autoclave aerated concrete, Kuenzel and Holm [*54*], for both liquid uptake and liquid redistribution (drying).

Directional Properties

Another important material property consideration in advanced hygrothermal models is that many materials exhibit very different behavior in the x, y, and z Cartesian directions. For example, moisture transport in wood is direction dependent. Thermal properties may also be spatial dependent, such as the thermal conductivity in fibrous materials depending on the packing arrangement. For the advanced hygrothermal models that include air flow, the spatial properties for air permeability are also of importance.

The predictive accuracy of advanced hygrothermal models depends more on the realistic material properties than those used in simplified models. As more and more transport processes are included in a model, the errors from uncertainties in each process propagate farther than in simple lumped models.

Currently, there is a need to develop material properties that are both more accurate and representative. It is expected that the recent ORNL state-of-the-art advanced hygrothermal property laboratory built in 2000 will bridge this gap and provide the needed heat and moisture transport properties for a wide range of North American construction materials.

Building Envelope System and Sub-System Effects

The hygrothermal performance of a building envelope depends on the integral performance of the building system under consideration and its sub-systems. A building system consists of all 1-D, 2-D, and 3-D components, such as material layer systems, and includes all unintentional cracks and openings. Sub-systems are defined by the close location and interactions of two material systems such as a brick-mortar masonry interface, gluing of two materials together forming a substrate (EIFS board), stapling on a weather resistive barrier, nailing a protective layer, coating on a surface etc. To date, limited analyses have been performed to understand these system and sub-systems effects, while at the same time they are the predominant influence of the envelope. Water penetration into a wall cavity is extremely important, and the overall performance of the wall depends on the sub-system that allowed this transport of moisture. Similarly, air gaps can induce airflow through the system and cause higher than critical levels of moisture accumulation, resulting in damage. They are a result of cracks and imperfections in an envelope system.

These system and sub-system effects (imperfections) in the building envelope are features that only an advanced hygrothermal model incorporates. The capability to include thermal and moisture sources into the wall domain, as a function of time and/or other parameters, permits such a model to predict results that are closer to reality than results without the sources (ideal conditions). Indeed, supplementary data (experimental) to describe the particular perfor-

TABLE 2—A List of some of the advanced hygrothermal models

Model Name		Author	D	LF	WDR	MEA	BED	MPD	MFF	AF	EIL	VD	SSF	ETU	DP	AP
1	WUFI	Kuenzel	1 & 2	3	3	3	3	3	2	1	3	3	2	3	2	A
	WUFI ORNL/IBP	Kuenzel and Karagiozis and Holm	1 & 2	3	3	3	3	3	3	3 & 5	4	3	2	3	2	—
2	LATENITE	Karagiozis and Salonvaara	1 & 2 & 3P	3	2	2	2	2	2	3	4	2	1	1	1	I
3	DELPHIN4.1	Grundewald	1 & 2	2	2	2	2	1	2	3	3	2	1	2	1	G
4	SIMPLE-FULUV	Okland	2	1	1	1	1	1	2	5	4	2	1	1	1	C
5	TCCC2D	Ojanen	1 & 2	1	1	1	1	3	2	3	4	3	1	1	1	D
6	HMTRA	Gawin., Schrefler	2	3	1	1	2	1	2	3	3	2	2	2	1	F
7	TRATMO2	Salonvaara	1 & 2	3	2	1	3	3	3	5	3	2	1	1	1	D
8	JAM-2	Arfvidson	1 & 2	3	1	2	1	3	3	1	3	3	1	1	1	—
9	FRET	Matsumoto Hokoi, Hatano	1 & 2	3	1	1	1	1	3	1	4	3	2	1	1	J
10	2DHAV	Janssens	2	1	1	1	2	3	3	4	3	3	1	1	1	H
11	FSEC	Gu, Swami,Fairey	2	1	1	1	1	1	2	3 & 5	4	2	1	1	1	K
12	MOISTURE -EXPERT	Karagiozis	2	2	2	3	2	2	2	5 4	4	2	1	1	2	B

D: Dimensionality 1:1-D, 2:2-D,3:3-D, P:Partial only at material level

LF: Liquid Capillary Flow 1: No, 2: Yes, 3:Yes + Pressure Driven

WDR:Wind-Driven Rain 1:No, 2:Yes (Assumed), 3:Yes Measured & Validated

MEA: Moisture Engineering Assessment Tools 1) None, 2)Graphical GUI of Primitive Variables, 3)Graphical and Engineering Assessment

BED: Building Envelope Dynamics (System-and Sub-System Performances) 1) No 2) Some 3) Extensive

MPD: Material Property Database 1)Other Sources 2)In-house data 3)Database

MFF: Material Functional Form 1)Simplified or Constant 2)Full-Functional

AF: Air Flow Dynamics 1) None 2) Assumed 3) Darcy's 4) Gap Flow & Darcy's 5) Navier Stokes

EIL:Exterior-Interior-Loads 1) Constant, 2)Dynamic, 3) Dynamic-I&E, 4) Dynamic-I&E with Pressure

VD: Validation Effort 1) None 2)Limited 3) Extensive

SSF:Super Saturated Flow: 1)No, 2)Yes

ETU: Ease of Use: 1)Only Authors, 2)Qualified Experts 3) All

DP: Directional Properties: (1) Uniform, (2) Different for water uptake and redistribution

APP: Appendix where model may be found (Appendix Number) mance of a sub-system is necessary and must be conducted for development of sound hygrothermal guidelines. These tests, performed in the lab or under field conditions, are the cornerstone of moisture engineering analysis as depicted in Figs. 6 and 7. The improvement in the quality of the results produced from advanced hygrothermal models depends solely on the level and accuracy to which the envelope is described. Water penetration, air leakage paths and amounts, description of anomalies, as well as interior and exterior sources, must be defined a priori.

ASHRAE SPC 160P committee, TenWolde [*57*], is developing criteria for moisture control, one being water penetra-

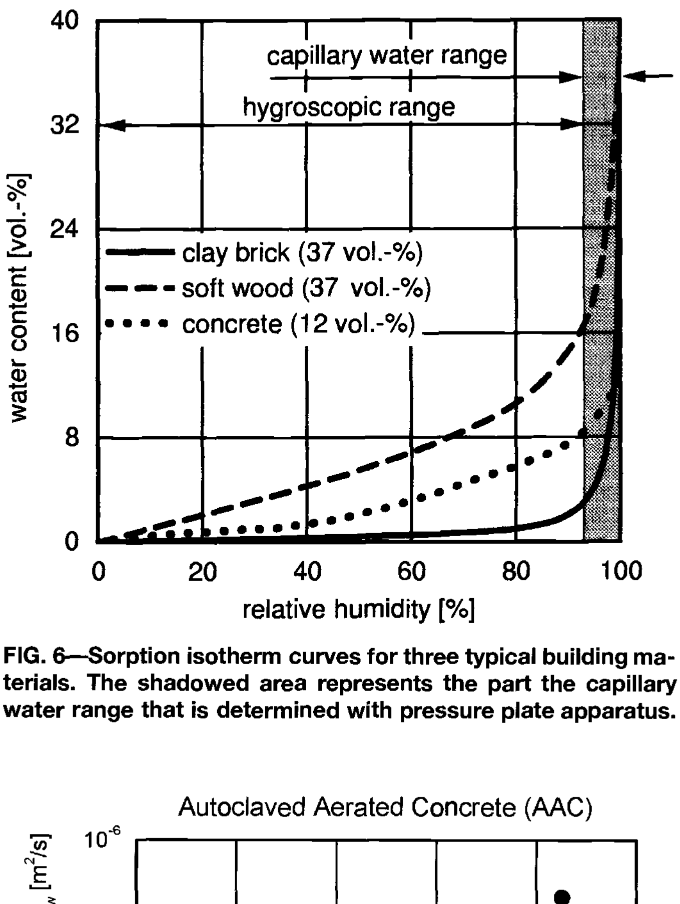


FIG. 6—Sorption isotherm curves for three typical building materials. The shadowed area represents the part the capillary water range that is determined with pressure plate apparatus.

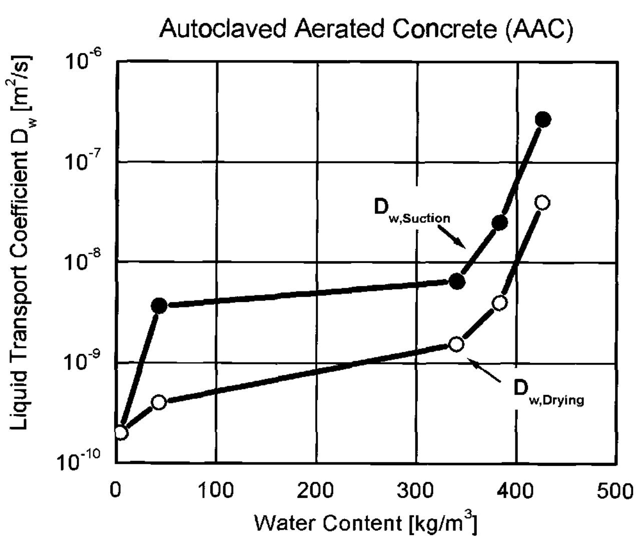


FIG. 7—Liquid diffusivity functions for AAC derived from NMR-scanning.

tion. This shift of paradim thinking that water at some point and time will enter the building envelope will allow development of building envelopes with enhanced water deflection (D), drainaged (D), drying (D) and durability (D) characteristics, the 4-D water management designs. In Fig. 8, the oriented strand board (OSB) sheathing moisture performance for a stucco clad wall in Seattle is shown for five different levels of water penetration levels, at 0%, 1%, 3%, 5%, and 10% of the amount striking the exterior surface due to wind-driven rain, Karagiozis [*25*]. Here the drying performance as a function of water penetration is shown for a period of two years starting July 1. For this particular stucco clad system the wall may perform acceptably for up to 1% of water penetration. This sub-system effect (water penetration) of the wall is found to be critical for the climate of Seattle.

WIND-DRIVEN RAIN

The largest source of moisture for any building envelope is rain. This source is several hundred times larger than the moisture content in the ambient air for a wall, roof, and basement system. However, even though rain, more precisely, wind-driven rain, is potentially the most important source of moisture, a limited amount of data exist.

Wind-driven rain is a complex phenomenon in itself, relatively unresearched and not fully understood. Rain droplets with a wide range of sizes are transported by wind with a distinct 3-D behavior near buildings. Rain droplet size distributions vary randomly with respect to time and space. For these reasons, the amount of rain striking the exterior surfaces of a building is unique to that building. It depends on the local geometry of the building, topography around the building, wind speed, wind direction, rain intensity, and rain droplet distribution.

Knowledge available on wind-driven rain, albeit limited, has been predominantly determined by field experiments [*16,44–48*]. Recently, however, investigations employing Computational Fluid Dynamics (CFD) methods by [*49,50*], Wisse [*51*], and Karagiozis and Hadjisophocleous [*52*] have appeared. Both experimental and numerical results show agreement on rain intensity factors. Typical rain trajectories for a full range of rain droplet sizes were generated using a commercially available CFD model TASCflow by Karagiozis et al. [*4,52*]. Correlations were then developed from many series of rain-droplet simulations and were included in the hygrothermal model on a case-by-case application. Wind-driven rain becomes a source term for the exterior wall surface. However, the amount of water that can penetrate into porous materials is limited by the maximum allowable moisture content in the exterior material. Figure 11 shows the dominant wetting pattern on a high-rise building. At the top corners of the building, when the wind flow is perpendicular to the building, the amount of water received can be many times higher than what strikes the ground. Karagiozis et al. [*55*], showed that up to 1.5 to 2 times more water striking the building at these locations. For example, if the rain intensity is 10 mm/h, the top may receive up to 15 to 20 kg/$m^2 \cdot h$ of water. This amount of water puts a severe hygric

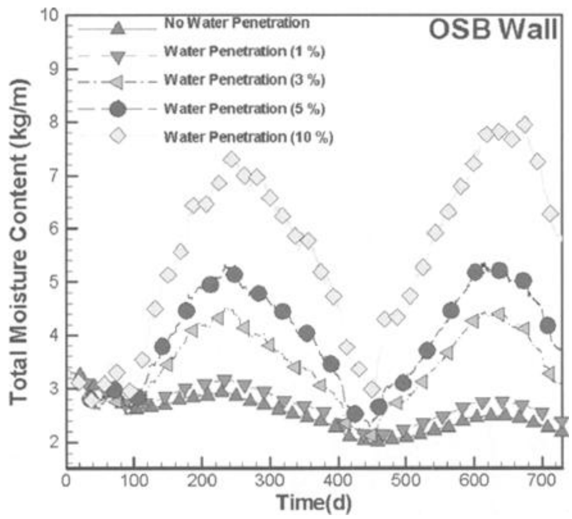


FIG. 8—Wetting distribution averaged along the height of the building.

load on the envelope. Work is currently been conducted (1999) by the University of Eindhoven, the University of Chalmers, the University of Leuven, the University of Waterloo, and the Oak Ridge National Laboratory to further quantify these environmental loads.

HOLISTIC HYGROTHERMAL ANALYSIS

Further advances in the area of moisture engineering are currently being achieved by taking a broader holistic approach to moisture design. In most applications, building envelope designers attempt to predict the hygrothermal performance of an individual building envelope, for example, a wall, roof, and basement by uncoupling the system not only from the interior environment but from interactions among envelope components and both the exterior and interior en-

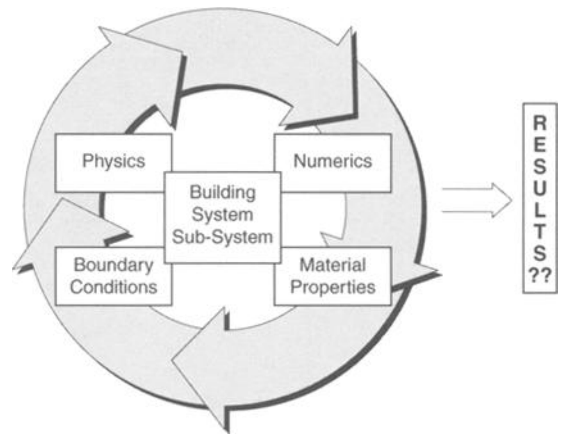


FIG. 9—Building system and sub-system function in advanced hygrothermal modeling.

vironments. This one-to-one interaction of a small part (section of a wall system perhaps) of a building is termed today as state-of-the-art. The stand-alone analysis of specific envelope parts is important in understanding the influences of various controlling elements (vapor retarder, air barriers, building papers) in terms of their effect on the hygrothermal performance of the envelope, but provide limited performance information on the overall heat and mass transfer of a building.

An iterative open loop approach of complete hygrothermal analysis of a building is demonstrated in Fig. 9. Holistic performance modeling requires the direct coupling of all building envelope systems with the interior environment and mechanical systems (HVAC) and the exterior environmental loads. A new integrator model and approach to holistic moisture engineering analysis has been presented by Karagiozis and Salonvaara [*6*]. Figure 12 shows the interactions of moisture engineering modeling with other important components of a building.

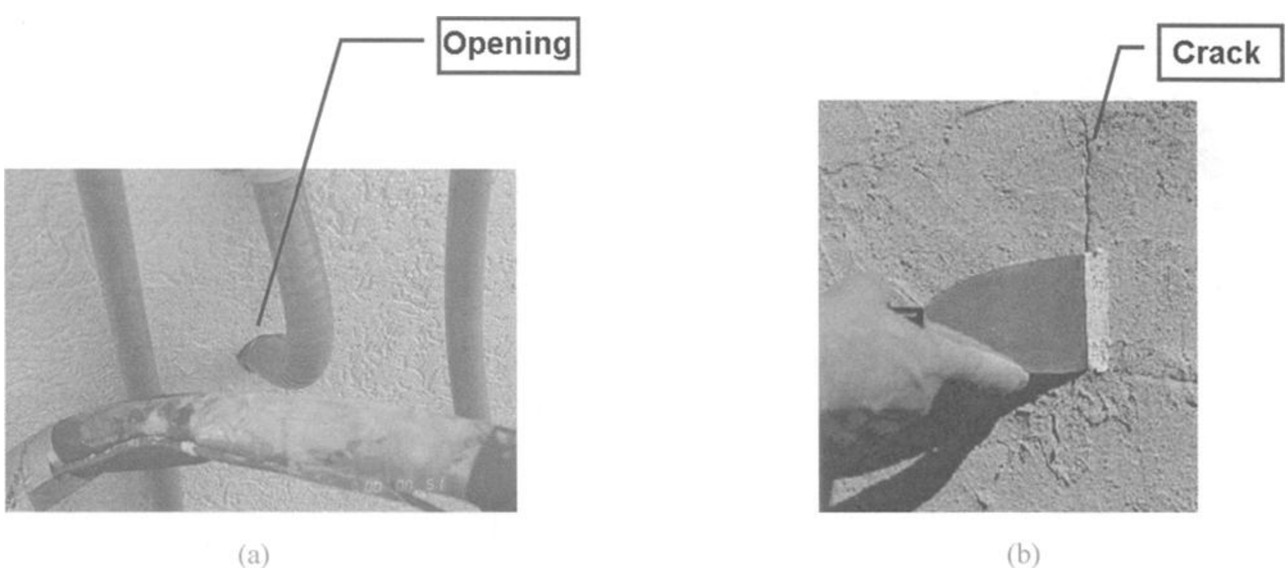


FIG. 10—Two-sub-system effects.

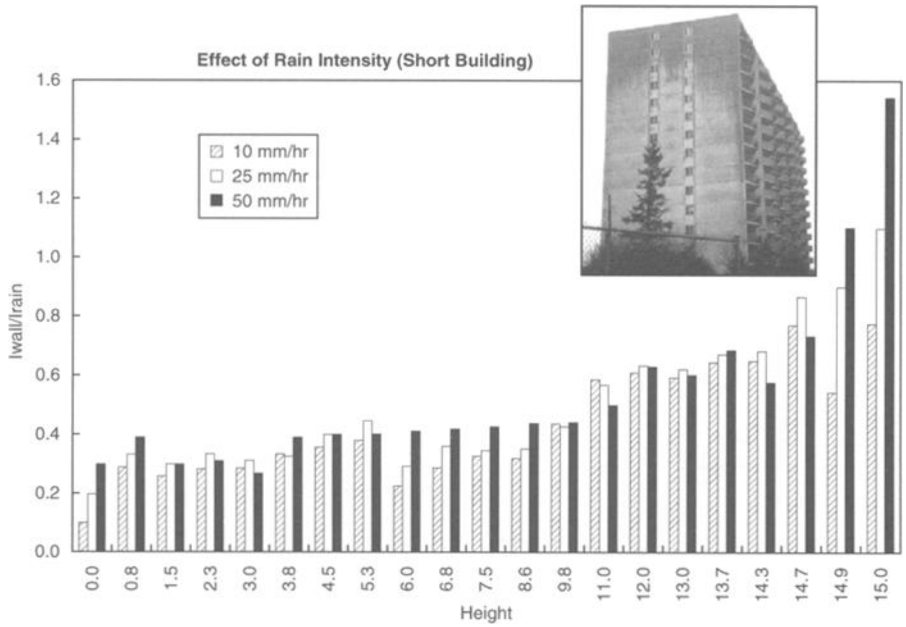


FIG. 11—Wetting distribution averaged along the height of the building.

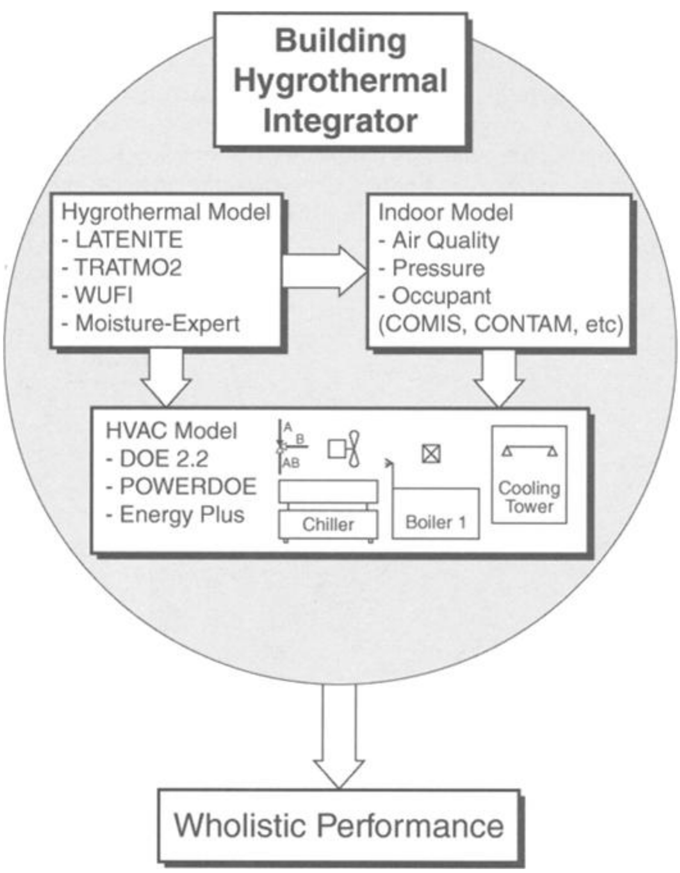


FIG. 12—Holistic performance modeling: integration approach.

OUTPUTS FROM HYGROTHERMAL MODELS

In most advanced hygrothermal models, moisture content, temperature, relative humidity, and the related fluxes are common outputs of simulations. Results have to be checked for consistency, accuracy, grid independency, and sensitivity to parameter changes. The results may be used to determine the moisture tolerance of an envelope system subjected to various interior and exterior loads. The heat fluxes may be used to determine the thermal performance under the influence of moisture and airflow. Furthermore, the transient output data may be used for durability and indoor air quality assessment. Post-processing tools concerning durability, e.g., corrosion, mold growth [*53*], freeze and thaw, hygrothermal dilatation, and indoor air humidity are currently being developed. For instance, a model to estimate the rate of mold growth and corrosion has been implemented by Karagiozis and Kuenzel [*7*]. It is expected that hygrothermal models will be incorporated in whole-building simulation tools [*6*].

CONCLUSIONS

This chapter classified and identified the features required by advanced hygrothermal models. As these models are very important to the development of design guidelines, a moisture engineering approach was presented that integrates experimental and modeling activities.

Advanced hygrothermal models may be coupled to mechanical, chemical, or even biological sub-models to determine the effect of hygrothermal processes. A list and presentation of a few of the more known models was given, followed by example cases. A new generation of models is expected to significantly enhance our current understanding of the effects of moisture on the overall performance of our envelopes in term of service life.

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7

Manual Analysis Tools

by Anton TenWolde[1]

THERE ARE TWO FUNDAMENTAL APPROACHES to design for moisture control. One approach focuses on the thermal and moisture properties of the building envelope (exterior walls, roofs, and ceilings) needed to withstand the interior and exterior conditions. The second approach attempts to adjust the indoor climate to the thermal and moisture characteristics of the building envelope. This chapter deals with design tools for the exterior envelope only. Recommendations for indoor climate control can be found elsewhere in this handbook.

The traditional tools currently available for design of the exterior building envelope all have severe limitations, and the results are difficult to interpret. However, for lack of better tools, these methods are used by design professionals and form the basis for current building codes dealing with moisture control and vapor retarders. The proper use and limitations of these methods are discussed in the first section of this chapter, Manual Design Tools. A few relatively simple numerical methods not included elsewhere are discussed briefly in the section on Numerical Tools.

MANUAL DESIGN TOOLS

The three-best known manual design tools for evaluating the probability of condensation within exterior envelopes (exterior walls, roofs, floors, or ceilings) are the dew point method, the Glaser diagram, and the Kieper diagram. All three methods compare vapor pressures within the envelope, as calculated by simple vapor diffusion equations, with saturation pressures, which are based on temperatures within the envelope. If the calculated vapor pressure is above the saturation pressure at any point within the envelope, condensation is indicated. The dew point method, used in North America, and the Glaser diagram, commonly used in Europe and elsewhere, are almost identical. They differ slightly in the formulation of the vapor diffusion equation for flow through a building material and in definition of terms; the main difference lies in the graphical procedures. These methods are often misused, especially when condensation is present. Like the dew point method and Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory.

Some people advocate abandoning these design tools because of their severe limitations. Perhaps the greatest limitation is that their focus is restricted to prevention of sustained surface condensation. Many building failures, such as mold and mildew, buckling of siding, or paint failure, are not necessarily related to surface condensation. Conversely, limited condensation can often be tolerated, depending on the materials involved, temperature conditions, and the speed at which the material dries out. Another weakness is that these methods exclude all moisture transfer mechanisms other than vapor diffusion and neglect moisture storage in the building materials. This severely limits the accuracy of the calculations, especially in the case of wet materials. There are no widely accepted criteria for using manual design methods. Recommendations for use and interpretation provided in this chapter are therefore primarily based on the opinions of the author.

Dew Point Method

The dew point method [*1*] is based on the following diffusion equation and definitions

$$w = -\mu \, \Delta p / d \tag{1}$$

where

w = vapor flow per unit of area, kg/m^2 · s (grain/ft^2 · h),
μ = water vapor permeability, kg/m · s · Pa or s (perm · in.)[2],
p = vapor pressure, Pa (in. Hg), and
d = flow path or thickness of the material, m (in.)

Water vapor permeability of a material is the permeance of 1 in. (United States) or 1 m of that material. The permeance of a sheet of material is assumed to be inversely proportional to its thickness; e.g., the permeance of 0.5-in. gypsum board is twice that of 1-in. gypsum board.

Water vapor resistance, Z, is the inverse of permeance and is expressed in reps (1/perm) or m/s

$$Z = d/\mu \tag{2}$$

Thus, Eq 1 can also be written as

$$w = -\Delta p / Z \tag{1a}$$

The dew point method is best explained and demonstrated with example calculations. As an example, we will use a

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[2]1 perm = 1 grain/ft^2 · h · in. Hg; 1 grain = 1/7000 lb; 1 rep = 1/perm.

TABLE 1—Example wall with approximate thermal and vapor diffusion properties.

Air Film or Material	Thermal Resistance (h · ft² · °F/Btu)	Thermal Resistance (m² · K/W)	Permeance,[a] perm	Diffusion Resistance $Z = d/\mu$, 1/perm	Diffusion Resistance $Z = d/\delta$, 10^9 m/s
Air film (still)	0.68	0.12	160[b]	0.0063	0.11
Gypsum board, painted	0.45	0.08	5	0.2	3.5
Vapor retarder	...	...	0.06	16.67	290
Insulation	11	1.9	30	0.033	0.6
Plywood sheathing	0.62	0.11	0.5	2	35
Wood siding[c]	1	0.18	35	0.029	0.5
Air film (wind)	0.17	0.03	1000[b]	0.001	0.02
Total	13.92	2.42	...	18.94[d] 2.27[e]	329.73[d] 39.73[e]

[a] 1 perm = 1 grain/ft² · h · in. Hg.
[b] Approximate values; permeance of surface air films is very large compared to that of other materials and does not affect results of calculations.
[c] Approximate values; permeance reflects limits ventilation of back of siding.
[d] Total diffusion resistance of wall with vapor retarder.
[e] Total diffusion resistance of wall without vapor retarder.

frame wall construction with gypsum board (painted), glass fiber insulation, plywood sheathing, and wood siding (Table 1). We will assume 21.1°C (70°F), 40% indoor relative humidity, and −6.7°C (20°F), 50% outdoor relative humidity. The wall in the first example has a vapor retarder on the warm side of the cavity; the wall in the second example is identical except for the omission of the vapor retarder.

EXAMPLE 1: WALL WITH VAPOR RETARDER

Step 1—The first step is to calculate the temperature drop across each material. The temperature drop is proportional to the *R* value as follows

$$\Delta T_{\text{material}}/\Delta T_{\text{wall}} = R_{\text{material}}/R_{\text{wall}} \tag{3}$$

Table 2 lists the resulting temperature drops and resulting temperatures at each surface.

Step 2—The next step is to find the saturation vapor pressures [Pa (in. Hg)] corresponding with the surface temperatures. These values can be found in Tables 6a & 6b or in psychrometric tables or charts (e.g., Ref *1*, Chapter 6). Table 2 lists the saturation vapor pressures for this example.

Step 3—Vapor pressure drops across each material can be calculated in much the same way as are temperature drops

$$\Delta p_{\text{material}}/\Delta p_{\text{wall}} = Z_{\text{material}}/Z_{\text{wall}} \tag{4}$$

where p is the vapor pressure [Pa (in. Hg)] and Z the vapor diffusion resistance [m/s (1/perm)]. In the example, the total resistance of the wall with the vapor retarder is as follows (see Table 1)

$$Z_{\text{wall}} = 329.73\ 10^9 \text{ m/s } (18.94 \text{ perm}^{-1})$$

The total vapor pressure drop across the wall is calculated from indoor and outdoor relative humidities and the indoor and outdoor saturation vapor pressures (see Table 2).

TABLE 2—Calculation of temperatures and saturation vapor pressures.[a]

Air Film or Material	Temperature, °C (°F) Drop	Temperature, °C (°F) Surface	Saturation Vapor Pressure, Pa (in. Hg)
Indoor air			
		21.1 (70)	2503 (0.7392)
Surface air film	1.3 (2.4)		
		19.8 (67.6)	2305 (0.6807)
Gypsum board	0.9 (1.7)		
		18.9 (65.9)	2174 (0.6419)
Vapor retarder	0		
		18.9 (65.9)	2174 (0.6419)
Insulation	22.0 (39.5)		
		−3.1 (26.4)	473 (0.1394)[b]
Plywood sheathing	1.2 (2.2)		
		−4.3 (24.2)	426 (0.1258)[b]
Wood siding	2.0 (3.6)		
		−6.3 (20.6)	359 (0.1060)[b]
Surface air film	0.4 (0.6)		
		−6.7 (20)	371 (0.1096)[c]
Outdoor air			

[a] Temperature drop across the air film or material. Surface temperatures and saturation vapor pressures are taken at the interface for each set of air films or materials.
[b] Saturation vapor pressure over ice.
[c] Saturation vapor pressure over water. Dewpoint temperature or RH, reported in weather data, usually relates to saturation over water, not over ice.

$$\begin{aligned}\Delta p_{\text{wall}} &= p_{\text{indoor}} - p_{\text{outdoor}} \\ &= (40/100)2503 - (50/100)371 \\ &= 1001 - 185 = 816 \text{ Pa } (0.2409 \text{ in. Hg})\end{aligned}$$

As with temperatures, the vapor pressures at the surfaces of each material can be easily determined from the vapor pressure drops. Table 3 lists the results for the example wall with vapor retarder.

Step 4—Figure 1 shows the saturation and calculated vapor pressures. It reveals that none of the vapor pressures exceeds the saturation vapor pressure, and therefore no con-

TABLE 3—Calculation of vapor pressures in wall with vapor retarder.[a]

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure [Pa (in. Hg)]	
		Drop	Surface
Indoor air (40% RH)[b]			
	2503 (0.7392)		1001 (0.2957)
Surface air film		0.3 (0.00008)	
	2305 (0.6807)		1001 (0.2956)
Gypsum board		8.6 (0.0025)	
	2174 (0.6419)		992 (0.2930)
Vapor retarder		717.9 (0.2120)	
	2174 (0.6419)		274 (0.0810)
Insulation		1.4 (0.0004)	
	472 (0.1394)		273 (0.0806)
Plywood sheathing		86.2 (0.0254)	
	426 (0.1258)		187 (0.0552)
Wood siding		1.2 (0.0004)	
	359 (0.1060)		185 (0.0548)
Surface air film		0.04 (0.00001)	
	371 (0.1096)		185 (0.0548)
Outdoor air (50% RH)			

[a]Vapor pressures are taken at the interface for each set of air films or materials.
[b]RH is relative humidity.

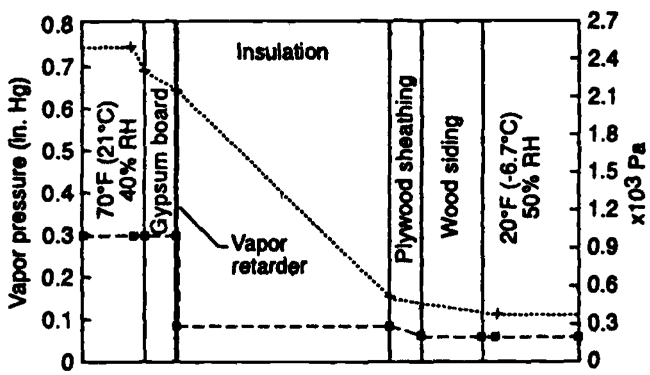

FIG. 1—Dew point method; example wall with vapor retarder. Dotted line is saturation vapor pressure; dashed line is calculated vapor pressure.

densation is indicated. Vapor flow is uniform throughout the wall and can be calculated easily as follows

$$w = \Delta p_{\text{wall}}/Z_{\text{wall}} \quad (5)$$

For this example, $w = 816/(329.73\ 10^9) = 2.5\ 10^{-9}$ kg/m$^2 \cdot$ s (0.013 grain/h $\cdot$ ft^2). This is a very small amount of water vapor flow.

EXAMPLE 2: WALL WITHOUT VAPOR RETARDER

Example 2 uses the same wall but without the vapor retarder. The vapor retarder has a negligible effect on temperatures (as long as air movement is not considered), and temperatures and saturation vapor pressures are therefore the same as in the wall in Example 1. Skip directly to Step 3, calculation of vapor pressures.

Step 3—The total vapor diffusion resistance of this wall is as follows (see Table 1)

$$Z_{\text{wall}} = 39.73\ 10^9 \text{ m/s } (2.27 \text{ perm}^{-1})$$

Vapor pressure drops can again be calculated with Eq 2. The initial calculations are shown in Table 4..

Step 4—Figure 2 shows the saturation and calculated vapor pressures. This time comparison with saturation pressures reveals that the calculated vapor pressure on the interior surface of the sheathing [915 Pa (0.2702 in. Hg)] is well above the saturation pressure at that location [472 Pa (0.1394 in. Hg)]. This indicates condensation, probably on the surface of the sheathing, because condensation within the permeable insulation is unlikely. If the location of the condensation or the condensation rate are of interest, additional calculations (Steps 5 and 6) are necessary.

Step 5—Figure 2 shows that the calculated vapor pressure exceeds the saturation vapor pressure by the greatest amount at the interior surface of the plywood sheathing. This is therefore the most likely location for condensation to occur. With condensation at that surface, vapor pressure should equal saturation at that location (see Table 4).

Step 6—The change of vapor pressure on the plywood sheathing alters all other vapor pressures as well as the vapor flow through the wall. The calculation of vapor pressures is similar to that in Step 3, but the wall is now divided into two parts: one part on the interior of the condensation plane (that is, gypsum board and insulation) and the other part on the exterior (plywood sheathing and wood siding). The vapor pressure drop over the first part of the walls is

$$\Delta p_1 = 1001 - 472 = 529 \text{ Pa } (0.156 \text{ in. Hg})$$

and that over the second part is

$$\Delta p_2 = 472 - 185 = 287 \text{ Pa } (0.085 \text{ in. Hg})$$

The vapor diffusion resistances of both parts of the wall are

$$Z_1 = (0.11 + 3.5 + 0.6)10^9 = 4.21\ 10^9 \text{ m/s } (0.24 \text{ perm}^{-1})$$
$$Z_2 = (35 + 0.5 + 0.02)10^9 = 35.52\ 10^9 \text{ m/s } (2.03 \text{ perm}^{-1})$$

The vapor pressure drops can now be calculated from

TABLE 4—Initial and final calculation of vapor pressures in wall without vapor retarder.

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure, Pa (in. Hg)	
		Drop	Surface
	INITIAL CALCULATION		
Indoor air (40% RH)			
	2503 (0.7392)		1001 (0.2957)
Surface air film		2.2 (0.0007)	
	2305 (0.6807)		999 (0.2950)
Gypsum board		71.9 (0.0212)	
	2174 (0.6419)		927 (0.2738)
Insulation		12.0 (0.0036)	
	472 (0.1394)		915 (0.2702)
Plywood sheathing		718.9 (0.2123)	
	426 (0.1258)		196 (0.0579)
Wood siding		10.3 (0.0030)	
	359 (0.1060)		186 (0.0549)
Surface air film		0.4 (0.0001)	
	371 (0.1096)		185 (0.0548)
Outdoor air (50% RH)			
	FINAL CALCULATION		
Indoor air			
	2503 (0.7392)		1001 (0.2957)
Surface air film		13.8 (0.0041)	
	2305 (0.6807)		987 (0.2916)
Gypsum board		439.8 (0.1299)	
	2174 (0.6419)		547 (0.1617)
Insulation		75.4 (0.0223)	
	472 (0.1394)		472 (0.1394)
Plywood sheathing		281.7 (0.0834)	
	426 (0.1258)		190 (0.0560)
Wood siding		4.0 (0.0012)	
	359 (0.1060)		186 (0.0548)
Surface air film		0.2 (0.00005)	
	371 (0.1096)		186 (0.0548)
Outdoor air			

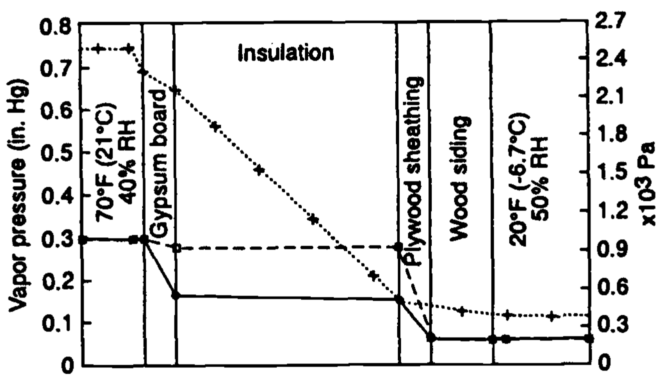

FIG. 2—Dew point method; example wall without vapor retarder. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

$$\Delta p_{\text{material}}/\Delta p_i = Z_{\text{material}}/Z_i \qquad i = 1,2 \tag{6}$$

Final calculations of vapor pressure are shown in Table 4. The vapor pressure no longer exceeds the saturation vapor pressure, which means that the condensation plane was chosen correctly. Figure 2 shows the vapor pressure profile (identified as vapor pressure, final calculation).

Vapor flow is no longer the same throughout the wall: vapor flow into the wall from the indoor air increased as a result of the lower vapor pressure at the plywood surface, while flow from the wall to the outside decreased. The difference between the two flows is the rate of water (solid or liquid) accumulation.

$$w_c = \Delta p_1/Z_1 - \Delta p_2/Z_2 = 529/(4.21\ 10^9) - 287/(35.52\ 10^9)$$
$$= 118\ 10^{-9}\ \text{kg/s} \cdot \text{m}^2\ (0.61\ \text{grain/h} \cdot \text{ft}^2)$$

In our example, the plywood surface is below freezing, and this moisture would probably accumulate as frost. About a week of condensation at this rate would increase the average moisture content of the plywood by 1%.

The limitations of this method and recommendations for its use can be found at the end of the section on manual design tools.

The dew point method can be summarized as follows:

1. Calculate temperature drops and surface temperatures.
2. Find corresponding saturation vapor pressures.
3. Calculate vapor pressure drops and vapor pressures.
4. Check if saturation pressure is above vapor pressure at all surfaces; if so, no condensation is indicated. Vapor flow through the wall may be determined if desired. (If condensation is indicated, continue with the following steps.)
5. Select condensation surface; vapor pressure at this surface equals the saturation vapor pressure.
6. Recalculate vapor pressures; if any vapor pressures are above saturation, Steps 5 and 6 should be repeated with a different condensation surface.
7. If needed, calculate rate of condensation.

Glaser Diagram

The Glaser diagram [2,3] is a variation on the dew point method. It is used primarily in Europe. The Glaser diagram is based on the following diffusion equation and definitions

$$w = -(\delta'/\mu')\,\Delta p/d \tag{7}$$

where

δ' = diffusion coefficient of water vapor in air, s,
μ' = diffusion resistance factor of the material, and
d = flow path or thickness of the material, m (in.).

The diffusion resistance factor is the ratio of the resistance to water vapor diffusion of the material and the resistance of a layer of air of equal thickness. The term *water vapor diffusion coefficient* is often used instead, defined by

$$\delta = \delta'/\mu' \tag{8}$$

Substituting δ in Eq 6 shows that diffusion coefficient δ and permeability μ (Eq 1) are the same. However, permeability is usually expressed in English units (perm · in.), while the diffusion coefficient is usually expressed in metric units (s). Vapor diffusion resistance is again defined as

$$Z = d/\delta$$

The only difference between the Glaser diagram and the conventional dew point method lies in the horizontal axis of the diagram. Rather than using thickness of the materials, the Glaser diagram uses the vapor diffusion resistance as the horizontal axis (Fig. 3 shows a repeat of Example 2). Thus, the materials with the largest resistance are featured most prominently. The advantage of this display is that the vapor pressure profiles are converted into straight lines. Thus, individual vapor pressures need not be calculated. In the example of the wall without vapor retarder and condensation on the plywood, the vapor pressure profile consists of two straight line segments. The saturation vapor pressure still needs to be determined from temperatures, as in the dew point method.

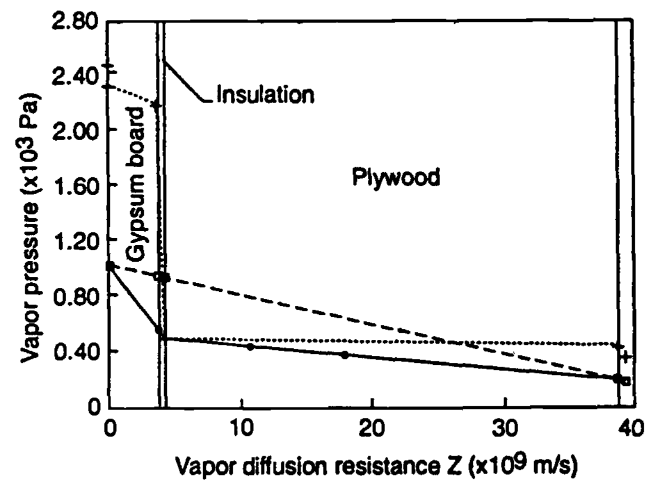

FIG. 3—Glaser diagram for example wall without vapor retarder. See caption to Fig. 2 for line designations.

Kieper Diagram

The Kieper diagram was first introduced by Kieper et al. [4] and described in greater detail by TenWolde [5]. As with the dew point method and the Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory. The advantages of this method are: (a) the same diagram can be used for different wall configurations, as long as indoor and outdoor conditions are not changed, and (b) the calculation does not need to be repeated if condensation is indicated.

Rather than graphing vapor pressures and saturation pressures, the Kieper diagram uses two parameters, x and y, representing thermal properties and vapor diffusion properties of the materials in the wall, respectively. The thermal property x parameter is defined as follows

$$\begin{aligned} x_1 &= R_1/R_{\text{wall}} \\ x_2 &= x_1 + R_2/R_{\text{wall}} \\ x_n &= x_{n-1} + R_n/R_{\text{wall}} \end{aligned} \tag{9}$$

where R_1 and R_2 are the R values of the individual materials and air films. Values of x range from 0 to 1. Temperature in the wall can be easily expressed as a function of x

$$T(x) = T_i - x(T_i - T_o) \tag{10}$$

where

T_i = indoor temperature °C (°F), and
T_o = outdoor temperature °C (°F).

The vapor diffusion y parameter is defined similarly as

$$y_n = y_{n-1} + Z_n/Z_{\text{wall}} \tag{11}$$

and also ranges from 0 to 1.

If there is condensation or evaporation of liquid water at location (x,y) the net moisture flow to that point can be stated as

$$\begin{aligned} w_c &= \frac{p_i - p_s[T(x)]}{yZ_{\text{wall}}} - \frac{p_s[T(x)] - p_o}{(1-y)Z_{\text{wall}}} \\ &= \frac{1}{Z_{\text{wall}}}\,\frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \end{aligned} \tag{12}$$

where

w_c = moisture accumulation rate, kg/m² · s (grain/ft² · h),
p_i = indoor vapor pressure, Pa (in. Hg),
p_o = outdoor vapor pressure, Pa (in. Hg),
$p_s[T(x)]$ = saturation vapor pressure, Pa (in. Hg).
Note: $T(x)$ is defined in Eq 10.

If w_c is positive, condensation (wetting) is indicated; if negative, evaporation (drying) takes place. The term w_c therefore indicates the wetting/drying potential at a given location in the wall or roof.

If we move the term Z_{wall} to the left side of Eq 12, the right side includes only x, y, and indoor and outdoor vapor pressures and contains no material property parameters

$$w_c Z_{\text{wall}} = \frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \tag{13}$$

The left term of Eq 13 has the dimension of a pressure (in.

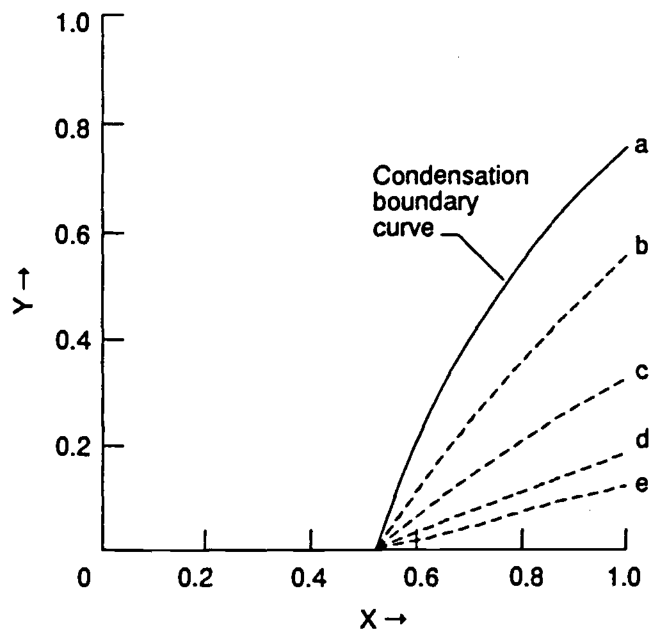

FIG. 4—Kieper diagram: moisture accumulation curves for indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (−6.7°C), 50% RH. W_cZ values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in Hg (5080 Pa).

Hg or Pa). Curves in the Kieper diagram connecting points where the product w_cZ_{wall} is constant represent curves of "equal wetting potential." The curve where the wetting potential is zero is often called the condensation boundary curve. These curves only change with changes in indoor or outdoor conditions and do not depend on the wall or roof construction. Figure 4 shows the Kieper diagram with the curves for 21.2°C (70°F), 40% relative humidity indoor conditions and −6.7°C (20°F), 50% relative humidity outdoors. Various constructions can be analyzed in a single Kieper diagram if indoor and outdoor conditions are the same.

Table 5 shows the x and y values associated with the examples used previously: a frame wall with and without a vapor retarder. When the wall profiles are entered in the Kieper diagram, as shown in Fig. 5, it is obvious that the wall with the vapor retarder is entirely outside the condensation region (the area below the condensation boundary curve). As expected, the curve for the wall without the vapor retarder penetrates the condensation region in the diagram. The point on the curve that penetrates the deepest (i.e., the plywood surface) represents the greatest wetting potential. This point falls between curve d (w_cZ = 1.0 in. Hg or 3386 Pa) and e (w_cZ = 1.5 in. Hg or 5080 Pa). The wetting potential can be estimated by interpolation:

$$w_cZ = 1.4 \text{ in. Hg (4740 Pa)}$$

With Z = 2.27 perm^{-1} (39.7 10^9 m/s), the estimated rate of condensation is

$$w_c = 1.4/2.27 = 0.62 \text{ grain/h} \cdot \text{ft}^2 \text{ } (120\ 10^{-9} \text{ kg/m}^2 \cdot \text{s})$$

Limitations of Manual Design Tools

The methods discussed previously have the same severe limitations and should therefore be used with caution. The methods only "predict" condensation, not moisture damage. Many constructions can sustain limited periods of condensation without significant damage, especially if the temperatures are near or below freezing and the material is able to dry quickly. In addition, performance problems such as mold and mildew or paint failure are not necessarily related to surface condensation.

The methods ignore air leakage. If air leakage is present, it tends to dominate moisture transport. Even small amounts of indoor air leakage into the wall (exfiltration) can more than double the condensation rate during winter [*6*]. However, where exfiltration increases the potential for wetting, infiltration of dry cold air decreases that potential. If the amount and direction of airflow are known, the effects may be estimated with more sophisticated methods, discussed later in this chapter. However, usually insufficient information is available on the airflow patterns in wall and roof cavities to estimate the effect on moisture conditions.

The methods do not recognize liquid capillary transport or any transport mechanisms other than diffusion. This tends to result in the underprediction of moisture transfer in materials such as wood at higher moisture contents. For instance, in plywood, moisture transfer may be as much as 16 times greater under wet conditions than under dry conditions and in waferboard, three to four times greater under wet conditions [*7*].

TABLE 5—Kieper diagram: x and y values for example wall with and without a vapor retarder.

Air Film or Material	Thermal resistance,[a] h · ft² · °F/Btu	Permeance,[b] perm.	Diffusion Resistance, rep	x	Vapor Retarder, y	No Vapor Retarder, y
Air film (still)	0.68	160	0.006	0.049	0.0003	0.003
Gypsum board, painted	0.45	5	0.2	0.081	0.011	0.091
Vapor retarder	. . .	0.06	16.67	0.081	0.891	. . .
Insulation	11	30	0.033	0.871	0.893	0.105
Plywood sheathing	0.62	0.5	2	0.916	0.998	0.986
Wood siding	1	35	0.029	0.988	1.000	0.999
Air film (wind)	0.17	1000	0.001	1.000	1.000	1.000
Total						
With vapor retarder	13.92		18.94			
Without vapor retarder	13.92		2.27			

[a] See Table 1 for SI values.
[b] 1 perm = 1 grain/ft² · h · in. Hg.

TABLE 6a—Saturation water vapor pressures (Pa) over water and ice, SI units.

Temperature		0	1	2	3	4	5	6	7	8	9
-30 °C to -39 °C	ice	38	34	31	28	25	22	20	18	16	14
	wtr	51	46	42	38	34	31	28	26	23	21
-20 °C to -29 °C	ice	103	94	85	77	70	63	57	52	47	42
	wtr	125	115	105	96	88	81	73	67	61	56
-10 °C to -19 °C	ice	260	238	217	198	181	165	151	137	125	114
	wtr	286	264	244	225	208	191	176	162	149	137
0 to -9 °C	ice	611	562	517	476	437	402	368	338	310	284
	wtr	611	568	528	490	455	421	391	362	335	310
0 to 9 °C	wtr	611	657	705	758	813	872	935	1001	1072	1147
10 to 19 °C	wtr	1227	1312	1402	1497	1598	1704	1817	1937	2063	2196
20 to 29 °C	wtr	2337	2486	2643	2809	2983	3167	3361	3565	3780	4006
30 to 39 °C	wtr	4243	4493	4755	5031	5320	5624	5942	6276	6626	6993
40 to 49 °C	wtr	7378	7780	8201	8642	9103	9586	10089	10616	11166	11740

note 1: for temperatures below 0°C saturation vapor pressures are listed over ice and water (wtr).
note 2: saturation vapor pressures for intermediate temperatures can be estimated by interpolation.

All three methods are steady-state and do not recognize the effects of moisture and heat storage. This may be a major drawback when trying to determine the potential for damage in a wall or roof with large storage capacity or in a climate with a low drying potential. In those cases, moisture stored during an earlier part of the season may cause damage at a later time.

When moisture condenses or evaporates, latent heat is released or absorbed, raising or lowering temperatures. The analysis does not take this into account. In most practical cases, this is not a major effect unless the condensation/evaporation takes place on an exposed surface (for example, window condensation).

All three methods are one-dimensional; that is, the effect of corners, holes, or cracks, studs, or other thermal "bridges" are not included.

Recommendations for Use

Although manual design tools have many limitations and are based on simplifying assumptions, they have the advantage of being relatively simple. For that reason, they will continue to be used, despite the increased availability of much more sophisticated computer programs such as MOIST. If steady-state tools are used, the author suggests the following:

- Only use these methods for analyzing airtight construction and in cases where wetting by rain or heating by direct sunlight does not play a significant role.
- Only use these methods to estimate seasonal mean conditions, rather than daily or even weekly mean conditions.
- Use monthly averages for indoor and outdoor temperatures and humidities.
- Results obtained with any of these methods should be considered as approximations and be used with prudent care.

NUMERICAL TOOLS

This section briefly discusses several relatively simple numerical analytical methods that are not included in other chapters. All the models discussed in this section are limited to one-dimensional analysis.

MOISTWALL, developed at the Forest Products Laboratory, is a numerical version of the Kieper diagram [5]. The program calculates moisture accumulation potential at each material surface using Eq 12. If all values are negative, no condensation is indicated. If some results are positive, the maximum is selected. MOISTWALL was implemented on a programmable calculator and has not yet been adapted to personal computers.

TABLE 6b—Saturation water vapor pressures (in. Hg) over water and ice, English units.

Temperature		0	2	4	6	8
-10 °F to -18 °F	ice	0.02203	0.01974	0.01766	0.01579	0.01410
	wtr	0.0277	0.0250	.02267	0.0204	0.0185
0 to -8 °F	ice	0.0376	0.0339	0.0305	0.0274	0.0246
	wtr	0.0448	0.0407	0.0370	0.0336	0.0305
0 to 8 °F	ice	0.0376	0.0418	0.0463	0.0513	0.0568
	wtr	0.0448	0.0492	0.0539	0.0591	0.0647
10 to 18 °F	ice	0.0629	0.0695	0.0767	0.0846	0.0933
	wtr	0.0708	0.0774	0.0845	0.0923	0.1006
20 to 28 °F	ice	0.1027	0.1130	0.1243	0.1366	0.1500
	wtr	0.1096	0.1193	0.1298	0.1411	0.1532
30 to 38 °F	ice	0.1645	0.1803			
	wtr	0.1663	0.1804	0.1955	0.2117	0.2290
40 to 48 °F	wtr	0.2477	0.2676	0.2890	0.3118	0.3363
50 to 58 °F	wtr	0.3624	0.3903	0.4200	0.4518	0.4856
60 to 68 °F	wtr	0.5216	0.5599	0.6007	0.6441	0.6902
70 to 78 °F	wtr	0.7392	0.7911	0.8463	0.9047	0.9667
80 to 88 °F	wtr	1.0323	1.1017	1.1752	1.2530	1.3351
90 to 98 °F	wtr	1.4219	1.5136	1.6103	1.7124	1.8200
100 to 108 °F	wtr	1.9334	2.0529	2.1786	2.3110	2.4503
110 to 118 °F	wtr	2.5968	2.7507	2.9125	3.0823	3.2606

note 1: for temperatures below 32°F saturation vapor pressures are listed over ice and water (wtr).
note 2: saturation vapor pressures for intermediate temperatures can be estimated by interpolation.

In the MOISTWALL-2 program, the effect of airflow was added to vapor diffusion [*6*]. The airflow is assumed to be a uniform one-dimensional exfiltrative or infiltrative flow. In all other respects, this method has the same limitations as the manual design methods. As with the original MOISTWALL program, MOISTWALL-2 has not been implemented on a personal computer and is therefore not readily available.

An analytical model of moisture in cavity walls or roofs was published by Cunningham [*8,9*]. This model is a simpler representation of moisture flow and storage: the cavity is treated as a single homogeneous region with the wood stud as a moisture storage medium. In a later version [*10*], separate moisture release into the cavity (such as leaks, soil moisture) are also included. This simpler approach is very useful for estimating approximate drying times for wet wall cavities, assuming different levels of air leakage. However, the method is less suited to estimating the response to large temperature gradients in the insulated cavity (very cold or hot climates) or to using hygroscopic insulation materials (e.g., cellulose).

A description of a one-dimensional finite-difference moisture transfer model was recently published by Spolek et al. [*11*]. The driving force within each material is assumed to be the moisture content gradient, whereas hygroscopic properties are considered at the surface of materials only. While

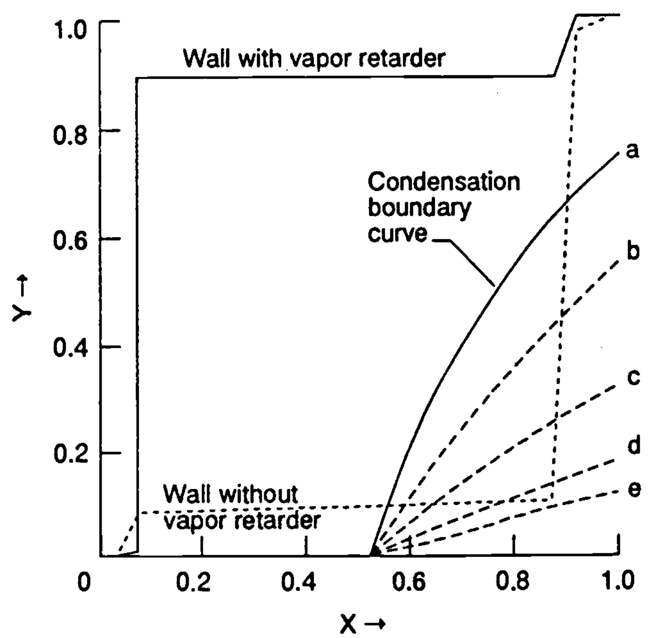

FIG. 5—Kieper diagram: example wall with and without vapor retarder, indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (−6.7°C), 50% RH. W_cZ values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in. Hg (5080 Pa).

this allows analysis of walls or roofs under isothermal conditions, the model does not account for increased moisture movement within hygroscopic materials (wood, masonry) under temperature gradients. Many other models, discussed in other chapters, more accurately account for this and usually are more suitable for analysis of exterior walls and roofs containing hygroscopic materials.

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8

MOIST: A Numerical Method for Design

by Doug Burch[1] *and George Tsongas*[2]

INTRODUCTION

MOIST (Release 3.0) IS A USER-FRIENDLY PERSONAL COMPUTER PROGRAM[3] that predicts the one-dimensional transfer of heat and moisture in walls, cathedral ceilings, and low-slope roof constructions [*1*]. It was developed at the National Institute of Standards and Technology (NIST) and released into the public domain in January 1998. It predicts the temperature and moisture content of each of the construction layers, or the relative humidity at the construction layer surfaces, as well as the moisture and heat transfer fluxes at both the interior and exterior boundaries of the construction, as a function of the time of year. The model also can be used to predict annual variations in indoor relative humidity.

With MOIST, the user can investigate a number of different possible applications, including the following examples: (1) predict the potential for elevated moisture contents that might lead to wood decay in wall or low-slope roof designs; (2) determine whether a vapor retarder is needed in a particular construction, and, if needed, where it should be placed; (3) determine drying rates for construction materials containing high original moisture; (4) predict the surface relative humidity at the construction layers in hot and humid or other climates, thereby analyzing the potential for mold and mildew growth; (5) determine the effect of moisture on thermal resistance; (6) analyze the effect of house tightness on wall moisture contents; (7) assess the effect of different wall construction materials or designs on wall moisture performance, and (8) investigate the effect of different indoor moisture generation, mechanical ventilation, or climate conditions on indoor relative humidity. Additionally, the user can investigate a wide range of applications for low-slope roofs and cathedral ceilings.

The MOIST computer program provides a tool for building practitioners to conduct an intermediate-level heat and moisture transfer analysis. The program provides building practitioners with considerably more meaningful and accurate moisture analysis predictions than the ASHRAE steady-state dew-point methods [*2*], but less information than more detailed models such as LATENITE [*3*]. The dew-point method unfortunately predicts only the presence of condensation, which can occur without any deleterious effects, and it doesn't give the user any assistance in determining if the condensation leads to problems such as decay or mold growth.

When building practitioners use MOIST, they will need to deal with a considerably smaller set of input data compared with that required for a more detailed model. However, they must choose appropriate values for that smaller set of input parameters. A user unfamiliar with commonly used terminology in building physics may experience some difficulty in selecting appropriate values for the input parameters in the MOIST program. Guidance on selecting appropriate input parameter values is covered in the program user manual.

MODEL THEORY

The theory and mathematical formulation of MOIST follows the theoretical approach recommended by International Energy Agency (IEA) Annex 24 [*4*]. This annex recently published a consensus document (Task 1—Modeling) that provided a theoretical approach to predict the combined transfer of heat, air, and moisture in insulated building envelope parts. Leading physicists and engineers, working in this area from around the world, participated in the development of this document.

A mathematical description of MOIST is given in the Appendix to this chapter. A brief summary of the model theory is given below.

A conservation of energy equation is applied to each material. This equation includes the storage of heat within both the dry material and moisture in the pore space. Additionally, this equation includes the latent heat effect of water evaporating from one place and condensing in another place in the construction. This equation is solved to give the transient temperature distribution within the material.

A conservation of mass (water) equation is also applied to each material. Water vapor and liquid (capillary) water are modeled as separate and distinct moisture transport mechanisms. For vapor transport, water-vapor pressure is used as a potential with water-vapor permeability serving as a transport coefficient. For liquid transport, the capillary (suction) pressure is used as a potential with the hydraulic conductivity (sometimes called liquid permeability) serving as a transport coefficient. This equation is solved to give the transient moisture content (and relative humidity) distribution within the material.

The above two conservation equations are recast into finite-difference equations similar to the approach used in the MATCH program developed by Pedersen[4] [*5*]. The finite-

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[2] Consulting engineer, 3070 S.W. Fairmont Blvd., Portland, OR 97201.
[3] MOIST 3.0 is designed to run on any IBM-compatible personal computer having a Microsoft Windows operating system.

[4] Carsten Pedersen has changed his name to Carsten Rode.

difference equations are solved using an efficient tri-diagonal matrix solution technique. The user may specify up to, but not exceeding, 500 finite-difference nodes. For most simulations a 1-h time step is recommended, although the user has the option to specify a smaller time step to achieve a stable mathematical solution required in a few applications.

Zarr, Burch, and Fanney recently verified the mathematical algorithms of the MOIST program by way of comparison to a series of laboratory experiments conducted at the National Institute of Standards and Technology [6]. In those experiments, several test walls were installed in a calibrated hot box where the outdoor boundary conditions were varied to induce moisture to first flow into the construction materials and subsequently flow out of the materials. Sensors were installed in the construction layers to measure the moisture content of the materials and the heat transfer rate at the interior surface as a function of time. These measurements were compared to corresponding predictions using the MOIST program. The agreement between measured and predicted results was very good, thereby supporting the validity of the model.

A number of other laboratory and field experiments have been conducted that have verified the accuracy of the MOIST model. These experimental studies are summarized in Table 1.

These other experimental studies generally found very good to fair agreement between measured values and corresponding values predicted by the MOIST program. Perhaps more importantly, the MOIST program predicted all trends in the measured results.

PROGRAM LIMITATIONS

One of the most significant limitations of the MOIST model is that it is one dimensional. This means that the model does not include the effect of framing members and two- and three-dimensional effects such as the vertical movement of moisture in an earth-coupled wall. Moreover, the model does not include the exterior wetting of the construction by rain and the insulating effect and change in roof absorptance from a snow load. In addition, the model does not include the transfer of heat and moisture by air movement. The construction is assumed to be airtight.

In applications where the above limitations become important, it is recommended that the building practitioner consider using more advanced models such as LATENITE [3] or conducting field and laboratory experiments to investigate the moisture performance of the building construction.

DESCRIPTION OF THE MOIST COMPUTER PROGRAM

The program installs in a fashion identical to professional software designed for a Microsoft Windows operating system. ASHRAE WYEC[5] hourly weather data [7] for the following six cities are installed with the program: Madison, WI; Boston, MA; Washington, DC; Atlanta, GA; Lake Charles, LA; and Portland, OR. Weather data for 45 other United States and Canadian cities are provided with the program and may be installed if needed for an analysis.

After the program is installed, a MOIST session may be launched by double-clicking on the MOIST Release 3 icon shown in Fig. 1. After the program starts, the Title Screen shown in Fig. 2 is displayed. After a few seconds, the title screen automatically disappears and the MOIST Main Dialog Box shown in Fig. 3 is displayed. From this screen, the user may launch a wide range of heat and moisture transfer projects. A flow chart for the MOIST program is given in Fig. 4. A brief description of the program is given below.

Selecting Units

Before a user sets up a problem for analysis, either metric (SI) or English (inch-pound) units are selected. After that, all computer screens and results are displayed in the system of units selected.

Input Processor

The computer program contains an input processor that permits users to enter and edit input parameters in a Microsoft Windows (point-and-click) environment. Clicking on the different command buttons grouped in the box under **Edit data** of the MOIST Main Dialog Box (see Fig. 3) takes you to the various input parameter screens of the program.

Building Construction

For example, clicking on the command button **Building Construction** takes you to the Construction Data Entry Box shown in Fig. 5. With some practice, the user can enter a

[5] *W*eather *Y*ear for *E*nergy *C*alculations.

TABLE 1—Other experimental studies verifying MOIST.

Person/Organization	Property Measurements	Description[a]	Agreement
Tsongas (1990) [*20*] U.S. DOE/BPA	No	MC of wall sheathing in 86 Pacific Northwest homes	Very Good
Bailey, Bauer, & Slama, et al. (1996) [*25*] Ortech Corporation	Yes	MC during lab drying of sheet materials	Good
Hosni, Sipes & Wallis (1999) [*26*] Kansas State University	Partial	RH in lab walls exposed to hot and humid climates	Good/Fair
TenWolde & Carll (1995) [*27*] Forest Products Lab.	Yes	RH in field walls	Fair
Graham, Tuluca, et al. (1997) [*28*] Steven Winter & Associates	Partial	RH in field walls	Good

[a]In the third column labeled "Description," MC-moisture content and RH-relative humidity.

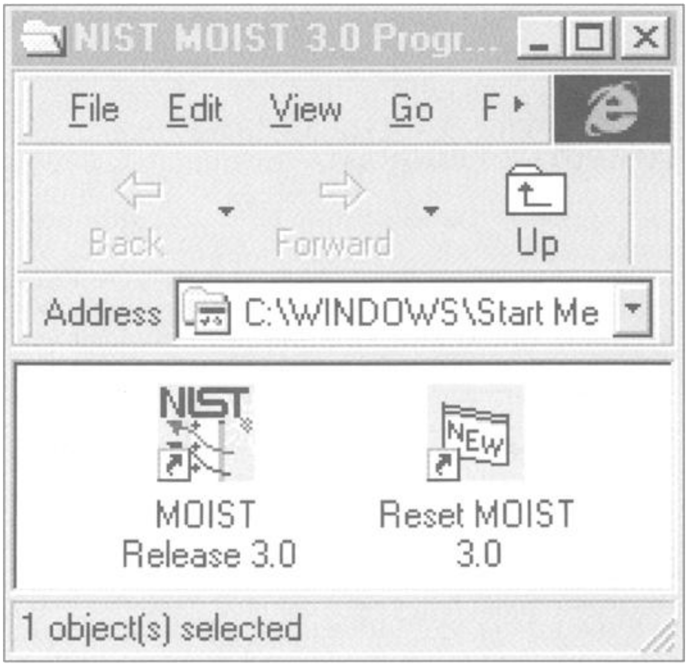

FIG. 1—MOIST program folder (group).

new building construction in a couple of minutes. The user may specify up to ten construction layers. Air spaces, vapor retarders, and insulation layers may be included in a simulation. Additionally, the water-vapor-transfer resistance offered by wall coverings such as wallpapers and paints applied to both the interior and exterior boundaries of the construction may be included in a simulation. Layers are added, edited, or deleted in a point-and-click Microsoft Windows environment.

In setting up a wall or roof construction, the user can select materials given in a material database within the program. In this way, the user does not have to enter material property data. Thirty different materials are included in the database. Most of the material properties included in the database are either based on NIST measurements or taken from measurements in the literature; in a few cases where measured data were not available (e.g., stucco finish) the properties were estimated.

Editing the Material Database

From the MOIST Main Dialog Box (see Fig. 3), clicking on **Material Database** takes the user to the Material Database Dialog Box shown in Fig. 6. From this screen, the user can revise the material property values for a material included in the database, provided that the user has valid property data for the material. Materials may be added to or deleted from the database. In some situations, the user may find that material property data for a particular material may not be given in the existing literature.

Input Parameters (Selecting Weather Data)

From the MOIST Main Dialog Box (see Fig. 3), clicking on **Input Parameters** takes the user into the Input Parameters Dialog Box shown in Fig. 7. In setting up an application, a

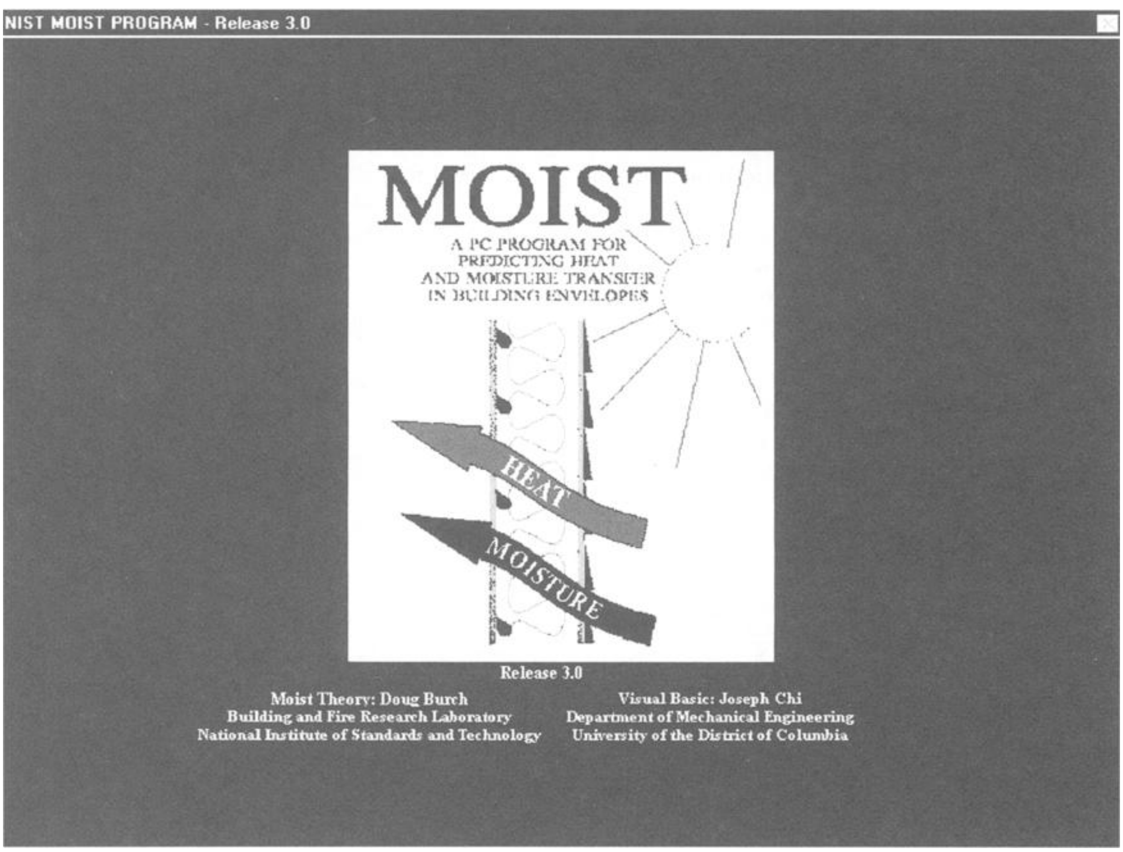

FIG. 2—Title screen of the MOIST program.

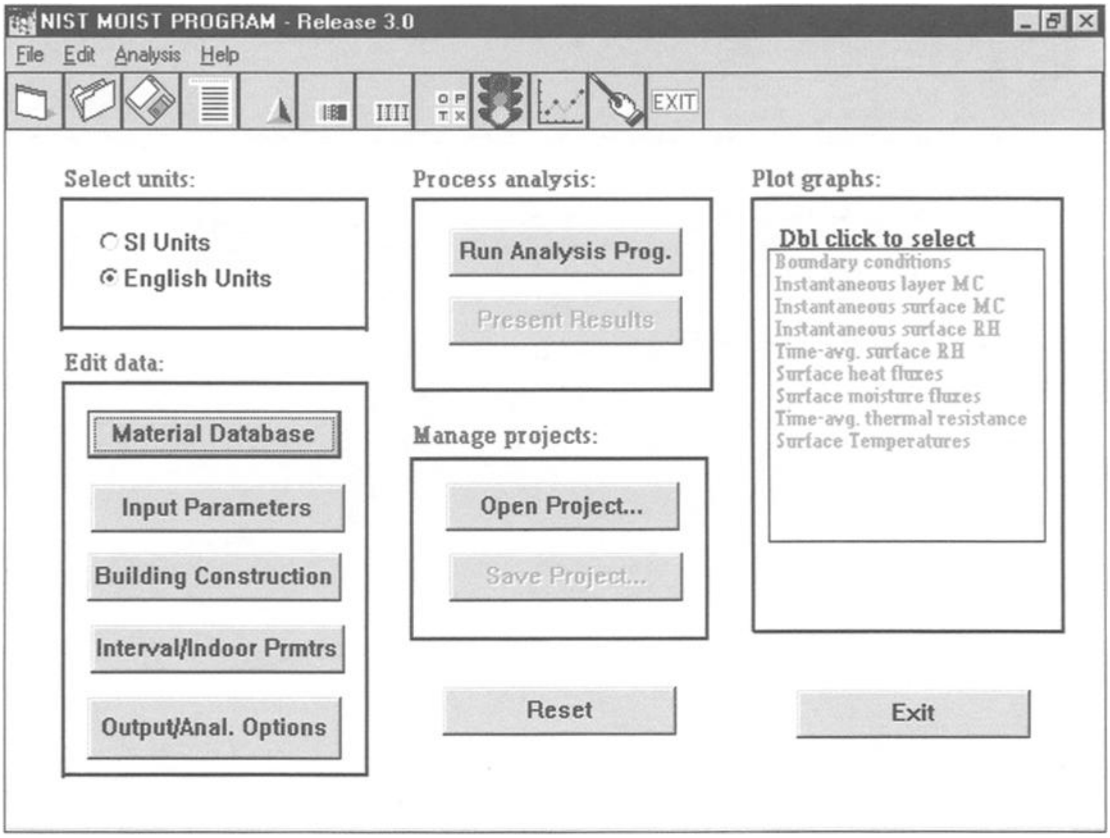

FIG. 3—MOIST main dialog box.

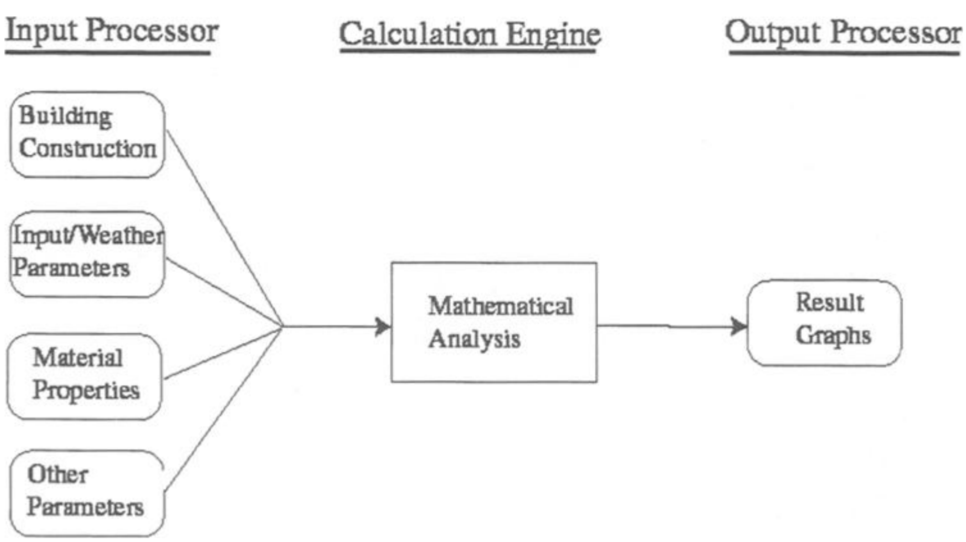

FIG. 4—Flow chart of the MOIST program.

user must specify the following input parameters: convective coefficients at the inside and outside surfaces, exterior surface solar absorptance, construction tilt angle, construction azimuth orientation, and the inside and outside surface paint or wall covering permeances. When the user is conducting a simulation with constant indoor conditions, an indoor temperature and indoor relative humidity must be specified. Guidance on selecting appropriate values for these input parameters is given in the program user manual.

From the Input Parameters Dialog Box, the user also selects the ASHRAE WYEC hourly weather data that he/she wants to use in the computer analysis. The program comes with WYEC weather data for 51 cities of the United States and Canada. The user can also use non-WYEC weather data

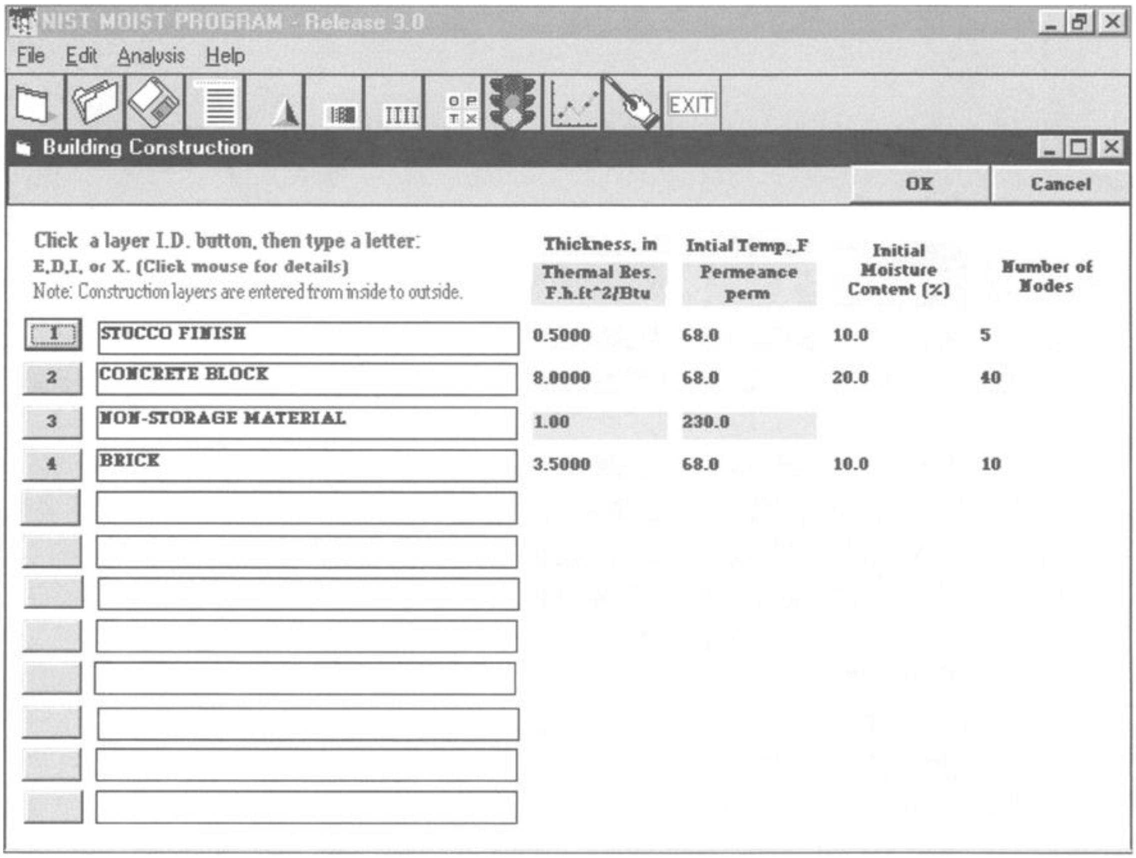

FIG. 5—Construction data entry box.

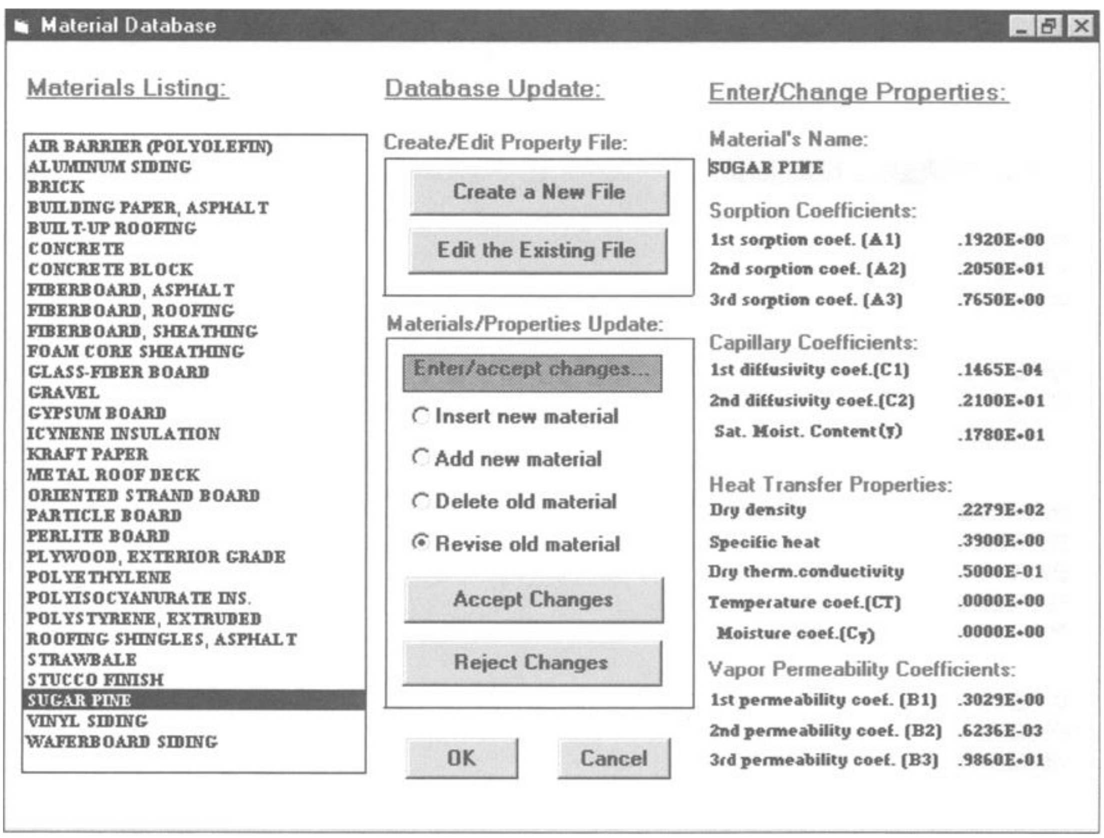

FIG. 6—Material database dialog box.

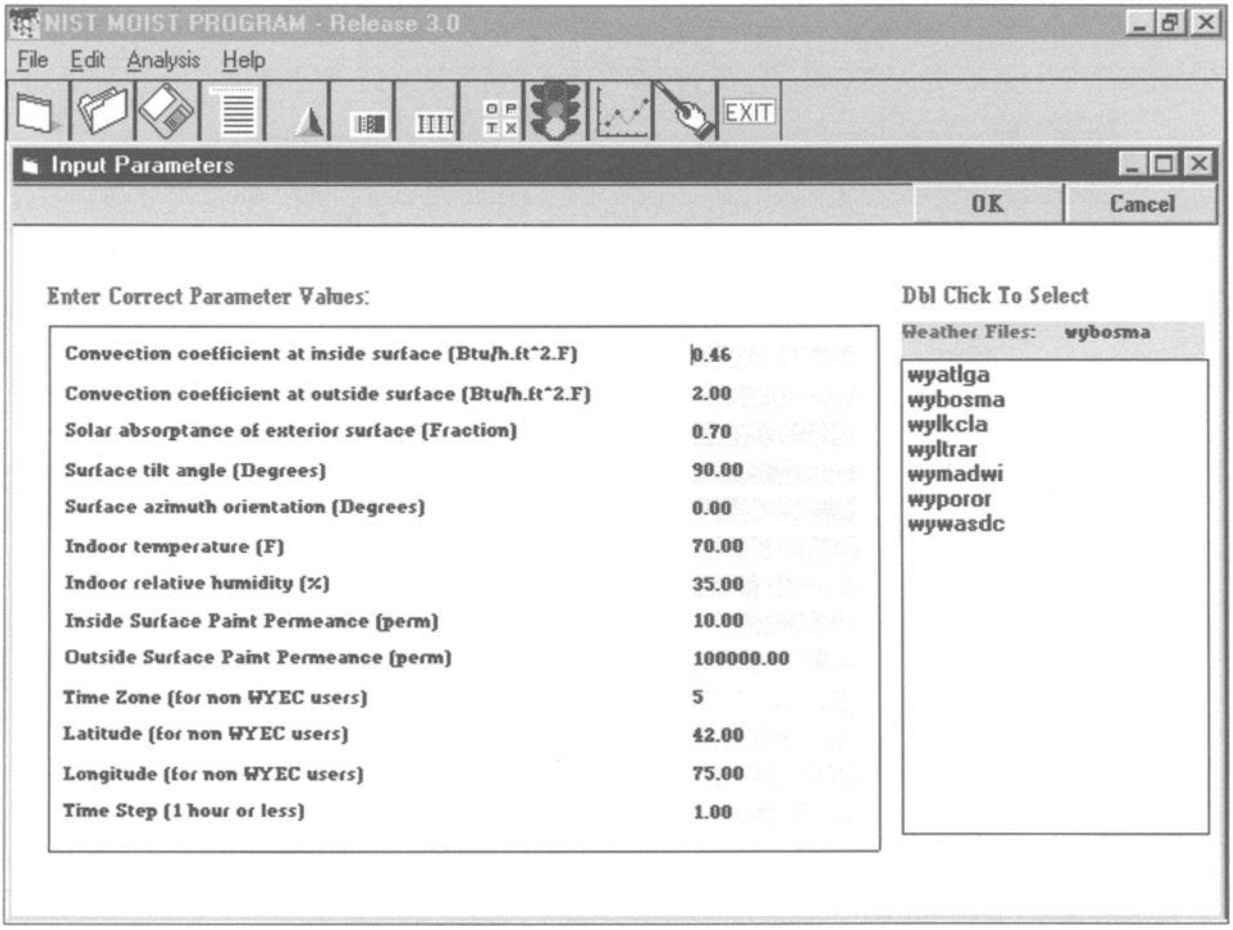

FIG. 7—Input parameters dialog box.

with the program, but he/she must first convert his/her weather data into WYEC format. This procedure is outlined in the program user manual.

Analysis Intervals and Indoor Parameters

From the MOIST Main Dialog Box (see Fig. 3), clicking on **Interval/Indoor Prmtrs** takes the user into the Data Box for Specifying Analysis Intervals and Indoor Parameters (see Fig. 8). From this screen, the user can select the period over which the computer analysis is carried out and the period during which result data are sent to output files.

The user can conduct a moisture analysis in which the relative humidity is permitted to vary during the winter months and is calculated from a moisture balance of the whole building. The user selects the variable indoor climate model under **Analysis Options** described in the next section. When the variable indoor climate model is activated, the user must specify the other parameters on this computer screen. Here the user selects a summer set-point temperature and relative humidity and a winter set-point temperature. In addition, the user specifies a moisture generation rate for occupant-related activities, a building air tightness coefficient called an effective leakage area (ELA), and stack and wind coefficients for a semi-empirical air infiltration correlation. The use of a variable indoor relative humidity model is believed to provide more realistic simulations that coincide more closely with field performance than using a constant indoor relative humidity. In fact, wall moisture content predictions using MOIST with variable indoor relative humidity have been found to be within a few percent of actual measured values [*8*].

Output and Analysis Options

From the MOIST Main Dialog Box (see Fig. 3), clicking on **Output/Anal. Options** takes the user into the Data Box for Selecting Output and Analysis Options shown in Fig. 9. Under **Analysis Options,** the user can select the indoor climate (variable indoor relative humidity) model. When this option is not selected, the MOIST simulation is carried out using the constant indoor temperature and relative humidity specified on the Input Parameter Dialog Box (see Fig. 7). For most situations, the user will usually not change the other parameters on this screen.

In the above discussion, the user transferred from the MOIST Main Dialog Box into the various input screens by clicking on appropriate command buttons under **Edit Data.** The user can also transfer into the various input data screens

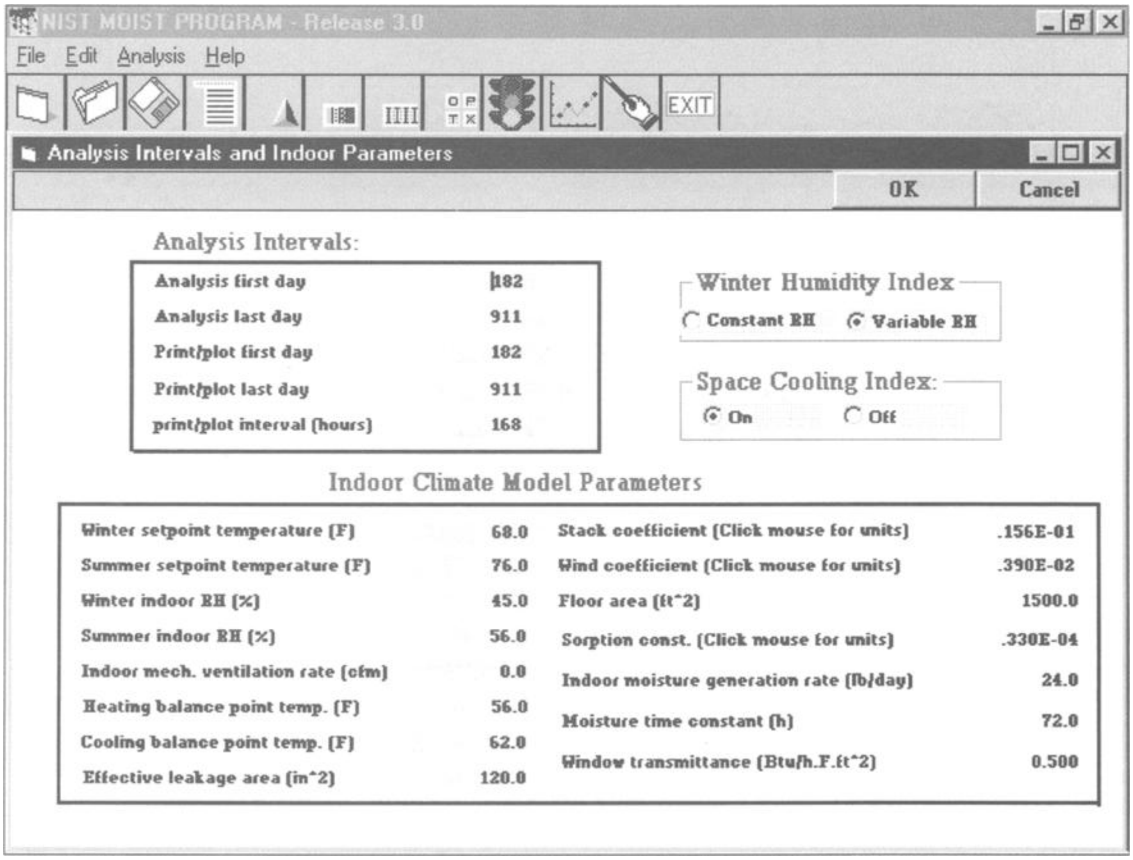

FIG. 8—Data box for specifying analysis intervals and indoor parameters.

by using pull-down menus, clicking tool icons displayed on a tool bar, or using short-cut keys.

Running a MOIST Analysis

After specifying a set of input data for his/her problem, the user commences a MOIST analysis by clicking **Run Analysis Prog** on the MOIST Main Dialog Box (see Fig. 3).

During the analysis, the program displays a plot of the moisture content of the construction layers versus time of year on the computer screen (see Fig. 10). With a Pentium III 750-Mhz computer, the program takes about 5 s to run a typical simulation. In the graph on the computer screen, the vertical axis displays the relative moisture content of the storage layers of the construction. The term "relative moisture content" is defined as the moisture content of the material layer divided by the moisture content of the material at maximum sorption. Maximum sorption is the moisture content of the material in equilibrium with saturated air at 100% RH. The dashed horizontal line in the center of the graph depicts a relative moisture content of 1. This is the critical moisture content above which liquid water appears in the open cell spaces of the material. That critical moisture content is essentially the fiber saturation point. Relative time is displayed on the horizontal axis. A relative time of 0 corresponds to the start of a simulation, while a value of 1 corresponds to the end of the simulation.

Plotting Result Graphs

After the user completes a MOIST simulation, result graphs can be viewed and plotted from within the program. They include: boundary condition parameters (such as indoor relative humidity), moisture content of construction layers, relative humidity at the surfaces of construction layers, boundary heat fluxes, boundary moisture fluxes, thermal resistance of the whole wall, and surface temperatures at construction layers. Result graphs are selected and edited in a point-and-click Microsoft Windows environment. Result graphs are displayed in a Graphing Dialog Box shown in Fig. 11. The result plots can also be sent to a printer by pointing and clicking with the mouse. In addition, the results can be imported into a spreadsheet for plotting, such as for cases where the results of more than one simulation run are compared.

Other Program Features

After plotting results, the user may print a hard copy of all the input data parameters used for the MOIST simulation. In addition, after the user analyzes a project, the inputs and results can be saved to a file. In this way, the user can open that project at a later time either to re-run it with revisions or to re-examine the results. The program comes with a full set of help menus.

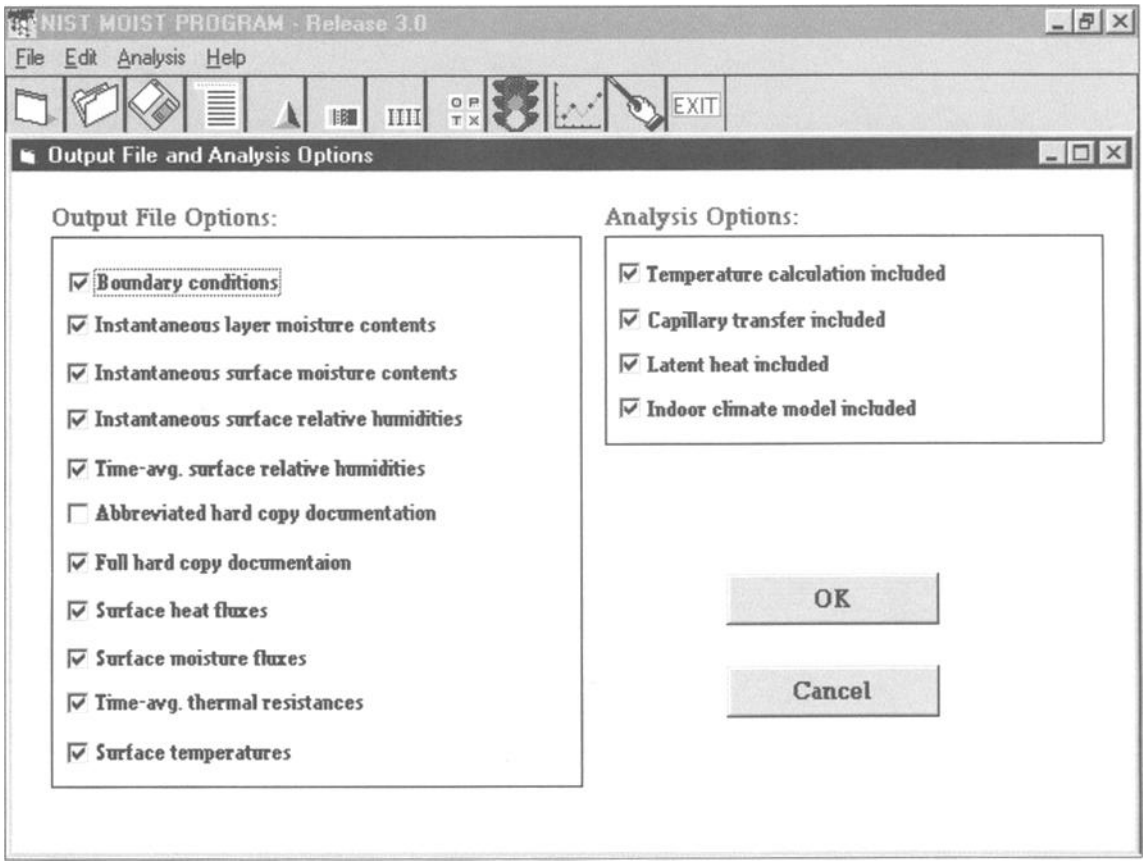

FIG. 9—Data box for selecting output and analysis options.

SPECIAL CAPABILITIES OF THE MOIST PROGRAM

The program has a number of special capabilities. They are described below.

Indoor Climate Options

The user may specify that the building interior is operated in the following different operating modes:

1. fixed indoor temperature and relative humidity during the entire simulation,
2. separate fixed indoor temperature and relative humidity during winter and summer, and
3. fixed or variable indoor temperature and relative humidity during the summer with fixed temperature but variable relative humidity during the winter.

For operating mode 3, the user specifies a moisture generation rate for the whole building and air leakage parameters for the building envelope. During the winter, the program performs a moisture balance on the whole building and predicts the indoor relative humidity at each time step of the analysis. Operating mode 3 is believed to provide a more realistic simulation that better represents actual field performance than a constant indoor relative humidity.

Including Paints and Wallpapers in Simulations

The program has the capability to include the water-vapor-transfer resistance offered by paints and wallpapers in computer simulations. The program user specifies a permeance for the inside and outside surface wall covering on the Input Parameter Dialog Box (see Fig. 7). Guidance on selecting appropriate permeance values for various paints and wallpapers is given in the program user manual. The thermal resistance of paints and wallpapers is neglected.

Modeling Air Spaces

The MOIST program has the capability to model the water-vapor-transfer resistance and thermal resistance offered by convective air spaces and stagnant air layers within a building construction. The program user includes an air space by specifying a permeance and thermal resistance for a non-storage layer in the Construction Data Entry Box (see Fig. 5). Guidance on selecting thermal resistance values for air spaces is given in the *ASHRAE Handbook of Fundamentals* [2], and guidance on selecting permeance values for convective air spaces and stagnant air layers is given in the program user manual.

Alternative Ways of Modeling Thermal Insulation

The MOIST Program provides two alternative ways to model thermal insulation. The user can treat thermal insulation as

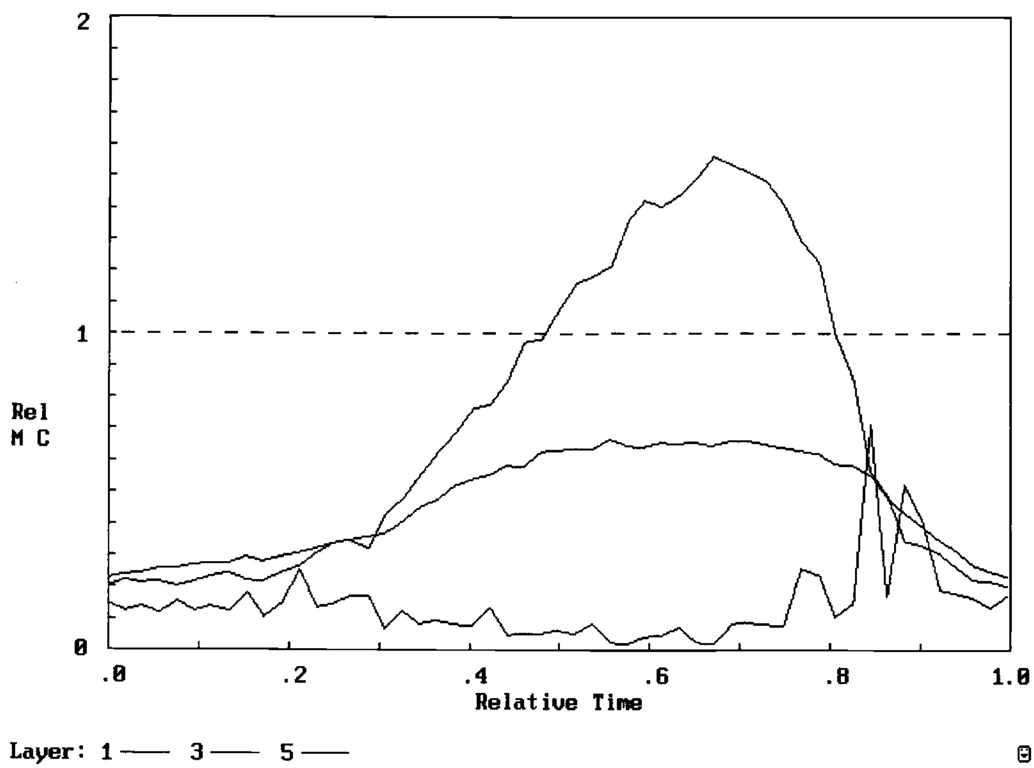

FIG. 10—Screen plot displayed during program execution. In this black and white image of the color computer screen, the lower curve is 1 (gypsum board), the middle curve is 3 (sheathing), and the upper curve is 5 (siding).

a "storage layer" in which the storage of heat and moisture is included as a transport process, or alternatively the thermal insulation can be modeled as a "non-storage layer" in which the storage of heat and moisture is neglected.

In many applications, the storage of moisture in thermal insulation has a small and unimportant effect on the moisture performance of the building construction. For example, glass-fiber insulation is weakly hygroscopic. When it is installed in a wood-frame cavity wall, very little moisture is stored in the thermal insulation. In this situation, neglecting the storage of heat and moisture in the insulation has a small effect on the heat and moisture performance of the wall.

Treating thermal insulation as a non-storage layer has several benefits to the program user. First, the program user only has to specify two parameters: the thermal resistance and permeance of the layer (see Construction Data Entry Box shown in Fig. 5). Second, the mathematical solution becomes very stable. However, the user gives up the capability of tracking the moisture content of the insulation as a function of time.

In some applications, it may be important to track the moisture content of the insulation as a function of time. For example, the user may be interested in predicting the drying rate of spray-applied cellulose after it is installed in a wall cavity. In this situation, the user must treat the thermal insulation as a storage layer. He/she specifies a material, its thickness, its initial temperature, its initial moisture content, and number of layer nodes (or sub-volumes) for the finite-different analysis (see the Construction Data Entry Box shown in Fig. 5). Additionally, if the thermal insulation is not given in the catalog of material properties (see the Material Database Dialog Box shown in Fig. 6), then 14 different material property data values must be specified to characterize heat and moisture transport within that material.

In treating thermal insulation as a storage layer, the user may experience difficulty in achieving a stable mathematical solution. This is because small changes in the moisture transport potential give rise to very large fluctuations in the moisture flux. In this situation, the mathematical solution tends to overshoot the actual solution, thereby leading to an unstable solution. To overcome this difficulty, the user must gradually decrease the size of the time step and increase the number of finite-difference nodes until a stable solution is reached. This process can be intimidating for an inexperienced user. Assistance in selecting the number of nodes and the time step is provided in the program user manual.

When examining cases where the moisture content of wood-based building components gets above their fiber saturation point (FSP) of about 28%, then extra effort may be necessary to achieve stable and correct solutions. In particular, if negative values of moisture content result, or if unrealistic or very spiky moisture content values occur, then one or more solution approaches may be required. They include: (1) choose more nodes in the materials, (2) break up the wettest materials into more than one subpart, or (3) reduce the solution time step below 1 h. In this situation, achieving stable and correct solutions involves a trial and error process. In fact, when dealing with moisture contents above the FSP, it always is a good idea to check the effect of increasing the number of nodes on the calculated values. Suggestions for undertaking all these approaches are presented in the program user manual.

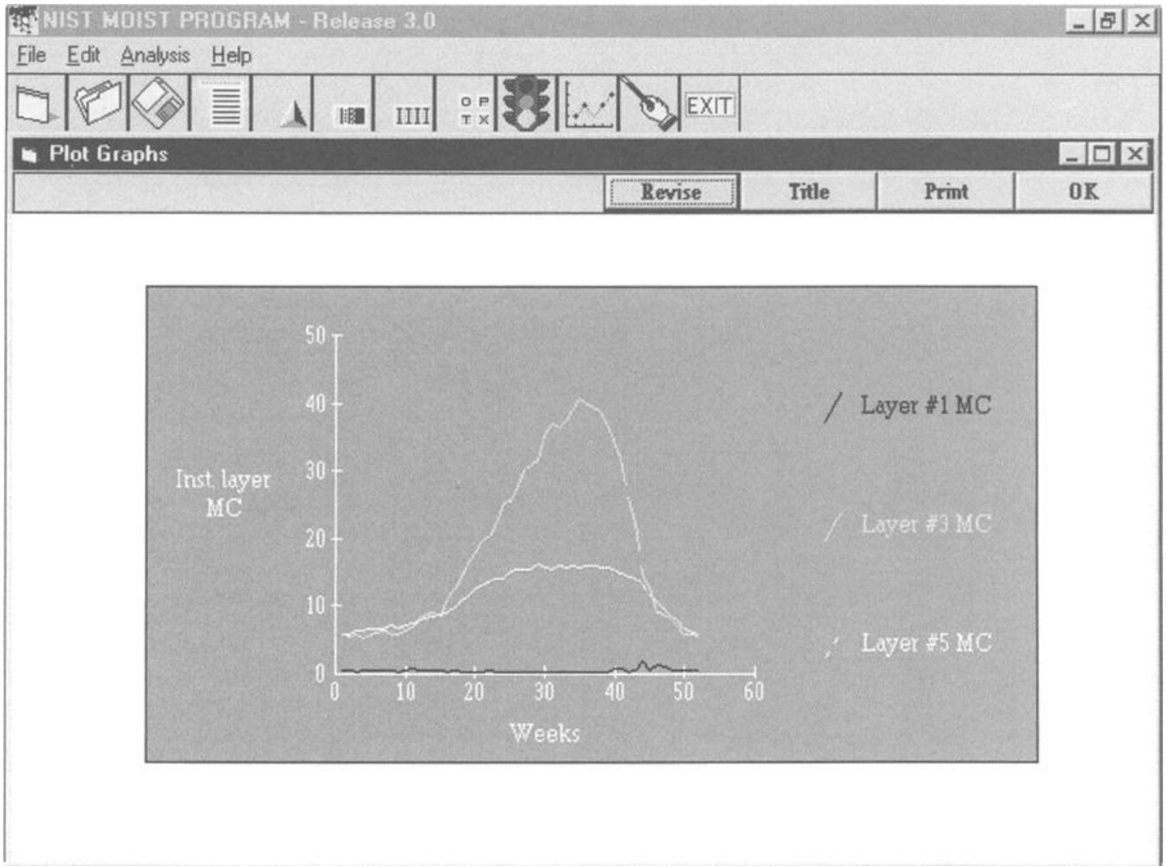

FIG. 11—Graphing dialog box. In this black and white image of the color computer screen, the lower curve is Layer 1, the middle curve is Layer 3, and the upper curve is Layer 5.

WORST CASE PARAMETRIC ANALYSIS

One of the more important questions posed by potential MOIST users is what is the most appropriate set of input conditions to use for an analysis. Clearly one must simulate as closely as possible the conditions that will exist in a building. However, conditions can vary. Buildings can be weatherized and thus airtightened. Occupants can change, and occupant moisture generation characteristics can vary. Furthermore, the location in a material where moisture conditions are assessed can impact whether or not a building component is moisture distressed in a particular application.

We believe it is important to assess the moisture performance of a wall or a roof by undertaking a series of computer simulation runs where key input parameters are varied over a range of possible conditions. Furthermore, it is instructive and even imperative to model a building wall or roof under so-called "worst case" conditions where the selected parameters produce the worst possible moisture performance for that particular building component. The difference in wall or roof component moisture contents between typical and worst case conditions can be substantial.

For example, it is important to include runs where the building is assumed to be very airtight in combination with high moisture generation. That combination typically produces worst case conditions. We typically assume an equivalent leakage area (ELA) of about 323 to 387 cm^2 (50 to 60 in.^{2}) that corresponds to a natural air exchange rate of about 0.25 ach for an air-tight 139-m^2 (1500 ft^2) dwelling, in combination with a high moisture generation rate of 21.8 kg/day (48 lb/day). It is also important to investigate the distribution of moisture in the layers, such as the outer layers, rather than looking at the average moisture content of the whole layer. North-facing walls or roofs are usually chosen for modeling because they always have higher moisture contents or surface relative humidities than those with other orientations (due to lack of solar heating).

ILLUSTRATIVE APPLICATIONS

The purpose of this section is to provide the user with several illustrative applications portraying appropriate use of the program.

A typical wood-frame cavity wall, shown schematically in Fig. 12, is used in most of the illustrative analysis. This wall is comprised of 1.27-cm (0.5-in.) gypsum broad, 8.9-cm (3.5-in.) glass fiber insulation, 1.27-cm (0.5-in.) fiberboard sheathing, and 1.27-cm (0.5-in.) sugar pine siding. Latex paint [574.5 ng/s·m^2·Pa (10 perm)] is applied to both the in-

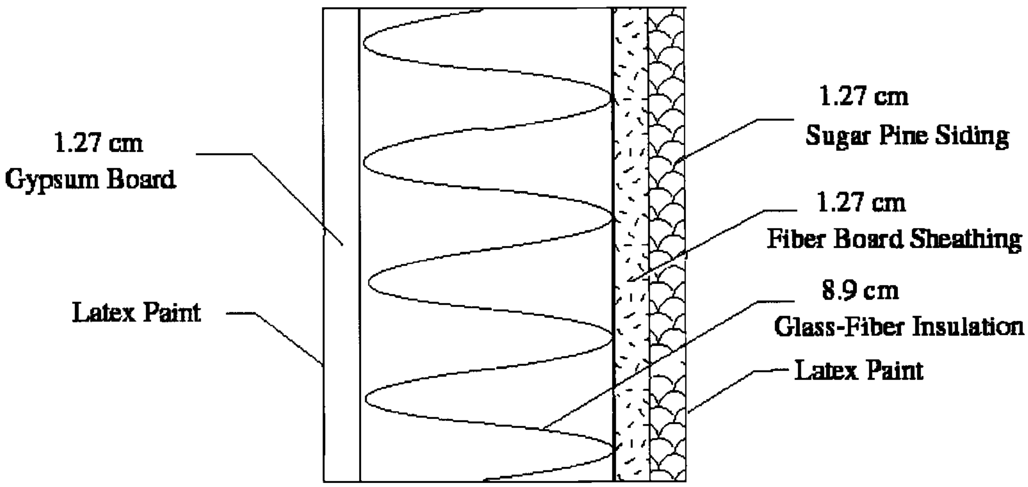

FIG. 12—Wall construction used in most of the illustrative applications.

side and outside surfaces of the construction, and the climate is Madison, WI, unless stated otherwise.

Determining If a Vapor Retarder Is Needed in a Cold Climate

During the winter, indoor moisture permeates outwardly through a wall construction and accumulates in the sheathing and siding of the construction. Of interest to building practitioners is whether an interior vapor retarder is needed to maintain moisture accumulation in the construction materials below fiber saturation.

Separate simulations of the wood-frame cavity wall were carried out for cases with and without an interior vapor retarder. When a vapor retarder was included in the simulation, it had a permeance of 57.45 ng/s·m^2·Pa (1 perm) and was placed between the gypsum board and the glass-fiber insulation. During the winter, the indoor relative humidity was permitted to vary and was calculated from a moisture balance of the whole building. The indoor moisture generation rate was assumed to be 10.9 kg/day (24 lb/day), and the building envelope was considered to be tight, having an effective leakage area (ELA) equal to 367 cm^2 (60 in.^{2}) corresponding to about 0.25 ach. The results are given in Fig. 13. In this plot, the first month is July, and winter occurs in the center of the plot.

The results show that moisture does accumulate in the sheathing and siding during the winter. It reaches a maximum in the latter part of the winter. When the wall did not contain a vapor retarder, the moisture contents of the fiberboard and the sugar pine rose to 24%. A moisture content of 24% is very close to fiber saturation for wood-base materials (i.e., about 28%). A potential risk of material degradation occurs in wood-base materials when their moisture content reaches and rises above fiber saturation. On the other hand, when a vapor retarder was present, the moisture contents of the two materials did not rise above 12%. The results indicate that the presence of a vapor retarder provided considerably lower moisture contents in the sheathing and siding during the winter.

Drying Rates for Construction Materials that are Initially Wet

When a construction material containing an initial high moisture content is used to construct a wall, building practitioners are interested in determining how long it takes for the construction material to dry. To illustrate this application, the program was used to investigate the drying rate for fiberboard in the wood-frame cavity wall with an interior vapor retarder. Here it was assumed that the initial moisture content of the fiberboard was 50% at the start of the simulation (August 1). Such a moisture content could occur if the fiberboard were left uncovered and was wetted by rain at a construction site. The moisture content of the fiberboard and the sugar pine are plotted as a function of time in Fig. 14. These results indicate that it takes about 60 days (or about two months) for the fiberboard to dry out.

Potential for Mold and Mildew Growth in Walls Exposed to Hot and Humid Climates

When vinyl wallpaper is used as an interior covering for walls exposed to hot and humid climates, a potential mold and mildew problem may occur during the summer. A computer simulation was conducted for the wall construction given in Fig. 12. Vinyl wallpaper having a permeance of 28 ng/s·m^2·Pa (0.5 perm) was used instead of latex paint at the interior surface. During the summer, the indoor temperature was 24°C (76°F).

The relative humidity behind the vinyl wallpaper is plotted as a function of time in Fig. 15. In this plot, the first month is January, and summer occurs in the center of the plot. During the summer, water vapor from the outdoor environment permeates inwardly under the influence of the outdoor-to-indoor temperature difference. The vinyl wallpaper offers high water-vapor-transfer resistance to this inward moisture flow that causes moisture to accumulate behind it. Note that the relative humidity approaches the critical relative humidity (80%) that supports mold and mildew growth. The International Energy Agency (IEA) Annex 14 [9] has reported that a monthly mean relative humidity exceeding 80% is conducive to mold and mildew growth.

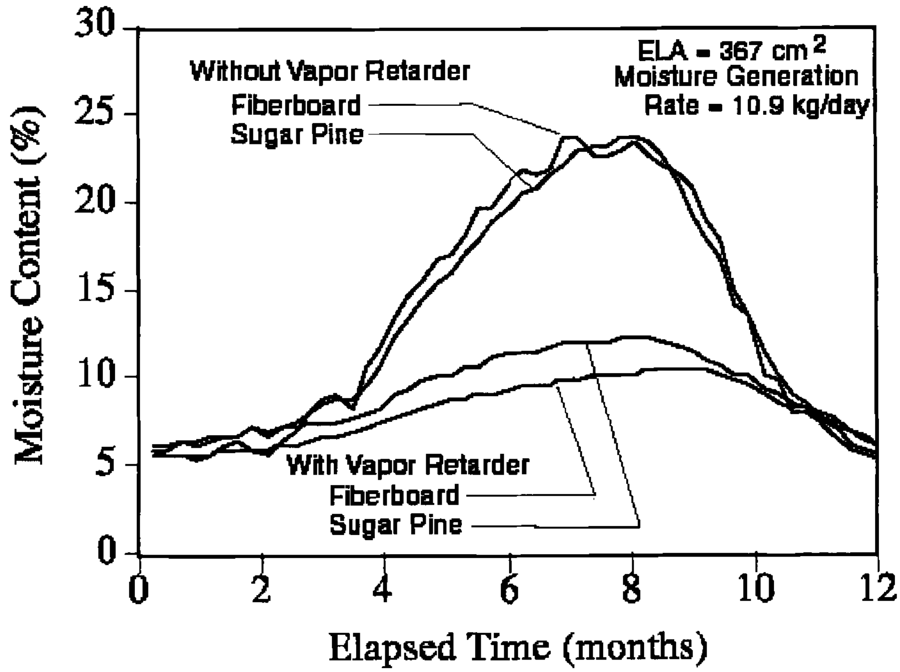

FIG. 13—Effect of interior vapor retarder on moisture content of fiberboard and sugar pine. First month is July.

Effect of House Tightness on Wall Moisture Performance

The computer program was next used to investigate the effect of house tightness on moisture accumulation in the fiberboard sheathing during the winter. In the analysis, the moisture generation rate in the house was taken to be 10.9 kg/day (24 lb/day). The following three levels of house tightness were analyzed: a tight house [ELA = 387 cm^2 (60 in.^{2})], a typical house [ELA = 774 cm^2 (120 in.^{2})], and a leaky house [ELA = 1548 cm^2 (240 in.^{2})]. The corresponding approximate natural air change rates for the three cases are: about 0.25, 0.5, and 1.0 ach.

The indoor relative humidity is plotted versus time of year for the three house tightnesses in the upper chart of Fig. 16. Note that the indoor relative humidity is highest in warm summer, spring, and fall periods and decreases significantly during cold winter periods. Air exchange between the indoor and outdoor air provides drying of the indoor air during the winter. The tight house has lower air exchange with the outdoor air, thereby providing less drying of the indoor air and higher indoor relative humidity. On the other hand, the leaky house has higher air exchange, more drying of the indoor air, and lower indoor relative humidity during the winter.

The moisture content of the fiberboard sheathing is plotted versus time for the three levels of house tightness in the lower chart of Fig. 16. House tightness (indoor relative humidity) is seen to have a profound effect on moisture accumulation in the fiberboard sheathing during the winter. The peak moisture content rose to 24% in the tight house and only 10% in the leaky house. Differences in sheathing moisture content are a direct consequence of the different indoor relative humidity levels provided by the three house tightnesses.

Effect of Indoor Moisture Generation Rate

The amount of moisture generated indoors as a result of the occupant activities also can have a pronounced effect on the moisture contents of wall and roof components. It turns out that doubling the amount of moisture generation has the same effect in the previous example as reducing the ELA by the same ratio, or vice-versa. That is, if the typical house with typical moisture production has the moisture generation rate doubled, the results are the same as those presented in Fig. 16 for the case where the ELA is halved.

Effect of Building Paper Permeance on Wall Moisture Performance

The program was next used to investigate the effect of permeance of the exterior sheathing paper (or building paper) on moisture buildup during the winter and spring in the fiberboard sheathing and sugar pine siding of the wood-frame cavity wall. The building paper was installed between the fiberboard sheathing and the sugar pine siding. The following four building paper permeances were analyzed: 2.3 × 10^4 ng/s·m^2·Pa (400 perm), 575 ng/s·m^2·Pa (10 perm), 287 ng/s·m^2·Pa (5 perm), and 57.5 ng/s·m^2·Pa (1 perm). The largest permeance [2.3 × 10^4 ng/s·m^2·Pa (400 perm)] corresponds to a spun-bonded polyolefin air barrier. The smallest permeance [57.5 ng/s·m^2·Pa (1 perm)] corresponds to a vapor retarder. The computer simulations were carried out for the tight house [ELA = 387 cm^2 (60 in.^{2})] with typical moisture generation.

The moisture contents of the sugar pine siding (upper plot) and fiberboard sheathing (lower plot) are plotted versus time in Fig. 17. The fiberboard moisture content rises markedly as the sheathing paper permeance is decreased. During the

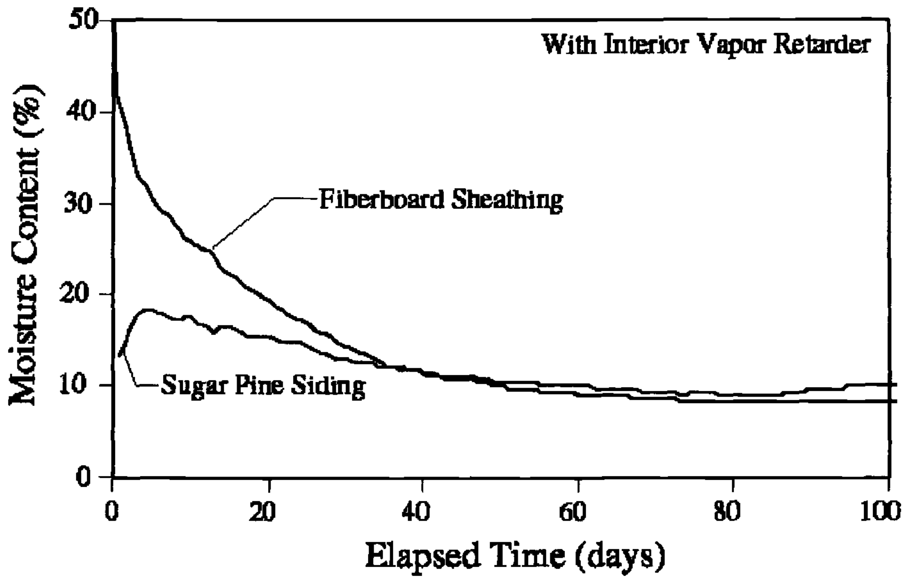

FIG. 14—Drying rate for fiberboard and sugar pine in wood-frame cavity wall. The first day of simulation is August 1.

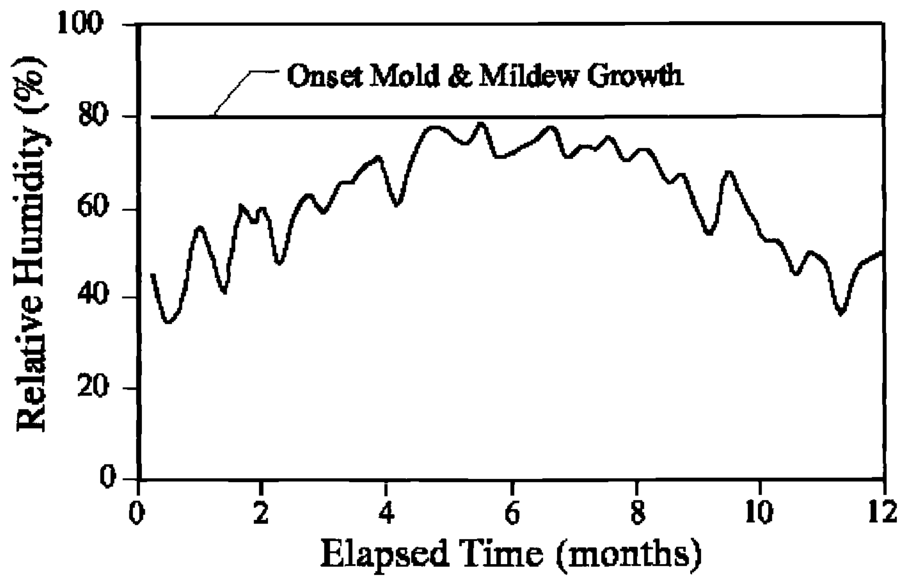

FIG. 15—Surface relative humidity behind vinyl wallpaper plotted versus time. First month is January.

winter, water vapor diffuses outwardly under the influence of the inside-to-outside temperature difference. As the permeance of the sheathing paper is decreased, it offers more resistance to the outward moisture flow and causes more moisture to accumulate in the fiberboard behind the sheathing paper. The horizontal line denotes maximum sorption (i.e., the maximum amount of vapor that the material can absorb), which is equivalent to the fiber saturation point (FSP). Above maximum sorption, liquid water begins to coalesce in the material pore space. It is worth mentioning that only in the wall with the spun-bonded polyolefin air barrier [2.3×10^4 ng/s·m^2·Pa (400 perm)] was the peak moisture content of the fiberboard below the FSP for these tight house (somewhat worst case) computer simulations in Madison, WI. In the less permeable sheathing paper, the peak fiberboard moisture content rose considerably above the fiber saturation point. As the sheathing paper permeance is decreased, smaller amounts of moisture are transferred through the building paper into the sugar pine siding, thereby lowering its moisture content.

What is notable is that the addition of a low-permeability building paper on the outside of the wall increases the time during warm late spring and early summer weather when the moisture content of the fiberboard is above the FSP and susceptible to the growth of decay fungus. In fact, widespread decay of plywood sheathing has been observed to occur as a result of installing a relatively impermeable building paper (average perm rating of 0.65) between the plywood

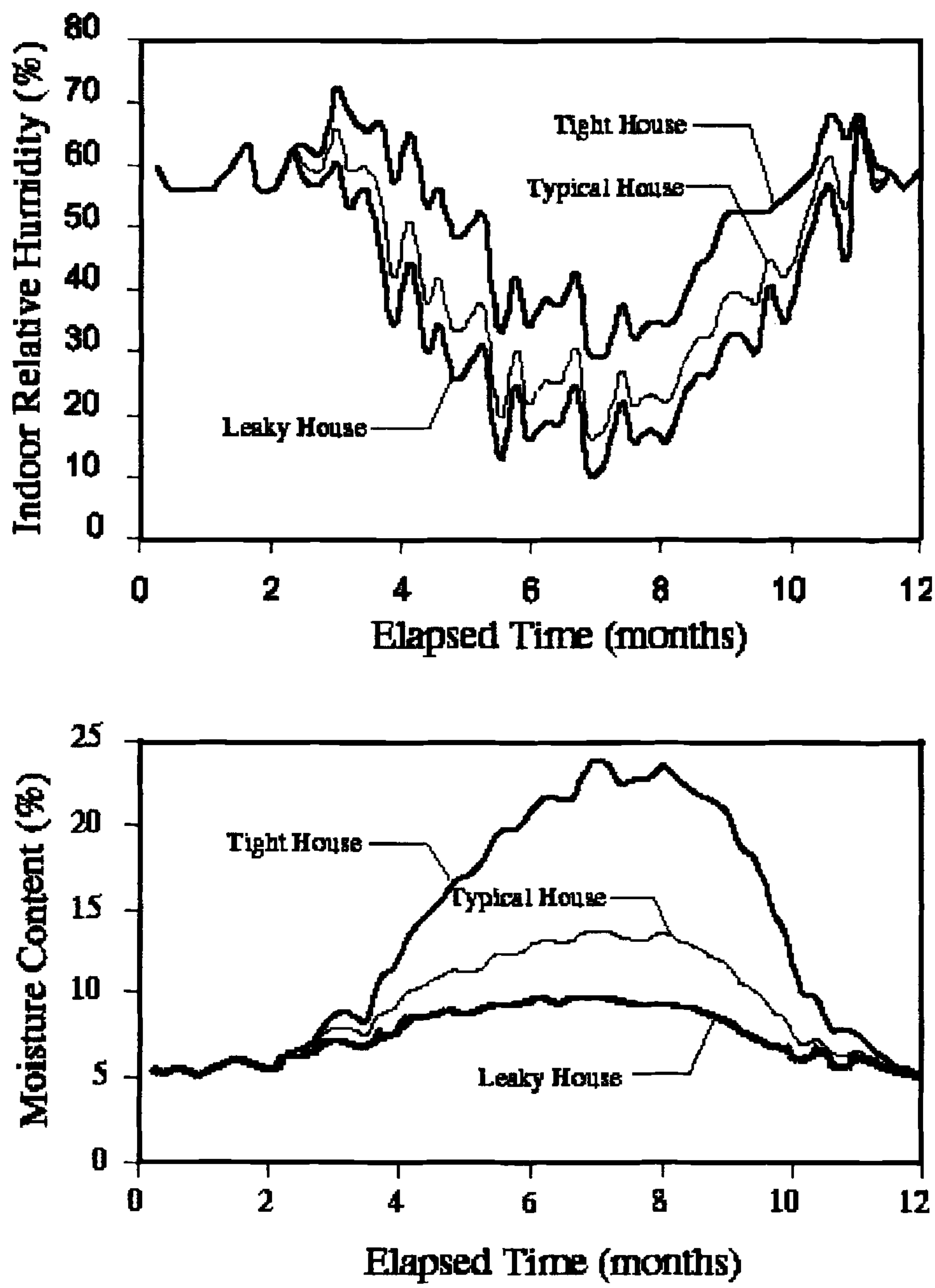

FIG. 16—Effect of house tightness on indoor relative humidity (upper chart) and sheathing moisture content (lower chart). First month is July.

and the wood siding [*10*]. In fact, computer modeling using MOIST was one of the ways that the reason for the decay was found. This combination of real world experience and computer modeling results illustrates why building scientists have for years suggested that breathable membranes should be installed at the exterior of buildings in northern heating climates.

Comparing the Moisture Performance of Different Sheathing Materials

Plywood, oriented strand board (OSB), and fiberboard are all commonly used wall sheathing materials. While they appear to be relatively similar sheathing materials, it is of interest to compare their moisture performance. For the analysis, the base case wall without an interior vapor retarder, with 15# felt building paper, and with fiberboard sheathing replaced by either plywood or OSB sheathing is assumed. The simulation results are shown in Fig. 18. They show that the moisture content performance of the three sheathing materials is surprisingly different. The wettest is fiberboard sheathing with a peak moisture content of about 41%. The driest of the three sheathing materials is OSB, with a peak moisture content of about 25%. The peak moisture content of plywood is more like that of OSB than fiberboard. Had the wall modeled assumed spin-bonded polyolefin-type

Symbol	Metric Permeance ng/s·m²·Pa	English Permeance perm
A	2.3×10^4	400
B	575	10
C	287	5
D	57.5	1

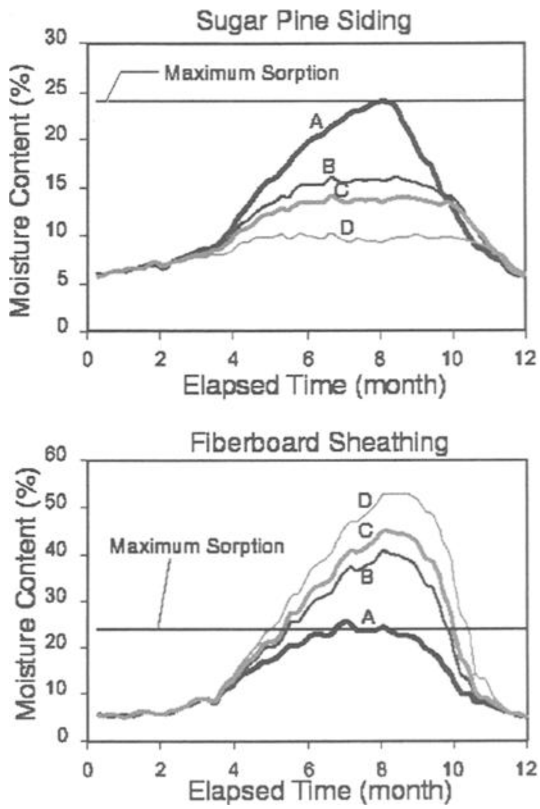

FIG. 17—Effect of building paper permeance on moisture build-up in fiberboard sheathing and sugar pine siding.

building paper rather than 15# felt, the results would have been different.

Other Applications

The program may also be used for the following applications: effect of moisture on heat transfer (and thermal resistance), predicting moisture accumulation in refrigerated warehouse constructions, and a wide range of low-slope roof and cathedral ceiling applications. Further information on MOIST applications may be found in Refs *11–14*.

CONDUCTING SIMULATIONS USING NON-WYEC WEATHER DATA

As previously mentioned, the MOIST software package comes with ASHRAE WYEC1[6] weather data for 51 cities of the United States and Canada. In most cases, it will suffice to conduct MOIST simulations using the nearest WYEC city. Alternatively, the user may use other hourly weather data files. For example, the National Renewable Energy Laboratory publishes Typical Meteorological Years (TMY2) for 239 cities of the United States [*22*]. However, the user must convert this alternative weather data into WYEC format as described below.

First, the user will need to reformat his/her alternative weather data file into WYEC format. A WYEC weather data file must contain 8760 h (or 365 days) of hourly weather data. Each hour is represented by a row of ASCI data. Beginning with hour zero of January 1, the weather parameters must appear in the following format:

Item	Field Position	Field Description
1	6–8	Dry bulb temperature, °F
2	12–14	Dew point temperature, °F
3	18–20	Wind speed, knots
4	26–27	Total cloud cover, tenths
5	56–59	Solar radiation, X10, Langleys
6	74–75	Month
7	76–77	Day
8	78–79	Hour (0 to 23)

In the above format, "field position" refers to the location of the data item in a horizontal field of data. Note that the solar radiation is multiplied by 10, and a solar radiation of 10.1 Langleys is entered as 101. Additionally, the file name must be a unique seven-character file name. The first two letters of the file name must be "WY." The next three letters should denote the city, and the last two letters should denote the state.

Next, the user will need to place this file in the MOIST directory. From the Input Parameters Dialog Box, he/she will select this weather data file and enter the latitude, longitude, and time zone for the weather data location. When the program runs, it will use the new weather data file.

ADDING A NEW MATERIAL TO THE MATERIAL PROPERTY DATABASE

The MOIST program is supplied with an onboard material property database for 30 different building materials. When the user specifies a material in the Construction Data Entry Box (see Fig. 5) that is not included in the onboard material property database, then he/she must first add this new material to the onboard material property database. The first step of this process is to locate material property data for the new material. Material property data required by the MOIST program are given in Table 2. A good place to look for material property data for a new material is in the Material Properties Report (Task 3) of the International Energy Agency Annex 24 [*4*].

For the sorption isotherm, liquid diffusivity, and vapor permeability, the user must curve fit data to the equations given in Table 2. Curve fitting the sorption isotherm for fiberboard roofing is illustrated below.

[6]WYEC1 refers to Weather Year for Energy Calculations (Version 1). ASHRAE recently published revised weather data called WYEC2.

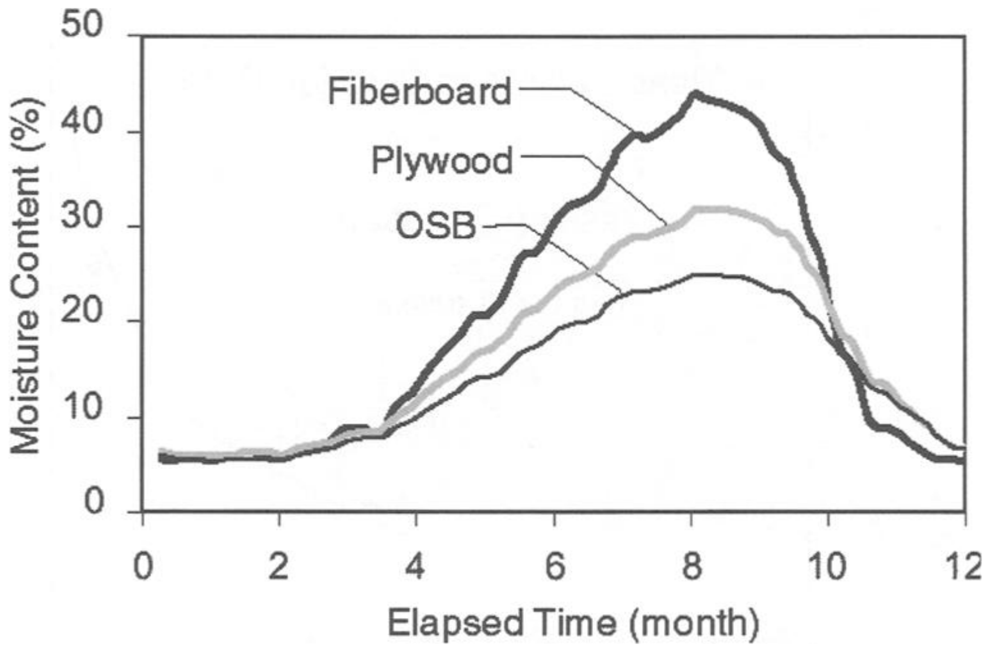

FIG. 18—Sheathing moisture content plotted versus sheathing type.

TABLE 2—Properties required for a new material.

Property Description	Units
Sorption isotherm	
$\gamma = \dfrac{A_1\phi}{(1 + A_2\phi)(1 - A_3\phi)}$	A_1 = kg$_d$/kg$_w$ (lb$_d$/lb$_w$) A_2 = dimensionless A_3 = dimensionless
Liquid diffusivity $D_\gamma = B_1 exp(B_2{\cdot}\gamma)$	B_1 = m^2/s (ft^2/h) B_2 = dimensionless
Capillary saturated moisture content, γ_s	γ_s = kg$_w$/kg$_d$ (lb$_w$/lb$_d$)
Thermal Conductivity $k = k_d + C_T(T - T_R) + C_\gamma\gamma$	k_d = W/m·°C (Btu/h·ft·°F) C_T = W/m·°C per °C (Btu/h·ft·°F per °F) C_γ = W/m·°C per kg$_w$/kg$_d$ (Btu/h·ft·°F per lb$_w$/lb$_d$)
Dry density, ρ_d	ρ_d = kg/m^3 (lb/ft^3)
Specific heat, C_d	C_d = J/kg·°C (Btu/lb·°F)
Vapor permeability $\mu = C_1 + C_2\text{Exp}(C_3{\cdot}\phi)$	C_1 = kg$_w$/s·m·Pa (perm·inch) C_2 = kg$_w$/s·m·Pa (perm·inch) C_3 = dimensionless

Note: The symbol *d* denotes dry and *w* denotes wet.

Sorption Coefficients

Sorption isotherm measurements for roofing fiberboard have been reported by Burch and Desjarlais [*23*], and they are summarized in Table 3.

The mean data given in Table 3 must be fit to the sorption isotherm equation given in Table 2. The constants (A_1, A_2, and A_3) are determined from a regression analysis procedure. A plot of the above-measured data showing the regression analysis equation is shown in Fig. 19.

In a similar fashion, liquid diffusivity and vapor permeability data must be found in the literature and curved fitted to the appropriate equation. After curve fitting, the curve-fitted coefficients and other material property data must be entered into the MOIST program following the procedure outlined in the program user manual [*1*].

TABLE 3—Sorption measurements of roofing fiberboard.

Ambient Relative Humidity, %	Equilibrium Moisture Content, %		
	Adsorption	Desorption	Mean
11.3	0.63	1.26	0.93
32.9	3.06	4.00	3.54
43.2	4.31	5.53	4.92
58.0	5.74	7.57	6.66
78.7	9.15	12.0	10.58
84.5	11.3	14.6	12.95
93.8	16.4	20.6	18.5
97.4	24.6	28.1	26.4

ORDERING THE PROGRAM AND GETTING HELP

The most current release of the program is provided on the enclosed CD Rom and may be downloaded from the MOIST web site at www.bfrl.nist.gov/863/moist.html.

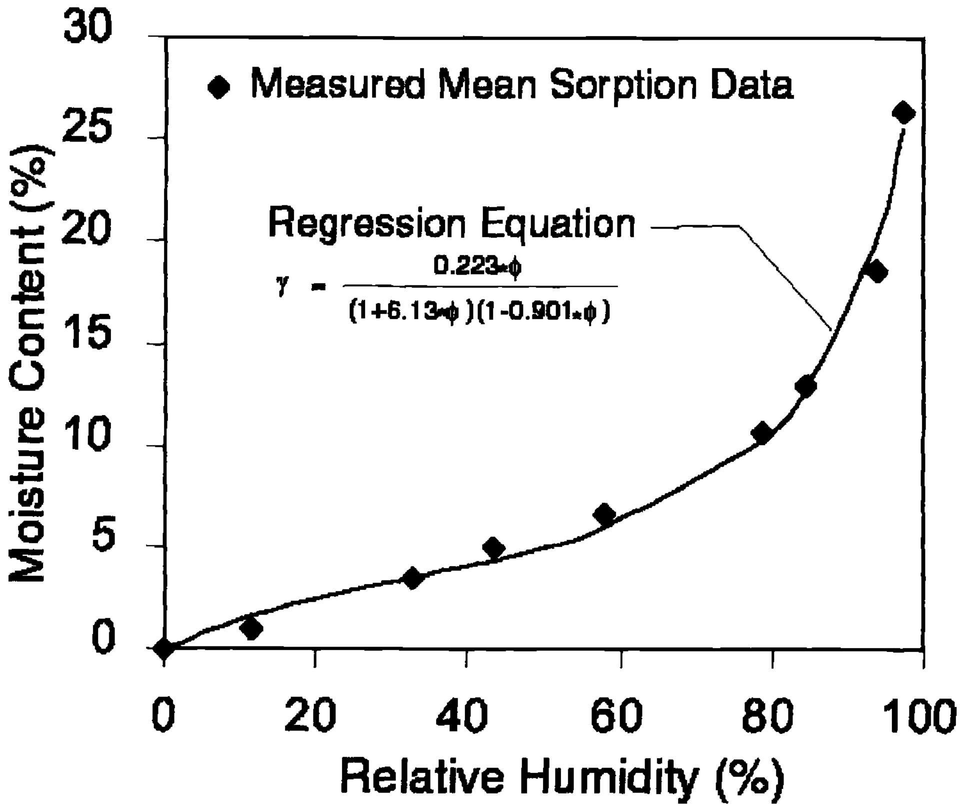

FIG. 19—Illustration of fitting sorption isotherm for roofing fiberboard to regression equation.

APPENDIX

Mathematical Description of MOIST (Release 3.0)

In the previous version of the MOIST Program (Release 2.1), temperature was used as the potential for heat flow, and moisture content was used as the potential for moisture flow. In the current release of the program, temperature is used as the potential for heat flow, water-vapor pressure is used as the potential for vapor transfer, and capillary pressure is used as the potential for liquid flow. The new model has the advantage that it uses transport potentials that are everywhere continuous, thereby leading to a computationally more efficient solution.

ASSUMPTIONS

Some of more important assumptions of the analysis are:

- heat and moisture transfer are one dimensional,
- construction is airtight, and the transport of moisture by air movement is neglected,
- wetting of exterior surfaces by rain is neglected,
- snow accumulation on horizontal surfaces, and its effect on the solar absorbance and thermal resistance is neglected,
- transport of heat by liquid movement is neglected, and
- surface condensation is neglected.

BASIC TRANSPORT EQUATIONS

Within each material layer of the construction, the moisture distribution is governed by the following conservation of mass equation:

$$\frac{\partial}{\partial y}\left(\mu \frac{\partial p_v}{\partial y}\right) - \frac{\partial}{\partial y}\left(K \frac{\partial p_l}{\partial y}\right) = \rho_d \frac{\partial \gamma}{\partial t} \tag{A-1}$$

The first term of the left side of Eq A-1 represents water-vapor diffusion, whereas the second term represents capillary transfer. The right side of Eq A-1 represents moisture storage within the material. The potential for transferring water vapor is the vapor pressure (p_v), with the permeability (μ) serving as a transport coefficient. The potential for transferring liquid water is the capillary pressure (p_l), with the hydraulic conductivity (K) serving as the transport coefficient. The potentials p_v and p_l were assumed to be continuously consistent with the theory of IEA Annex 24 [*4*]. The signs on the first two terms are different because water vapor flows in the opposite direction of the gradient in water vapor pressure, and capillary water flows in the same direction as the gradient in capillary pressure. Other symbols contained in the above equation include the dry density of the material

(ρ_d), moisture content (γ), distance (y), and time (t). The sorption isotherm[7] (i.e., the relationship between equilibrium moisture content and relative humidity) and the capillary pressure curve (i.e., the relationship between capillary pressure and moisture content) were used as constitutive relations in solving Eq A-1.

In the computer algorithms, Eq A-1 was recast into two finite-difference equations—one for the vapor phase and the other for the liquid phase. In the vapor phase equation, the diffusion transport is treated in an implicit way, and the liquid transport is treated in an explicit way. The sorption isotherm is used as an equation of state. In the liquid transport equation, the liquid transport is treated in an implicit way, and the vapor transport is treated in an explicit way. The suction pressure curve serves as an equation of state. During each time step, these two equations are solved for the water vapor pressure (p_v) and the capillary pressure (p_l). A new moisture content is subsequently calculated from these two potentials. This approach was developed by Carsten Pedersen (now Carsten Rode) and is described in Ref *5*.

The hydraulic conductivity (K) in Eq A-1 is related to the liquid diffusivity (D_γ) by the relation:

$$K = -\frac{\rho_d D_\gamma}{\dfrac{\partial p_l}{\partial \gamma}} \tag{A-2}$$

where the term in the denominator of the right side of the equation is the derivative of the capillary pressure with respect to moisture content. When the temperature is below freezing, the liquid diffusivity is taken to be zero.

The temperature distribution is calculated from the following conservation of energy equation:

$$\frac{\partial}{\partial y}\left(k\,\frac{\partial T}{\partial y}\right) + h_{1v}\,\frac{\partial}{\partial y}\left(\mu\,\frac{\partial p_v}{\partial y}\right) = \rho_d(c_d + \gamma\, c_w)\,\frac{\partial T}{\partial t} \tag{A-3}$$

The first term on the left side of Eq A-3 represents conduction, whereas the second term is the latent heat transfer derived from phase change associated with the movement of moisture. The right side of Eq A-3 represents the storage of heat within the material and accumulated moisture. Symbols in the above equation include temperature (T), the dry specific heat of the material (c_d), the specific heat of water (c_w), and the latent heat of vaporization (h_{1v}).

In Eq A-1, the water vapor permeability (μ) and the hydraulic conductivity (K) are strong functions of moisture content. In Eq A-3, the thermal conductivity (k) is also a function of temperature and moisture content.

ADJACENT LAYER BOUNDARY CONDITIONS

The temperature, water-vapor pressure, and capillary pressure are continuous at adjacent material layers.

[7] In this paper, the sorption isotherm was assumed to be independent of temperature. This is consistent with other heat, air, and moisture transfer models cited in IEA Annex 24 [*4*]. Some researchers have reported a small effect of temperature on the sorption isotherm [*24,29,30*].

INDOOR BOUNDARY CONDITIONS

At the indoor boundary of the construction, the moisture transfer through an air film and paint layer (or wallpaper) at the indoor surface is equated to the diffusion transfer into the solid material surface, or:

$$M_{e,i}(p_{v,i} - p_v) = -\mu\,\frac{\partial p_v}{\partial y} \tag{A-4}$$

where the quantities are evaluated at the indoor boundary. Here, an effective conductance ($M_{e,i}$), defined by:

$$M_{e,i} = \frac{1}{\dfrac{1}{M_{f,i}} + \dfrac{1}{M_{p,i}}} \tag{A-5}$$

has been introduced. The effect of a thin paint layer is taken into account as a surface conductance ($M_{p,i}$) in series with the convective mass transfer coefficient ($M_{f,i}$) associated with the air film.

At the same boundary, the heat transferred through the air film, ignoring the thermal resistance of the paint layer, is equated to the heat conducted into the indoor boundary, giving:

$$(h_{r,i} + h_{c,i})(T_i - T) = -k\,\frac{\partial T}{\partial y} \tag{A-6}$$

where all quantities are evaluated at the indoor surface.

OUTDOOR BOUNDARY CONDITIONS

At the outdoor boundary of the construction, a similar equation is applied to compute the moisture transfer. The heat conducted into the outdoor boundary and the absorbed solar radiation is set equal to the heat loss to the outdoor air by convection and radiation, or:

$$-k\,\frac{\partial T}{\partial y} + \alpha\, H_{sol} = h_{c,o}(T - T_o) + h_{r,o}(T - T_{sky}) \tag{A-7}$$

where all quantities are evaluated at the outdoor surface. Here $h_{r,o}$ is the radiative heat transfer coefficient defined by the relation:

$$h_{r,o} = E\sigma(T_s + T_{sky})(T_s^2 + T_{sky}^2) \tag{A-8}$$

where E is the emittance factor which includes the surface emissivity and the view factor from the outdoor surface to the sky, T_s is the surface temperature, and T_{sky} is the sky temperature. The solar radiation (H_{sol}) incident onto exterior surfaces having arbitrary tilt and orientation was predicted using algorithms given in Duffie and Beckman [*15*]. The sky temperature was calculated using an equation developed by Bliss [*16*].

VARIABLE INDOOR HUMIDITY MODEL

When the interior of a residential building can be modeled as a single zone with a uniform temperatue and relative humidity, the program has an option to permit the indoor relative humidity to vary during the winter. *The variable indoor relative humidity feature is only applicable to residential buildings and should not be applied to non-residential buildings.* When this option is selected, the indoor conditions are determined in the following fashion.

Space Heating Operation

When the daily average outdoor temperature is less than or equal to the balance point temperature for space heating, the house operates in a space-heating mode. The indoor temperature is taken to be equal to the heating set-point temperature. The indoor relative humidity is permitted to vary and is calculated from an indoor humidity model developed by TenWolde [*17*].

The rate of moisture production by the occupants is equal to the rate of moisture removed by natural and/or forced ventilation plus the rate of moisture storage at interior surfaces and furnishings, or:

$$\dot{W} = \rho_a \dot{V}_{h,t}(\omega_i + \omega_o) + \kappa\, A_f(\phi_i - \phi_{i,\tau}) \qquad \text{(A-9)}$$

Using the psychometric relationship between humidity ratio (ω) and relative humidity (ϕ) as a constitutive relationship, the above equation may be solved for the indoor relative humidity.

The hygroscopic memory ($\phi_{i,\tau}$) is computed from the scanning function:

$$\phi_{i,\tau} = \frac{\sum_{n=N-4\tau}^{N-1} Z(n)\phi_i(n)}{\sum_{n=N-4\tau}^{N-1} Z(n)} \qquad \text{(A-10)}$$

In the above equation, the hygroscopic memory at the current time step N is found from a past-history relative humidity time series. The time series is evaluated over four time constants (τ). The exponential weighing factors $Z(n)$ are defined as:

$$Z(n) = e^{-(N-n)/\tau} \qquad \text{(A-11)}$$

TenWolde [*17*] has conducted experiments and determined the sorption constant per unit floor area (κ) and the time constant (τ) for several manufactured and site-built houses.

The natural ventilation rate for the house is predicted by the single-zone Lawrence Berkeley Laboratory (LBL) infiltration model developed by Sherman and Grimsrud [*18*] and described by ASHRAE [*2*] which is given by:

$$\dot{V}_{h,n} = L_h\, [C_{\Delta T}|T_i - T_o| + C_v\, V^2]^{0.5} \qquad \text{(A-12)}$$

When mechanical ventilation $V_{h,m}$ is present, the total ventilation rate $V_{h,t}$ in Eq A-9 is determined by the relation developed by Palmiter and Bond [*19*]:

$$\begin{aligned} &\text{If } \dot{V}_{h,m} < 2\, \dot{V}_{h,n},\ \dot{V}_{h,t} = \dot{V}_{h,n} + 0.5\, \dot{V}_{h,m} \\ &\text{If } \dot{V}_{h,m} \geq 2\, \dot{V}_{h,n},\ \dot{V}_{h,t} = \dot{V}_{h,m} \end{aligned} \qquad \text{(A-13)}$$

It should be noted that in Eq A-13, $V_{h,m}$ is the actual mechanical ventilation rate produced by the ventilation equipment installed in the house, as opposed to the rated value. The actual value is typically about half of the rated value (see Tsongas [*20*]).

In the hourly calculations, the dew-point temperature of the indoor air is compared with the temperature of the inside glass surface to determine if window condensation occurs. When condensation occurs, the vapor pressure of the indoor air is taken to be equal to the saturation pressure at the inside glass surface. The indoor relative humidity is calculated from the indoor temperature and vapor pressure using psychrometric relationships.

Space Cooling Operation

When the daily average outdoor temperature is greater than or equal to the balance point temperature for space cooling, the house operates in a space cooling mode. The indoor temperature and relative humidity are maintained at constant specified values.

Window Opened Operation

When the daily average outdoor temperature is greater than the balance point for space heating but less than the balance point for space cooling, then neither space heating nor space cooling are required. It is assumed that the windows are opened and the indoor temperature and relative humidity are equal to the outdoor values. When the space cooling equipment is turned off, it was assumed that the occupant will open the windows, and the building again operates in an opened window mode.

SOLUTION PROCEDURE

Finite-difference equations were developed to represent the basic moisture and heat transport equations (Eqs A-1 and A-3). The finite-difference equations were solved using an efficient tri-diagonal matrix solution technique. The user may specify up to, but not exceeding, 500 finite-difference nodes. For most simulations a 1-h time step is recommended, although the user has the option to specify a smaller time step to achieve a stable mathematical solution required in a few applications.

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[*2*] ASHRAE, *ASHRAE Handbook-Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1997.

[*3*] Karagiozis, A., "Overview of the 2-D Hygrothermal Heat-Moisture Transport Model LATENITE," *Internal Report*, National Research Council Canada, Institute for Research and Construction, Ottawa, Canada, 1993.

[*4*] International Energy Agency, Annex 24 (*Heat, Air and Moisture Transfer in Insulated Envelope Parts*), 1996.

[*5*] Pedersen, C. R., "Combined Heat and Moisture Transfer in Building Constructions," Report No. 214, Technical University of Denmark, September 1990.

[*6*] Zarr, R. R., Burch, D. M., and Fanney, A. H., "Heat and Moisture Transfer in Wood-Based Wall Construction: Measured vs. Predicted," *Building Science Series 173*, National Institute of Standards and Technology, 1995.

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9

A Hygrothermal Design Tool for Architects and Engineers (WUFI ORNL/IBP)

by H. M. Kuenzel,[1] *A. N. Karagiozis,*[2] *and A. H. Holm*[3]

As the number of moisture-induced damages in buildings are increasing, demand is increasing for calculation methods in building engineering to assess the moisture behavior of building components. Current events, such as moisture-originated failures of wood frame construction in low-rise residential buildings, increased heat losses due to the presence of wet insulation materials, the heat pump effect due to evaporation condensation cycling, measures taken for the preservation of historical buildings, or retrofitting insulation in existing buildings, are closely related to the moisture performance of the building structure. However, solutions to moisture-induced problems may be difficult when several interacting mechanisms of moisture transport are present.

Experimental investigations are expensive and of limited transferability. There is need for realistic heat and moisture data. An alternative is the use of validated models. To date a sophisticated, simple-to-use model for an end user has not been available. This chapter will describe the development of an advanced hygrothermal model called WUFI ORNL/IBP that is tailored for architects and building envelope designers. Its purpose is to assist during the design stage to optimize the heat and moisture performance of the envelope.

WUFI ORNL/IBP is an easy-to-use, menu-driven program for use on a personal computer that can provide customized solutions to moisture engineering and damage assessment for various building envelope systems. Examples of systems are sections of walls, roofs, and basements exposed to natural climatic conditions. It is based on state-of-the-art understanding of building physics regarding sorption and suction isotherms, vapor diffusion, liquid transport, and phase changes. This model is well documented and has been validated by many comparisons between calculated and field performance data.

The model requires a limited number of standard material properties that are readily available. A material database is part of the program and includes a full range of materials commonly used in North America. Hourly weather data, such as temperature, relative humidity, wind, driving rain, and solar radiation, are employed in the hygrothermal calculations. These data are available for a wide range of North American climate zones.

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WUFI ORNL/IBP can be used to estimate the drying times of masonry and lightweight structures with trapped or concealed construction moisture, investigate the danger of interstitial condensation, or study the influence of driving rain on exterior building components. The program can also help to select repair and retrofit strategies with respect to the hygrothermal response of particular roof or wall assemblies subjected to various climates. This allows comparison and ranking of different designs with respect to total hygrothermal performance. This design tool can aid the development and optimization of innovative building materials and components. WUFI simulations led to the development of a smart vapor retarder [*1*].

The predecessor of this program was released in Europe in 1994 [*2*] and has since been used widely by building envelope designers, architects, building physicists, consulting bureaus, and universities in Europe. In Spring 2000, a special North American version was developed by a joint research collaboration between the Oak Ridge National Laboratory in the USA (ORNL) and the Fraunhofer Institute for Building Physics in Germany (IBP). This advanced model will be described in detail and is enclosed on the CD Rom to this ASTM manual. Future free updates will be available at the following two Internet sites:

www.ornl.gov/btc/moisture/models and www. wufi.de.

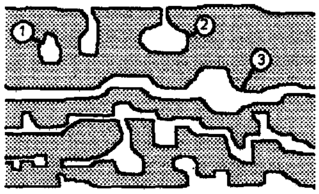
PHYSICAL BACKGROUND

Almost all construction materials are porous in nature. Water continually undergoes several physical and chemical processes and interacts with nearly all materials. Water can exist inside a building material in three states: solid (ice), liquid (water), and gas (vapor).

Moisture can migrate by various modes of moisture transport, such as vapor transport, liquid transport, and phase changes, due to the evaporation/condensation and freeze/thawing processes. Different types and shapes of pores exist (Fig. 1). Their diameters can vary from 10^{-9} to 10^{-3} m (10^{-11} to 10^{-6} in.). These transport mechanisms are dependent on the driving potentials and the transport coefficients for each mode of transport [*2*].

Moisture Storage

The combined heat and moisture performance of a particular building envelope system is dictated by the individual and collective transport/storage for all building envelope layers.



where :

1 := isolated pores

2 := dead-end pores

3 := continues channel pores

FIG. 1—Different pore types and shapes in porous building materials.

A building material is dry when it contains no or only chemically bounded water. When a material is in contact with moist air, non-hygroscopic building materials remain dry while hygroscopic materials absorb water molecules at the inner surfaces of their pore system until they reach equilibrium with the humidity of the ambient air. Due to the reduced saturation vapor pressure in the smaller capillaries, there is some condensation which, at relative humidities above 60 to 80%, results in a marked increase in the equilibrium moisture storage. The moisture storage function describes the relationship between ambient relative humidity and absorbed moisture. It has to be pieced together from sorption isotherms (up to ~93% RH) and pressure plate measurements (suction isotherms above 95% RH) [*3*] because of limitations of the respective measuring procedures. The hysteresis between absorption and desorption isotherms is usually not very pronounced, so that it is sufficient to use the absorption isotherm. Where necessary, a mean isotherm may be used or even separate absorption or desorption isotherms employed. The dependence on the temperature is usually neglected [*4*].

If a building material absorbs water by capillary forces, the material is called capillary active. In contact with water, such a material may reach an intermediate state of saturation called free water saturation or capillary saturation, w_f. It is equal to the moisture storage function at a relative humidity of 100%. Because of air pockets trapped in the pore structure, the free saturation is less than the maximum water content W_{max} determined by the porosity. Moisture contents exceeding w_f may result from condensation in the presence of a temperature gradient. Insulation materials are especially prone to moisture exceeding w_f. (They often are not capillary active and have w_f near 0).

The moisture storage function of nonhygroscopic materials (mostly insulating materials and air layers) is theoretically approximately zero for relative humidities between 0 to 100%. For relative humidities near 100%, it takes on some indefinite value between zero and w_{max}. Numerical requirements for a definite value dictate that an extremely low moisture storage function is assigned to all materials for which the user does not input the actual function [*2*].

MOISTURE TRANSPORT

Table 1 and Table 2 summarizes moisture transport processes in building materials and components. In principal, any transport process is brought about by a driving force or a potential. However, only gas diffusivity and liquid transport as a consequence of capillary forces (capillary flux) are of interest for calculations in building physics [*5*].

TABLE 1—General summary of vapor transport in porous materials.

Vapor Transport	
Mechanism	Potential (difference)
Convection	Air pressure
Effusion	Vapor pressure
Gas diffusion	Vapor pressure
Thermal diffusion	Temperature

TABLE 2—General summary of liquid transport in porous materials.

Liquid Transport	
Mechanism	Potential (difference)
Capillary conduction	Capillary suction pressure
Gravitational conduction	Height
Surface diffusion	Relative humidity
Osmosis	Ion concentration
Electrokinesis	Electric field

Vapor Diffusion

The kinetic theory of gases describes the driving forces for diffusion of molecules in multi-component gas mixtures: these are mass fraction, temperature, and total pressure. In most building applications, total pressure gradients are negligible, and thermo-diffusion based on temperature gradients is also very small. Therefore the water vapor diffusion in a porous material is reduced in comparison to that in still air by a resistance that corresponds to the volume fraction of air-filled pores a and a tortuosity factor α. This can be described as:

$$g_v = -\alpha\, a\, D_v \frac{M}{RT} \nabla P_v$$

where

g_v = mass flux rate of vapor flow, kg/m²·s, (grains/ft² h),
D_v = diffusion coefficient of vapor air, m²/s, (ft²/h),
R = universal gas constant, 8.314 J/(mol·K), (1543.3 ft-lb/lb mol R),
P_v = partial vapor pressure, Pa (lb_f/ft^2), and
M = molar weight of water, 0.018 kg/mol, (lb_m/mol).

In most European countries a diffusion resistance factor is introduced as $\mu = 1/(\alpha \cdot a)$ leading to the following flux equation for vapor flow:

$$g_v = -\frac{D_v}{\mu} \frac{M}{RT} \nabla P_v$$

In the measurement of the water vapor permeance, or water vapor permeability (permeance multiplied by thickness), using ASTM Test Methods for Water Vapor Transmission of Materials (E 96) standard or the EN 12086:1997, the factor δ_p is used, and that is equivalent to:

$$\delta_p = \frac{D_v}{\mu} \frac{M}{RT}$$

This is termed the water vapor permeability and has units of kg/(Pa·m·s) or (perm in.) or (grains[4]/h ft^2 in. Hg in.). The diffusion resistance factor μ of a dry material is a basic material parameter.

Measurements of δ_p or μ performed at different levels of relative humidity (dry-cup and wet-cup) may result in different values. This is due to surface diffusion, which becomes noticeable at higher humidities but is more properly treated as liquid transport [3]. This additional moisture transport is usually not separated out in the measurements but is lumped together with vapor diffusion. For porous materials it is more appropriate to use dry-cup and adjust the liquid transport coefficients to include surface diffusion. An exception are plastic films or coatings where the vapor permeability can increase considerably with humidity because water molecules creep between the polymers.

LIQUID TRANSPORT

Liquid flow is defined in two ways since it is transported differently within the two regions of interest in building materials. The first region is defined as the capillary water region. It follows the hygroscopic sorption region and extends from above 95% RH until free water saturation. Similar to the hygroscopic region, this region is characterized by states of equilibrium. Liquid transport occurs under the influence of a suction pressure or force in the capillary regime. The supersaturated capillary region follows the capillary region. In it, normal suction pressures are zero, and, therefore, liquid flow is not physically plausible. Moisture transport in this region occurs through diffusion under a temperature gradient or by external pressure A state of equilibrium is difficult to define.

For capillary transport, Krischer [6] has introduced the following equation:

$$g_w = -D_w(w)\,\frac{dw}{dx}$$

[4]Note: 7000 grains equal 1 lb of water.

where

g_w = liquid transport flow density, kg/(m^2·s), or (lb/ft^2 h),
$D_w(w)$ = liquid transport coefficient, m^2/s or (ft^2/h), and
w = water content, kg/m^3, or (lb/ft^3).

In his theoretical derivation Krischer [6] assumed a capillary bundle model consisting of parallel cylindrical capillaries of varying diameter interconnected without any resistance. In contact with water the larger pores transport the liquid faster than the smaller ones due to the law of Hagen-Poseuille. This leads to the water front (see Fig. 2*a*, left). If the supply of water is cut off, the spread of the liquid continues (see Fig. 2*b*, right), because the smaller pores not yet filled suck dry the larger-filled pores through the cross-connections by virtue of their greater suction power. It is anticipated that this ongoing movement of fluid proceeds slower than the transport during the absorption process. Therefore, it is necessary to apply different fluid transport coefficients depending on the boundary conditions (water absorption or redistribution, respectively, drying).

Because it is discontinuous at material interfaces, the liquid transport in the WUFI ORNL/IBP model does not employ moisture content as driving potential. The continuous potential relative humidity φ is used instead. The relative humidity is related to the capillary pressure by Kelvin's law. The transport is then described in the following form:

$$g_w = -D_\Phi\,\nabla\,\Phi$$

where

g_w = liquid transport flux density, kg/m^2 s, or (lb/ft^2 h),
D_Φ = liquid conduction coefficient, m^2/s, or (ft^2/h), and
Φ = relative humidity.

The liquid conduction coefficient is related to the liquid transport coefficient by:

$$D_\Phi = D_w \cdot \frac{\partial w}{\partial \Phi}$$

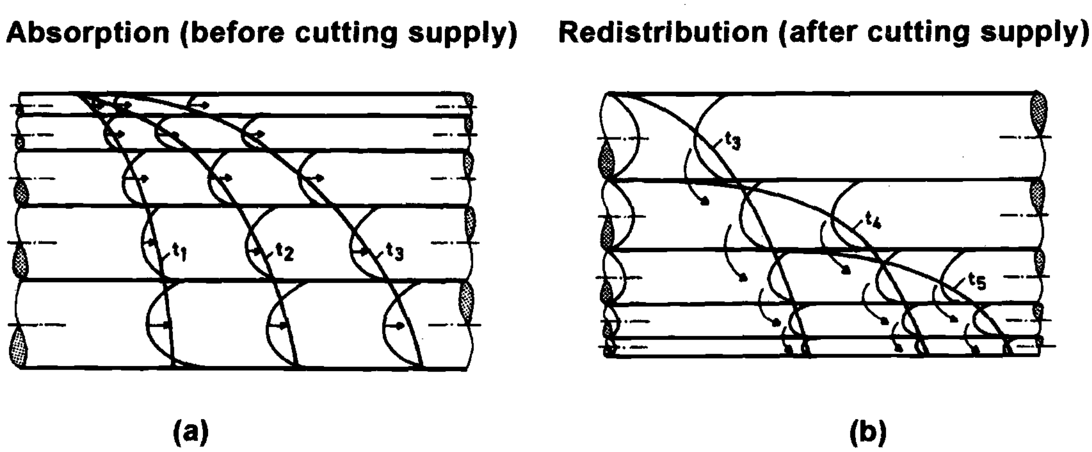


FIG. 2—Capillary transport phenomena represented by a model of interconnected cylindrical capillaries of various diameters at times t_1, t_2, and t_3 [7].

where

D_w = liquid transport coefficient, m^2/s or (ft^2/h), and
$\partial w/\partial \Phi$ = derivative of the moisture storage function.

For most building materials, the capillary transport coefficient can be approximated satisfactorily by an exponential function [2,7]:

$$D_w(w) = D_{wo} \exp\left(\frac{w}{w_f} \ln \frac{D_{wf}}{D_{wo}}\right)$$

where

D_{wf} = transport coefficient at capillary saturation, m^2/s or (ft^2/h), and
D_{wo} = transport coefficient in the sorption moisture range, m^2/s or (ft^2/h).

GOVERNING TRANSPORT EQUATION

The governing equations employed in the WUFI ORNL/IBP model [2] for mass and energy transfer are:

Moisture transfer

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot (D_\phi \nabla \phi + \delta_p \nabla(\phi\, p_{sat}))$$

Energy transfer

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla(\phi\, p_{sat}))$$

where

ϕ = relative humidity, %,
t = time, s or (h),
T = temperature, K or (F),
c = specific heat, J/kgK, or (Btu/lb °F),
w = moisture content, kg/m^3, or (lb/ft^3),
p_{sat} = saturation vapor pressure, Pa, (in. Hg),
λ = thermal conductivity, W/(mK), or (Btu/h ft °F),
H = total enthalpy, J/m^3, or Btu/ft^3, and
D_ϕ = liquid conduction coefficient, kg/ms or (lb/ft h).
δ_p = vapor permeability, kg/(m·s·Pa) or (perm in.) or (grains[5]/h ft^2 in. Hg in.).
h_v = latent heat of phase change, J/kg, or (Btu/lb).

On the left hand side of both equations are the storage terms. The fluxes on the right hand side are in both equations influenced by heat and moisture. The conductive heat flux and the enthalpy flux by vapor diffusion with phase changes in the energy equation depend strongly on the moisture fields respective fluxes. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on D_Φ. The vapor flux, however is simultaneously governed by the temperature and moisture field due to the exponential changes of the saturation vapor pressure with temperature. Due to this close coupling and the strong nonlinearity of both transport equations, a stable and efficient numerical solver had to be designed for their solution.

[5]Note: 7000 grains equal 1 lb of water.

The discretization of the transport equations is done by a fully implicity finite volume scheme with variable grid spacing. In the one-dimensional case this leads to difference equations that can be solved efficiently by the Thomas algorithm for tridiagonal matrices. The coupling of the discretized equations is assured by iterative consecutive solution of theses equations using underrelaxation factors adapted to the progress of solution. Special care had to be taken formulating the difference equations containing the vapor pressure which is a function of the two transport variables temperature and relative humidity [2].

The calculation procedure including the necessary input and the obtainable results are demonstrated with the aid of Fig. 3. The input data comprises:

- The geometry and composition of the building assembly as well as the numerical grid whose spacing has to be chosen according to the expected local gradients (steep gradients in temperature and relative humidity necessitate a fine mesh for high accuracy of the results).
- The hygrothermal properties of the relevant building materials.
- The climatic indoor and outdoor boundary conditions including the surface transfer or symmetry conditions at the boundaries.
- The time steps and the numerical control parameters. Since the discretization is implicit, there is no limit to the length of the time step. For accuracy purposes, however, a time step of 1 h is generally appropriate.

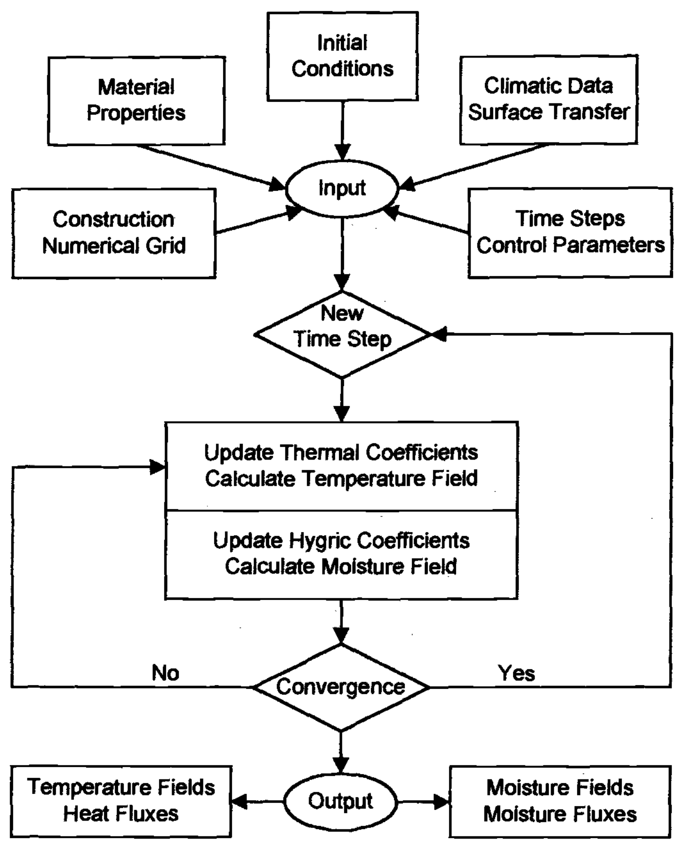


FIG. 3—Flow chart of the solution procedure in the WUFI ORNL/IBP model.

After compilation of the input data, the transient calculations start from initial temperature and moisture conditions, which are based either on measurements or derived from previous calculations respecting practical experience. At each time step, the heat and moisture transport equations are solved consecutively with a continuous update of the transport and storage coefficients until the convergence criteria are achieved. The calculated temperature and moisture fields as well as the heat and moisture fluxes at the surfaces of the building component form the output data.

MATERIAL PROPERTIES USED IN WUFI

In order to solve the above moisture and energy transfer equations, the material properties must be known. One of the unique features of the WUFI ORNL/IBP hygrothermal model is that the program provides an easy-to-use input approach without sacrificing the advanced features of its capabilities. The user is allowed to work in either SI or IP unit systems, and data can be entered in without conversion to the desired output system. Material properties in this version release of the model incorporate early 2000 material properties representative of North American construction practice. After ORNL/DOE's state-of-the-art laboratory for measuring the hygrothermal properties is completed in June 2000, and by continued use of the existing state-of-the-art facilities at Fraunhofer Institute in Building Physics, many newer material properties may become available. It is expected that this material property database will be scrutinized and updated in the future when better data become available. ASHRAE's material properties are and will be included into the WUFI ORNL/IBP database.

The minimum material properties required for the simulation are:

- Bulk density [kg/m³] [lb/ft³], which serves to convert the specific heat by mass to the specific heat by volume.
- Porosity [m³/m³] [ft³/ft³], which determines the maximum water content w_{max} (by multiplication by ρ_{water} = 1000 kg/m³ or [62.2 lb/ft³]).
- Heat capacity [kJ/kg K] [Btu/lb °F], the specific heat capacity by mass. Rough values are 0.85 kJ/kg K (0.203 Btu/lb °F) for mineral materials and 1.5 kJ/kg K (0.3583 Btu/lb °F) for organic materials.
- Heat conductivity dry [W/m K] or [Btu/h ft °F]—the heat conductivity of the material in dry condition. A moisture-dependent heat conductivity is optional.
- Diffusion resistance factor dry [−]— the diffusion resistance factor (μ value) of the material in dry condition. The D/R/F. indicates how many times the diffusion resistance of the material is higher than that of stagnant air. A moisture-dependent D/R/F. is also available. (If the values are entered in I-P units, the permeability [perm in.] of the material is needed.)
- Sorption/suction isotherms [kg/m³] or [lb_m/ft³] that give the equilibrium moisture content of materials as a function of relative humidity in both the hygroscopic and the capillary water regime up to water saturation.
- Liquid diffusivity [m³/s] or [ft²/s] both for uptake and redistribution of materials as a function of moisture content w.

As an example of a typical datasheet, Fig. 4 displays material properties for lime silica brick, as employed by WUFI. (All values are in S-I units, but are also available in I-P.)

BOUNDARY CONDITIONS FOR INDOOR AND OUTDOOR

The heat and moisture exchange between a building assembly and its environment can be rather complex. Figure 5 shows a number of hygrothermal phenomena between an insulated cathedral ceiling and the outdoor and indoor environment. It is important to note that most of the heat and moisture exchanges between the surfaces of the assembly and the surrounding climate are highly transient and may even be subject to daily changes in direction. The heat exchange is governed by:

- convection (in contact with air or water)
- conduction (in contact with earth or snow)
- short and longwave radiation
- moisture enthalpy and phase change

The moisture exchange is governed by

- vapor convection (in contact with air)
- vapor diffusion (in contact with earth or snow)
- precipitation, drainage or ground water absorption

At the indoor surface of the building assembly, the situation is rather simple. The heat transfer by convection and radiation can be lumped together in a surface transfer resistance that has a value of about 0.13 m² K/W or (7.374e^{-3} °F h ft²/Btu) at the undisturbed surface and about 0.2 m² K/W (1.1350e^{-2} °F h ft²/Btu) in corners and behind furniture. For vapor transfer this surface resistance is determined from the convective heat transfer resistance by the similarity principle. The equivalent stagnant air layer thickness for the surface resistance is usually approximately 8 mm (425 perm).

The situation is more complex at the outdoor surface of the building structure. Here the heat transfer by convection and radiation have to be treated separately. During day-time hours, the solar radiation can be treated as a heat source depending on the direct radiation and the energy absorptivity of the surface. The long wave emission may be lumped with the convective heat transfer resistance as long as the radiative energy absorption is greater than the long wave emission. This is not the case during night time when the building surface temperature can fall below the ambient air temperature; then convective heat transfer and long wave irradiance to the sky flow in opposite directions.

The vapor transfer is described adequately by a surface resistance determined from the convective heat transfer resistance similar to the indoor situation. However, this surface resistance depends on the wind velocity and direction at the location of the construction. It can either be calculated by CFD or approximated from the annual average of the wind velocity. For most applications such an approximation is sufficient because its effect on the moisture behavior of a building assembly is significant only as long as the surface is wet.

The absorption of rainwater at the surface can be treated similar to the solar radiation absorption as a source term at

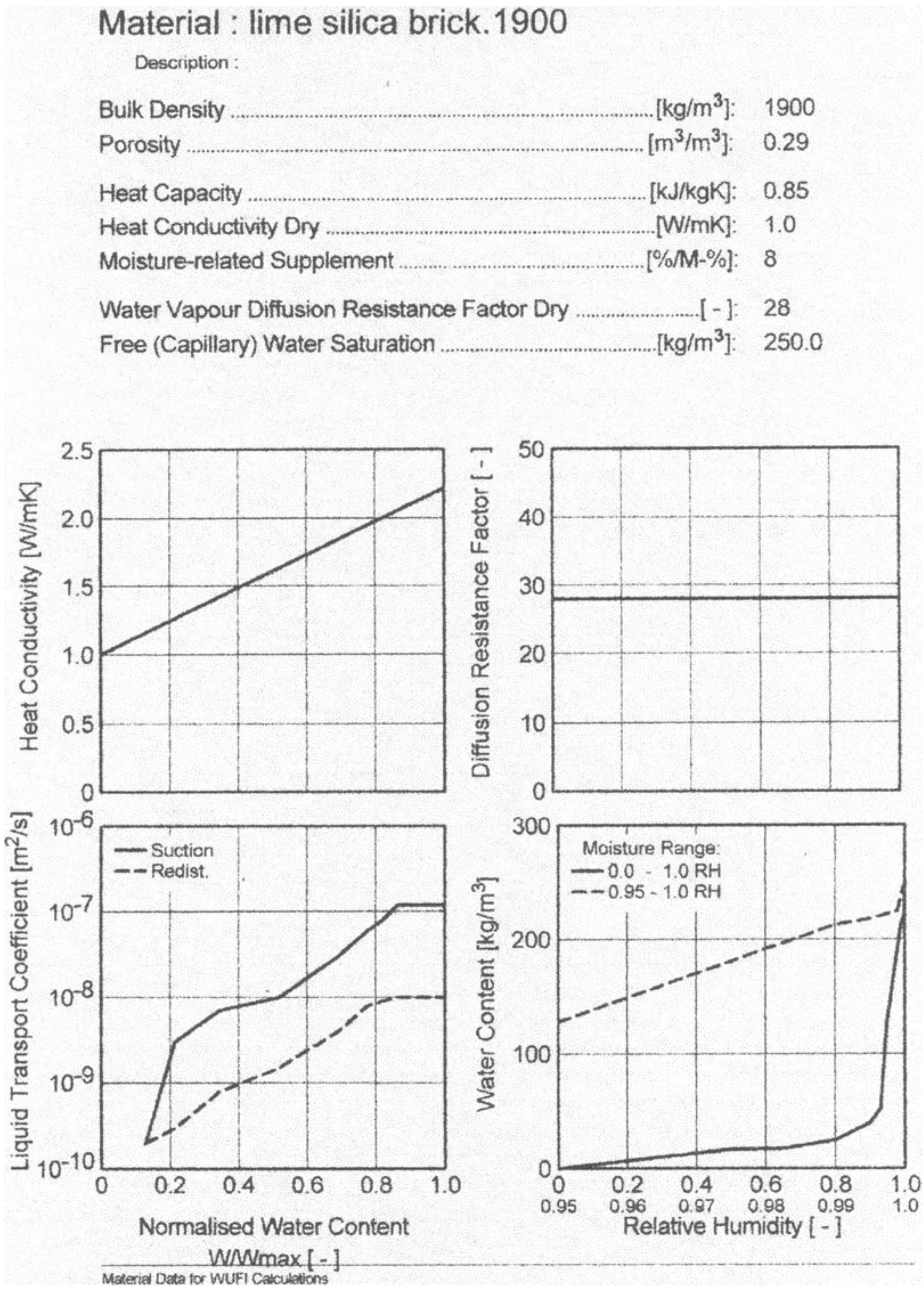


FIG. 4—Example of one complete set of material data used in WUFI ORNL/IBP.

the surface or beneath it if the rain penetrates the first layer due to its momentum. In contrast to the radiation, the water absorption capacity of the surface layer may be limited, resulting in a drainage of water that has to be accounted for. In general, no water will be absorbed below 0°C or (32°F). The cooling of a building surface when rainwater of lower temperature hits it is negligible compared to the evaporative cooling during the subsequent drying process [2].

OUTDOOR CLIMATE

Starting from specified initial conditions, WUFI computes the temporal evolution of the temperature and moisture distributions within the building component. This evolution is determined not only by the underlying transport equations that govern the processes in the component, but also by the heat and moisture exchange with the surroundings. Thus,

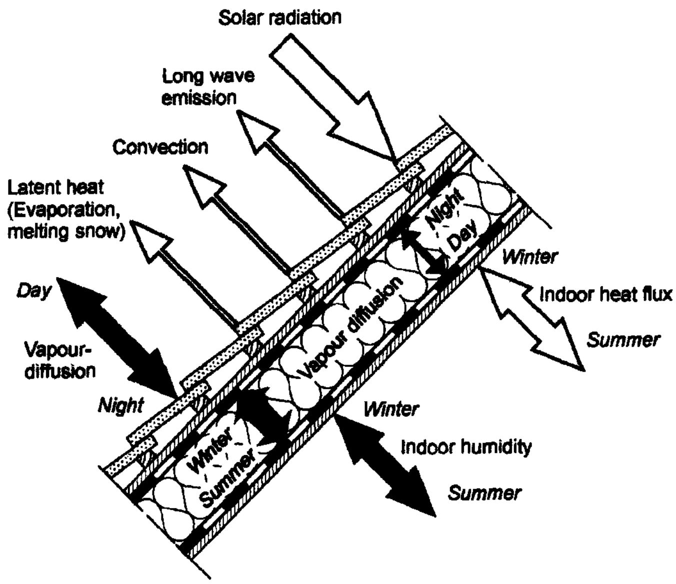


FIG. 5—Indoor and outdoor boundary conditions.

there are heat and moisture flows through the surfaces, the direction and magnitude of which depend on the conditions in the component as well as on the conditions in the surroundings.

Because WUFI ORNL/IBP has been developed specifically for building physics applications, the surrounding medium is in most cases the ambient air (outdoor air, indoor air). Since it was designed to calculate the behavior of building components exposed to the weather, it is natural to describe the conditions of the surrounding air in terms of meteorological parameters such as temperature, relative humidity, solar radiation, wind speed and orientation, horizontal precipitation, cloud cover, etc. In this way, WUFI ORNL/IBP employs boundary data that are usually measured for other climatological purposes. Hourly weather data are available to the model for a wide range of North American climate zones. Currently 60 locations are available within North America. These weather files are complete years, but have been selected to represent years that are more appropriate for moisture design purposes than average weather years for energy design. For each location, 30 or more recent years have been analyzed. ASHRAE (Mr. Seaton, Research Manager) is gratefully acknowledged for providing the weather data for this model. To provide a basis for comparison, one or two years of data have been selected for each location. Depending on the construction type, winter or summer condensation may occur and either a cold or a warm year should be chosen. This approach allows the user to select either weather file depending on the expected risk of moisture-induced failure, or even both files.

A unique feature of the model is the capability to include the effects of wind-driven rain. The model incorporates a set of equations to predict the amount of wind-driven rain on the exterior facade of a building system. Extensive experimental work [9] has validated the approach. Additionally, use of 3-D computational modeling has allowed the development of wind-driven rain shape factors [*11–13*]. For more information on wind-driven rain, the user should review Refs *8* to *13*.

INDOOR CLIMATE

In general, the interior temperature and relative humidity of different-conditioned buildings show relatively minor variations. Therefore it is sufficient to differentiate four different interior climates:

- heating conditions
- cooling conditions
- mixed conditions
- constant controlled conditions

WUFI ORNL/IBP includes features to generate the interior temperature and relative humidity from a sine wave with a period of one year whose mean value, amplitude, and date of maximum are set automatically. These are internally set values, but may be modified by the user. The model will include the indoor environmental classes in accordance to ASHRAE SPC 160P [*14*] when available.

LIMITATIONS OF WUFI ORNL/IBP

Any software has its share of limitations, requires a certain skill level, and the user must be aware of what the model can and cannot do.

WUFI ORNL/IBP is no exception. Results must be checked for plausibility. There are numerous circumstances that can degrade the quality of a calculation or even render it worthless. (A slightly inaccurate result may be more difficult to diagnose than a totally wrong one since it may not be easily recognized as wrong.) Some possible problems are:

- programming errors
- input errors
- insufficient knowledge of the required input data
- limitations of the underlying mathematical model
- numerical problems

These items will be discussed in turn.

PROGRAMMING ERRORS

WUFI ORNL/IBP has been tested rigorously to eliminate errors that might affect the calculation results. Considering its complexity, errors may not be ruled out completely and problems can arise under certain circumstances. Please report any problems to karagiozisan@ornl.gov or holm@hoki.ibp.fhg.de.

INPUT ERRORS

Many errors in the results can be traced back to input errors. It is strongly recommended that the user save the input file and review and recheck the entries in the entire sequence of menus to make sure all entries are correct.

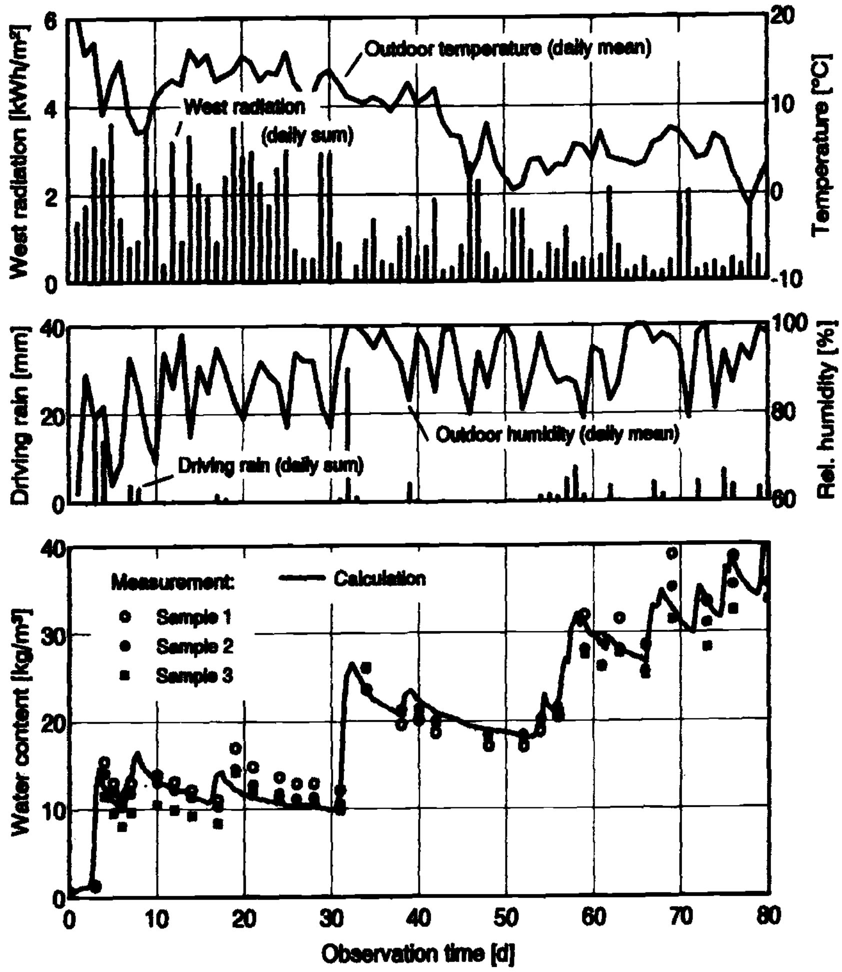


FIG. 6—Transient behavior of a stone-faced façade. The output is the measured and calculated mean water content evolving with time. The actual weather input conditions are shown in the two figures above. The output is in the figures below.

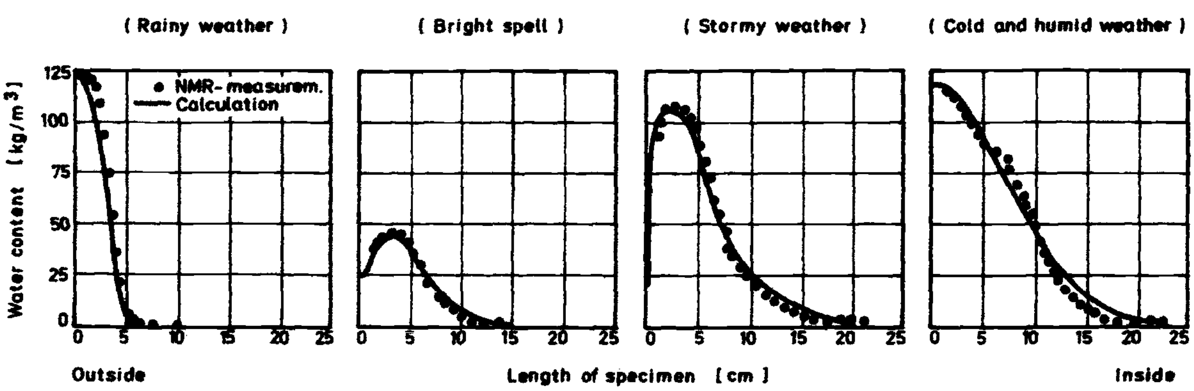


FIG. 7—Transient behavior of a stone façade. Measured and calculated moisture content profiles for four subsequent time periods.

INSUFFICIENT KNOWLEDGE OF THE REQUIRED DATA

It often happens that material data, coefficients, or boundary conditions required for the calculation are not known. Under these circumstances a single "precise" result is not possible. Instead, estimate the possible variation range of the input data and perform some parametric calculations for this range. From the variation the user may determine to what degree the results are affected by the uncertainty. A low de-

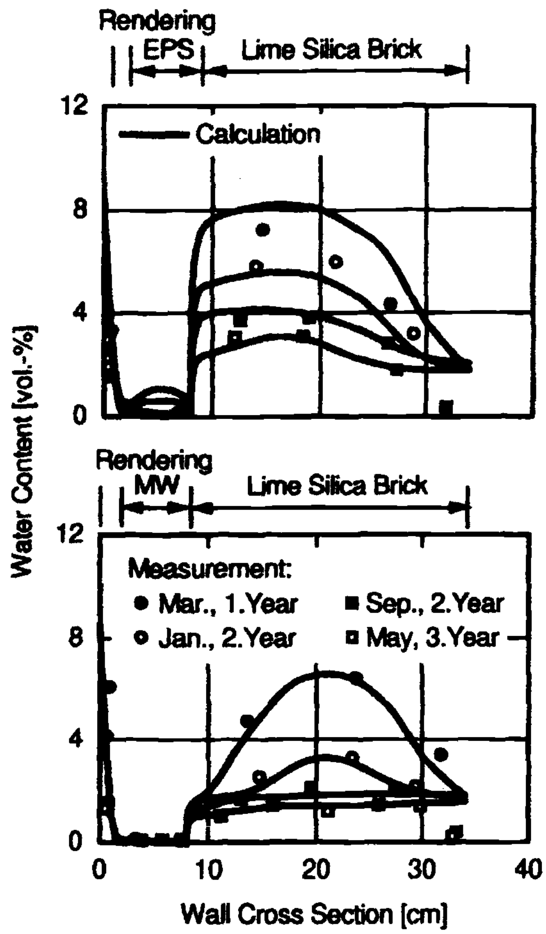


FIG. 8—Measured and calculated moisture content profiles at different time periods after finishing the construction for an EIFS with EPS insulation (top) and mineral wool (bottom).

gree of influence justifies an approximation of the concerned material properties. Otherwise, more precise determination of some input data may be necessary.

Even, in cases where "reliable" data are available in practice there are also variations in the materials or workmanship that might cause deviations from the theoretical results. It can be more instructive to know the effect of the variations of an estimated parameter on the results than to use a single set of data to arrive at a single numerical result of uncertain precision.

LIMITATIONS OF THE MATHEMATICAL MODEL

The complex hygrothermal processes in a building component need to be simplified to make their simulation accessible to present-day computers. WUFI ORNL/IBP has been designed for the most important applications in building physics, but several limitations must be accepted. WUFI ORNL/IBP deals only with one-dimensional processes. Situations that cannot be adequately reduced to one dimension (e.g., multi-dimensional thermal and moisture bridges) cannot be treated by WUFI ORNL/IBP. In these cases please refer to the 2D version of the WUFI model.

Several transport phenomena have been neglected, such as airflows in the component, uptake of groundwater under hydrostatic pressure, and gravity effects. Water and heat sources and sinks inside constructions, as well as extremely high-temperature ranges (fire conditions), cannot be calculated. The interface between two capillary-active materials (e.g., rendering/brick) is treated as ideally conducting, whereas in reality there often is a transfer resistance, which may reduce the moisture transport considerably.

Some materials do not lend themselves to the simplified transport equations. Wood and concrete may change their

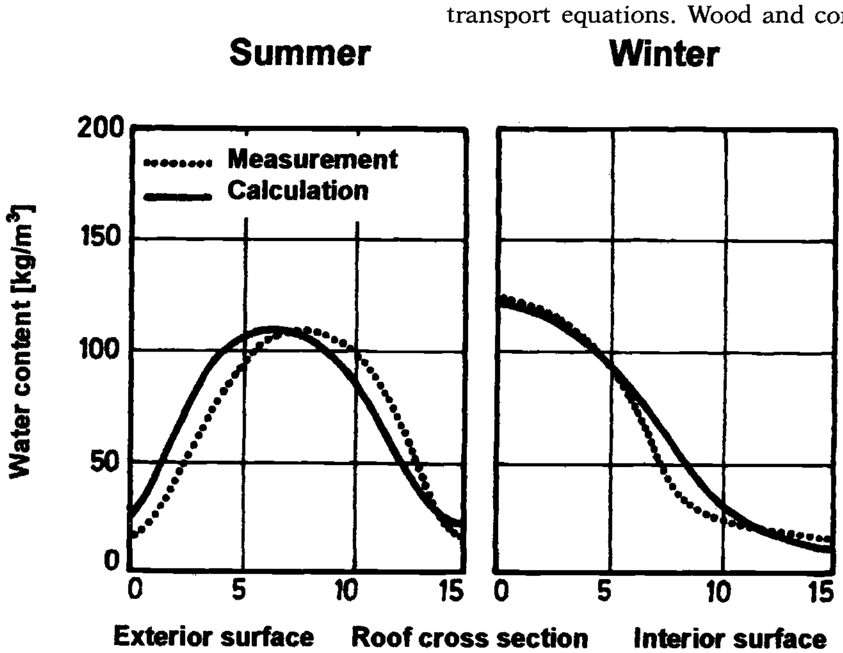


FIG. 9—Measured and the calculated moisture distribution at the end of the first summer and in the following winter.

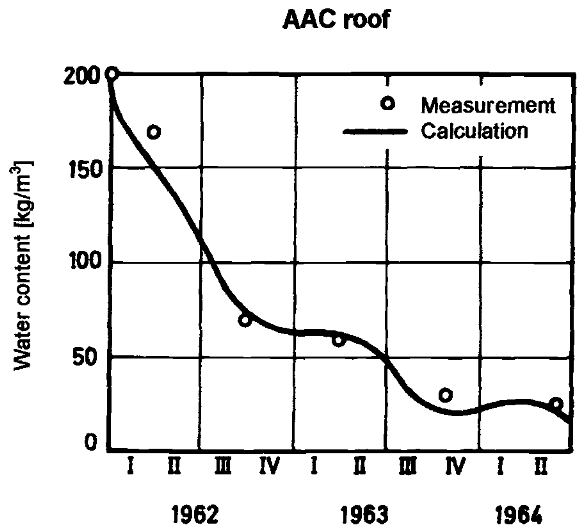


FIG. 10—Moisture performance of the AAC flat roof.

material properties as a function of their present and past moisture content. The consequences of this may be negligible or serious depending on the component assembly and the boundary conditions. Only a comparison with samples exposed to natural weather can show whether the calculation results are reliable or not. The WUFI ORNL/IBP model currently employs and averages absorption and desorption isotherms and does not account for hysteresis in its moisture storage function. The enthalpy flows resulting from the transport of liquid water across a temperature differential are ignored, i.e., the impact of cold rainwater does not cool the surface of a building component in the calculation. The cooling effect by the subsequent evaporation of the absorbed water—which is considerably greater in general—is, however, correctly included.

One further limitation of the model is that it does not include time-dependent hygrothermal material properties. This means that, for example, contaminated surfaces due to exposure and cracks due to freeze thawing, swelling, and shrinkage are not accounted for in the current version.

NUMERICAL PROBLEMS

If boundary conditions relevant to building physics are to be applied, the coupled differential equations describing heat and moisture transport can only be solved numerically. The grid density may be enhanced to minimize numerical errors. For this purpose, WUFI ORNL/IBP displays a water balance after the calculation has finished. Viewing the animation film, one may see "flutter" appearing in the results for no apparent reason. If so, the choice of the grid should be rechecked.

EXPERIMENTAL VALIDATION

The WUFI model is most likely the most validated and benchmarked model for hygrothermal applications. The validation of a numerical model requires reliable experimental investigations with well-documented initial and boundary conditions, as well as accurate material properties. The following three examples were chosen because they meet these criteria.

Moisture Behavior of an Exposed Natural Stone Facade

The degradation of natural stone facades is due mainly to moisture-induced weathering or damage processes. Therefore, these facades are often treated with water repellent or reinforcing chemicals that may not always be beneficial. Such a treatment not only reduces the water absorption but also the drying rate. In order to investigate the hygrothermal behavior and the durability implications of natural stone facades, sandstone samples were thoroughly examined in the laboratory to obtain reliable material parameters for the WUFI ORNL/IBP simulations. Afterwards, the samples were dried and exposed to the natural climate in a field test. During this test the exact climate conditions were recorded and the moisture behavior of the samples was determined by weighing and NMR-profile measurements. The material parameters and the recorded weather data (hourly values of indoor and outdoor temperature, relative humidity, driving rain, and solar radiation) served as input for the calculations. Figure 6 shows a comparison of the calculated and the recorded water content of the facade samples as well as the climate conditions during the observation period.

This excellent agreement in total water content between experiment and calculation can be confirmed by examining the moisture profiles at certain time intervals in Fig. 7 recorded for Sample 2 in Fig. 6 [*2*].

Drying of Masonry with Exterior Insulation

Exterior insulation finish systems, EIFS, applied on masonry can prolong the dry-out time of masonry. In severe cases, the construction moisture in the masonry can severely damage the stucco of the EIFS if moisture is accumulating beneath it through vapor diffusion. Therefore a test house was erected with calcium silica brick masonry and insulated with two types of EIFS. The insulation layers were 80 mm thick and consisted of expanded polystyrene slabs (EPS) or high-density mineral fiber. Mineral fiber insulation is used mainly for fire protection or sound insulation purposes.

The drying process of the walls was monitored by drill probing the walls several times after completion of the house. Figure 8 depicts the measured and calculated moisture profiles over the cross section of the walls at subsequent time intervals. The results correspond well and show a great influence of the insulation material on the drying behavior of the wall. Due to the rather low water vapor permeance of the EPS, the masonry in the top graph dries mainly to the interior of the building, which prolongs the dry-out process compared to the wall in the bottom graph. The high vapor permeability of the mineral fiber insulation results in an effective dryout to both sides. However, in this case the stucco must also have a high permeability to avoid excessive condensation beneath its surface, which can cause frost damage.

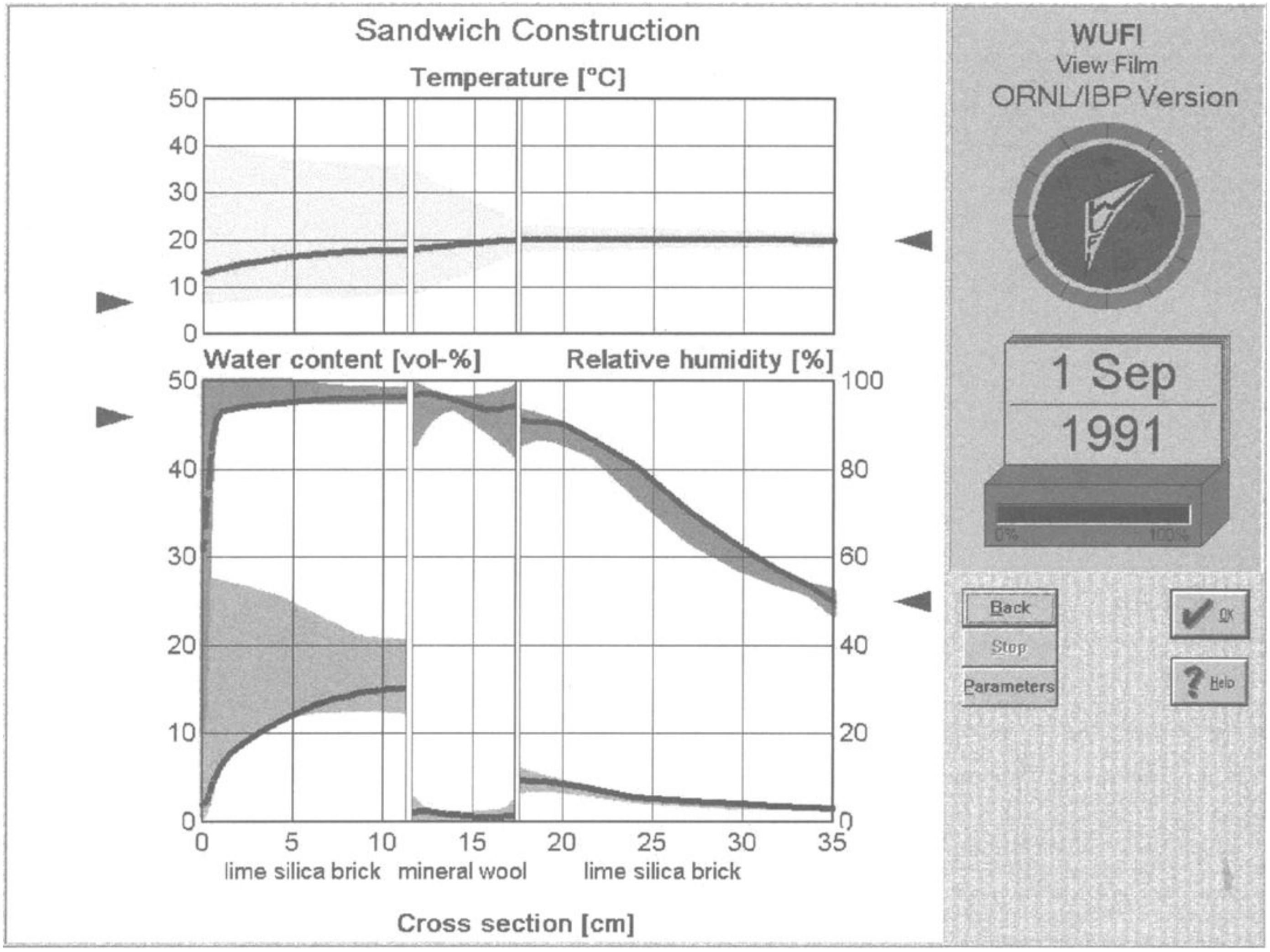


FIG. 11—Visualization of the calculated results with WUFI film.

Seasonal Moisture Migration in a Flat Roof

To protect a flat roof from interstitial condensation, a vapor retarder is required in cold climates. However, in the case of an autoclaved aerated concrete (AAC) roof, a vapor retarder would also prevent the construction moisture from drying out and thereby severely impairing the thermal insulation quality of the AAC. To find out whether an unvented flat roof of AAC works without a vapor retarder, an air-conditioned test hall with such a roof was built and the moisture migration in the initially wet roof was monitored by drill probing. This field test was done in the 1960s and the exact weather data are missing. They were replaced by data recorded in recent years at the same location. Parametric studies with the data of different years justified this choice [*2*].

Figure 9 demonstrates the measured and the calculated moisture distribution at the end of the first summer and in the following winter. In summer, the solar radiation leads to high temperatures and consequently elevated vapor pressures under the impermeable bituminous felt. Moisture is moving, mainly through vapor diffusion, to the colder parts of the roof and condenses somewhere in the middle or dries to the interior. In winter the temperature gradient is reversed and the moisture accumulates beneath the roofing membrane. If there were a vapor retarder at the bottom of the roof this seasonal migration would go on forever. Without a retarder the drying process is very efficient. It can be concluded from Fig. 10 that within 2½ years the AAC has lost most of its construction moisture and is reaching its hygroscopic equilibrium. Because there is good agreement between the measured and the calculated results, the influence of the indoor climate can be estimated by a WUFI ORNL/IBP parametric study. This shows that such a roof would perform reasonably up to a relative humidity of 60% during the heating season.

FEATURES OF THE MODEL

The WUFI ORNL/IBP model was developed exclusively for university-trained architects and building envelope designers. The input to the model was kept to a bare minimum without sacrificing the performance capability of the software. This was achieved by keeping the inputs necessary and critical to simulation. The model is equipped with both

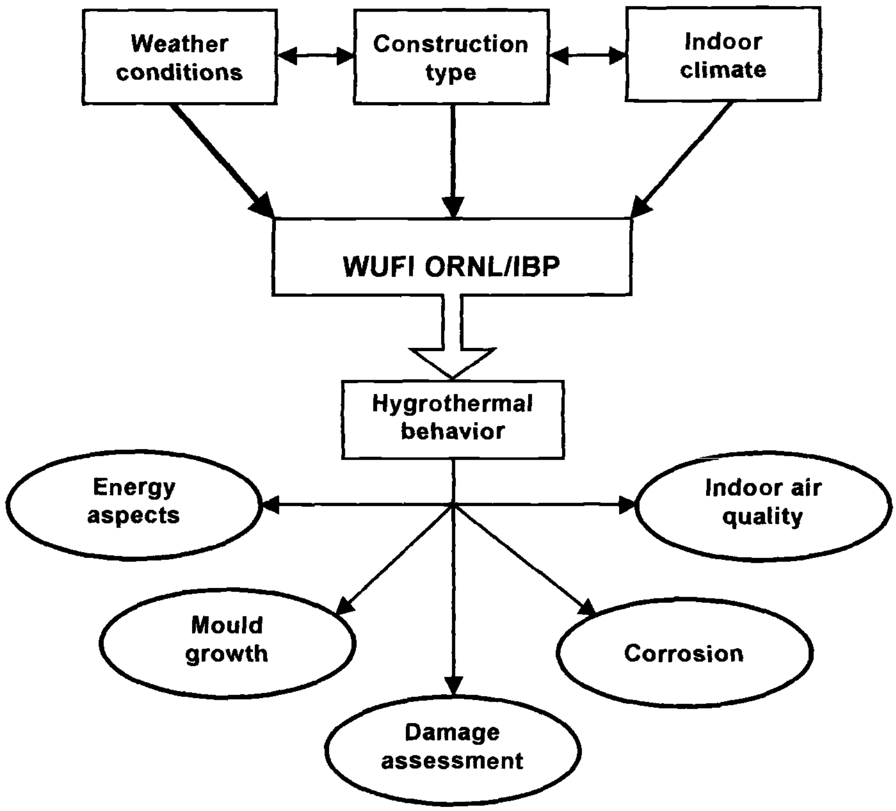


FIG. 12—Software architecture of WUFI ORNL/IBP.

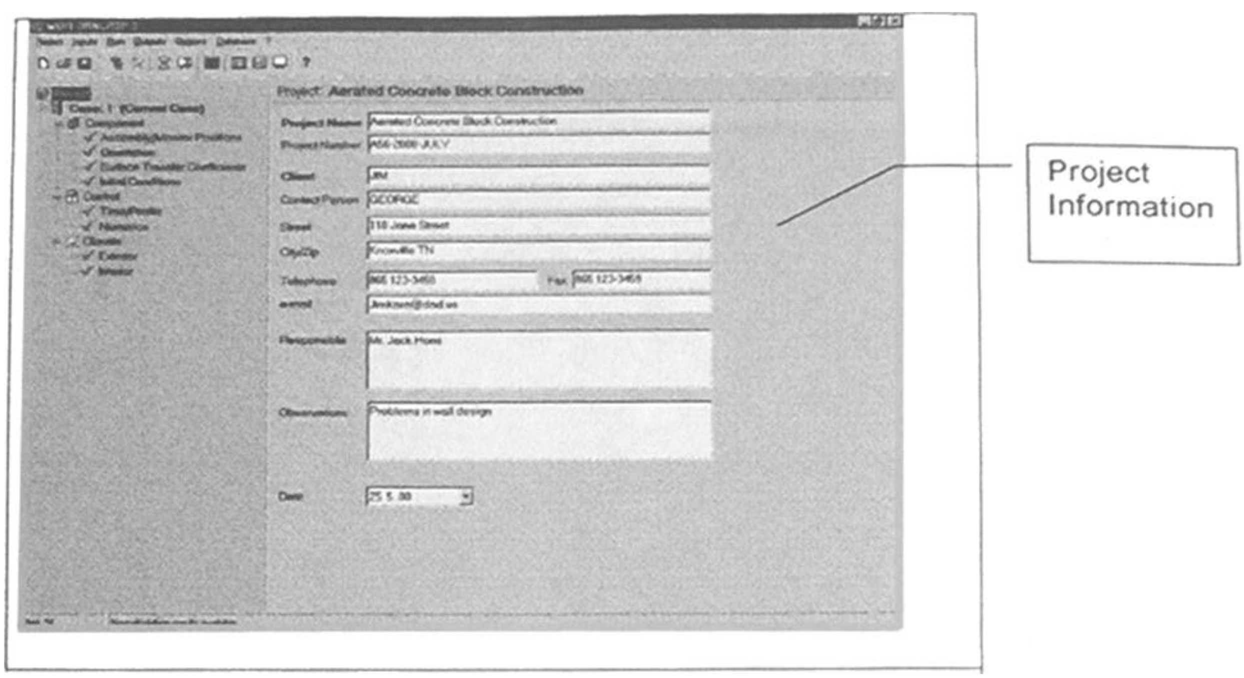


FIG. 13—Project definition menu.

weather data and a material property database. Because of the modular structure, updates may be implemented with ease. The main/central engine module to WUFI ORNL/IBP is the one that solves the system of transport equations. Other modules that produce details of the weather, construction type, and indoor climate are peripheral. Once the modules are linked, the central WUFI/ORNL simulation begins. The calculated results can be visualized with WUFI-FILM.

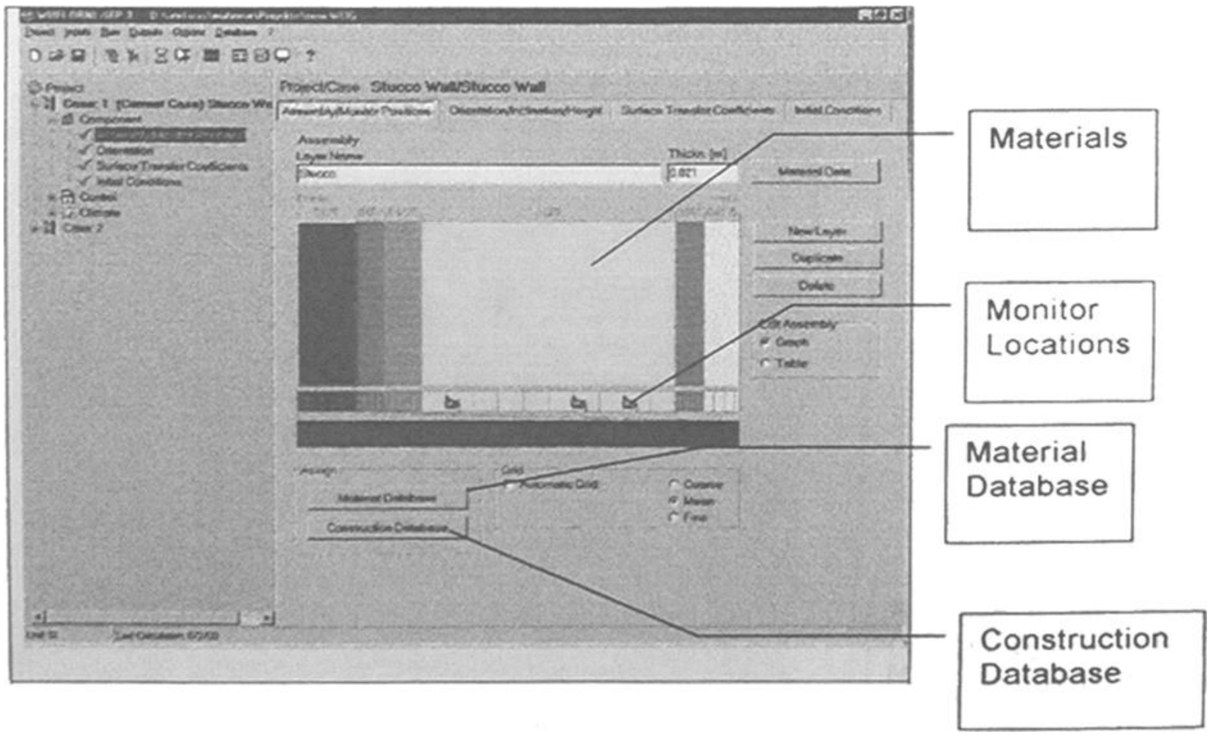


FIG. 14—Definition of construction component.

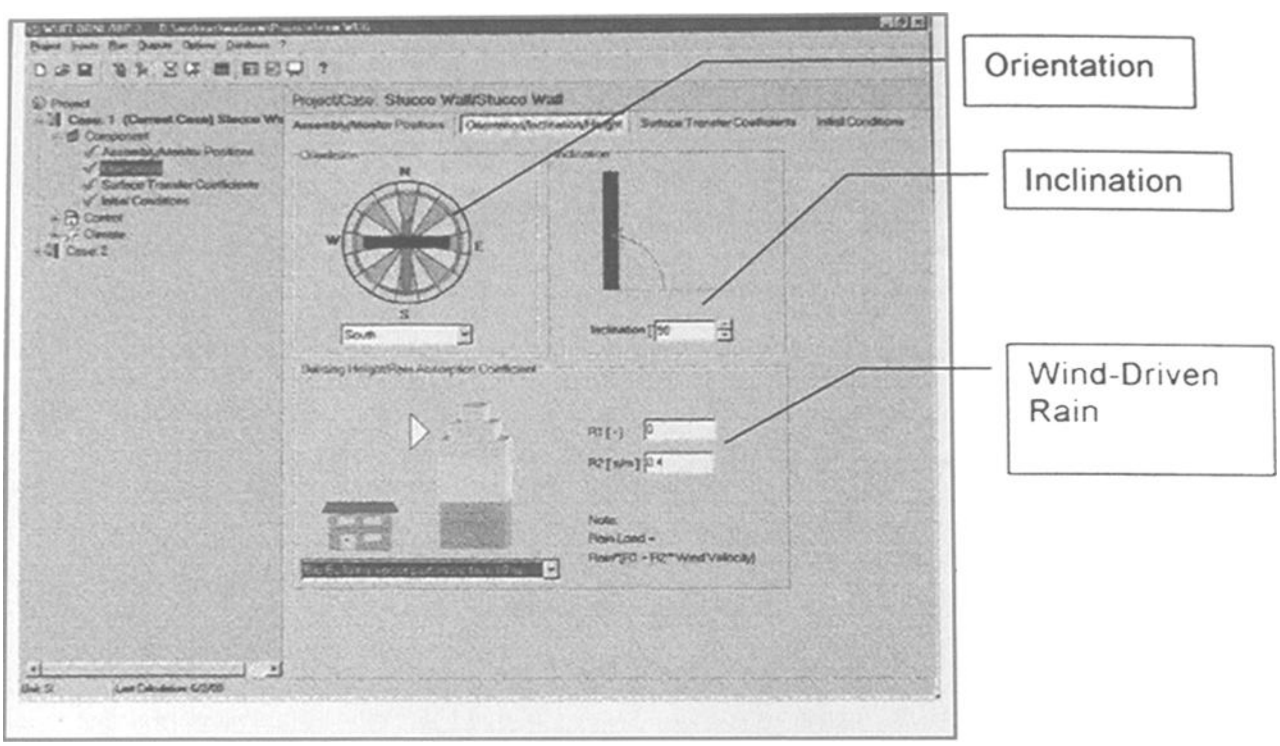


FIG. 15—Definition of orientation and inclination effects.

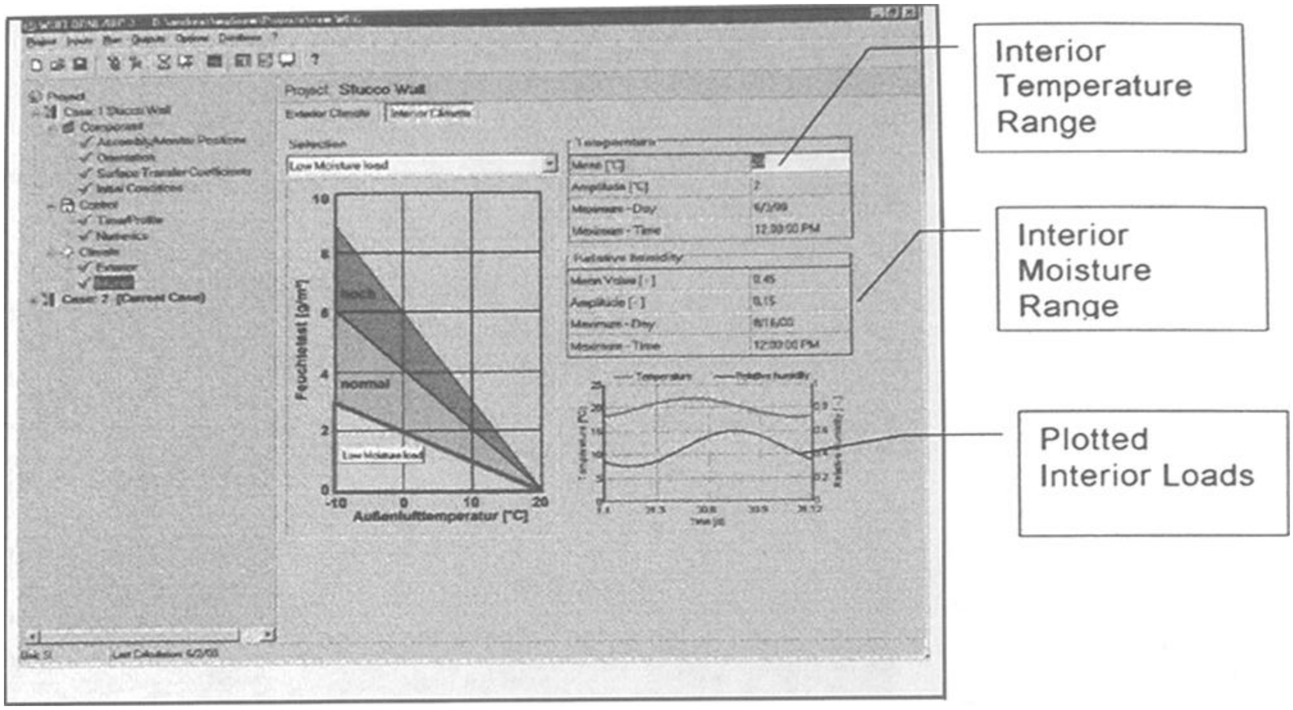


FIG. 16—Definition of exterior environmental loads.

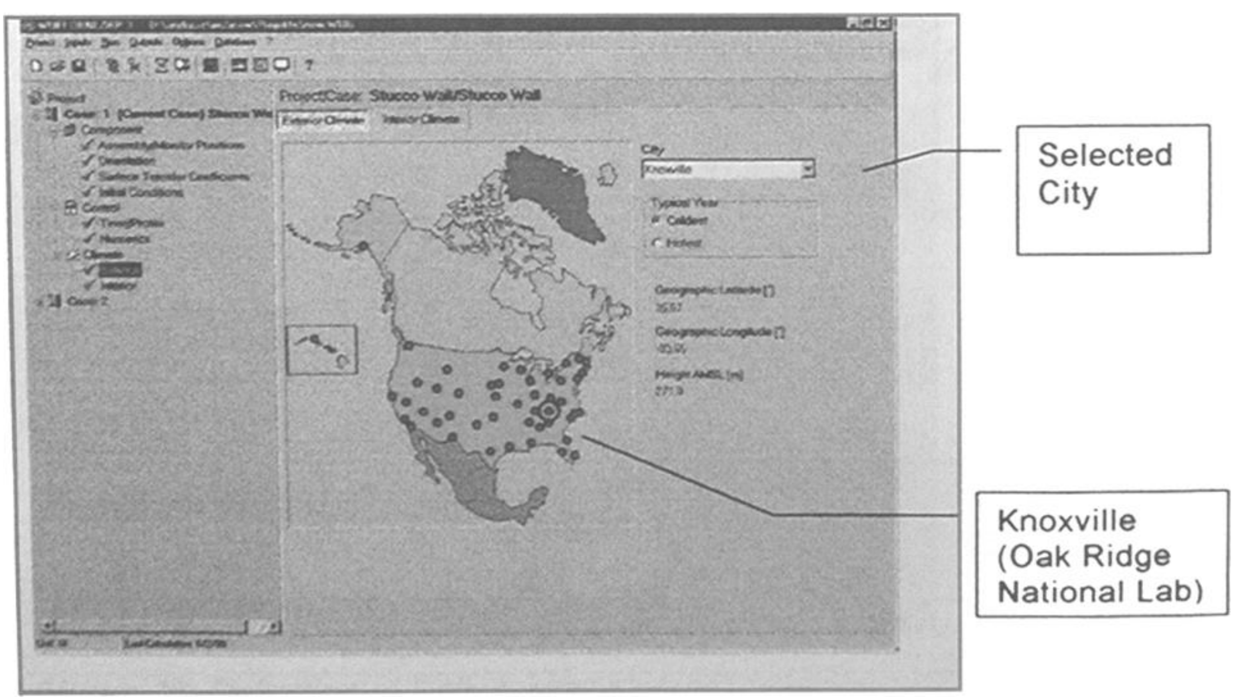


FIG. 17—Definition of interior environmental loads.

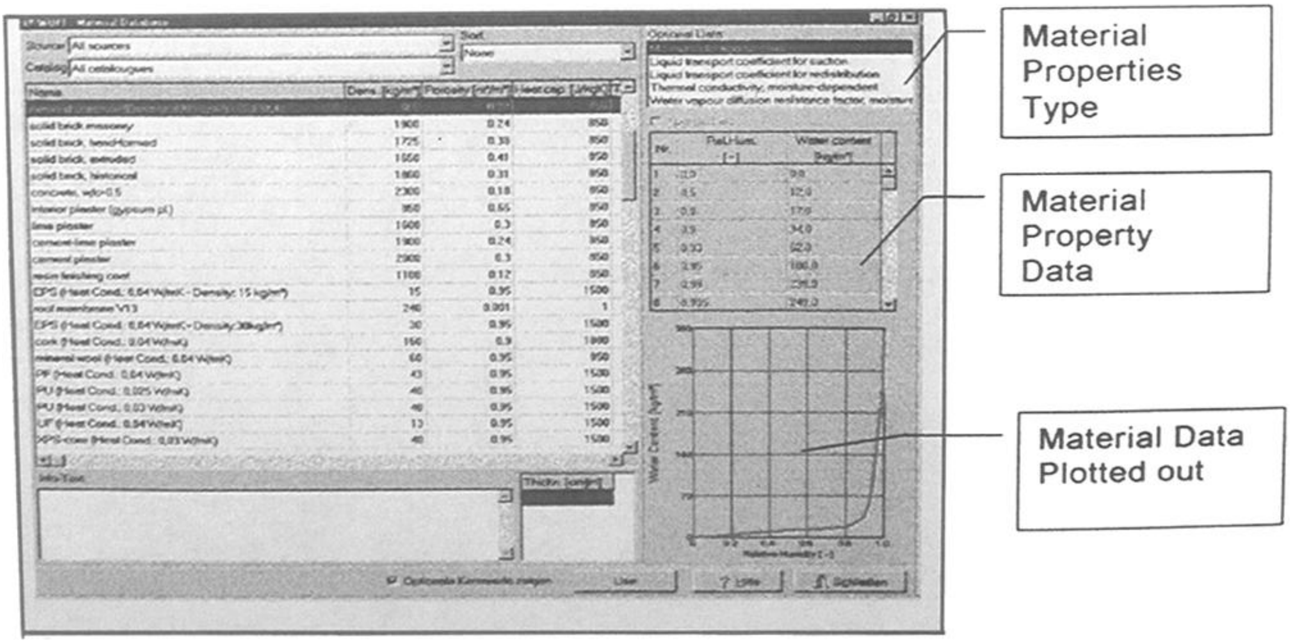


FIG. 18—Definition of definition of material properties.

With WUFI-FILM the daily and annual development of the water and the temperature profiles can be observed. Figure 11 displays a hardcopy from this visualization tool.

At the end of the simulation, peripheral post-processing modules will be available that further analyze and process the hygrothermal performance results of the investigated construction. These modules include an energy module, a mold growth module, a damage assessment module, a corrosion module, and an indoor air quality module. Currently only the energy and mold growth modules are available. The future software architecture is shown in Fig. 12.

WUFI® ORNL/IBP MODEL INTERFACE

WUFI® ORNL/IBP is a user-friendly model and interface that was developed specially for Microsoft Windows and runs under Windows 95, 98, 2000, and Windows NT. A logical setup is followed in the design of the interface. First, the user develops a project. Within each project, the user may introduce many sets of modeling cases, such as the parametric investigation of various exterior weather-resistive barriers, for example. The user may copy over the basic case input into a new case and then proceed to execute the simulation. The WUFI® ORNL/IBP interface uses three pathways that compose the input runstream file as the basics for its functional organization. These pathways are:

1. *Component:* Where you specify the modeling scenario and details of the envelope system of the modeling.
2. *Control:* Where you define the numerical characteristics of the project case.
3. *Climate:* Where you define the exterior and interior environmental exposure conditions of the construction.

The WUFI® ORNL/IBP interface also uses four pathways that compose the running and output runstream as the basics for its functional organization. These pathways are:

4. *Run:* Where you specify whether to run the simulation with or without the result film.
5. *Output:* Where you can print out and check input data summary, check the status of the simulation, view results, include measured data, export results, and export result film.
6. *Options:* Where you define your unit system, view warnings, and save project case results.
7. *Database:* Where you may include or review materials.

All these pathways are needed to establish each case within a project. In the WUFI® ORNL/IBP interface, each of these pathways is presented in a menu bar. Following the sequence order in the pathway, you can successfully prepare all inputs and review output results.

In Figs. 13 to 18, several menu screen shots are presented to display the user-friendly design of the program.

Acknowledgment

This program was a collaborative work between the Fraunhofer Institute for Building Physics (Director: Univ.-Prof. Dr.-Ing. habil. Dr. h.c. mult. Dr. E. h. mult. K Gertis) and DOE/ORNL. The authors would like to acknowledge for support in this research activity Dr. Jan Radon, Mr. Andre Desjarlais (ORNL Program Manager), and Arun Vohra (DOE Program Manager) and Thomas Schmidt. Dr. Tom Petrie is gratefully acknowledged for his thorough review of this document.

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10

A Look to the Future

by Carsten Rode[1]

THIS CHAPTER WILL REPORT on some tendencies as seen from the researchers' viewpoint on technologies for moisture performance of building structures that will become available to building designers and practitioners within the coming years.

Tendencies that are envisaged to have an impact on modeling, analytical methods, and practical capabilities are:

- Current research topics will be available more widely, especially concerning modeling and measuring capabilities.
- The increased development and use of information technology and knowledge systems will have a significant impact.
- There will be an increased practical knowledge about well-insulated structures and their moisture performance.

The chapter is divided much like the moisture manual itself, with main sections on Weather Data, Material Data, Failure Criteria, Analysis Methods, and Practice.

WEATHER DATA

Wind-Driven Rain

Analytical models are becoming able to handle wind-driven rain as one of the moisture impacts on building constructions. It is therefore anticipated that in the future weather data will be prepared to represent the data needed to calculate wind-driven rain and be prepared in such a way that the required weather data are statistically representative. The data needed to calculate wind-driven rain are rain intensity, wind speed, and direction.

Too, a formal, possibly international, standard should be prepared on how to process such weather data for an actual building and for a given position on it. British standard BS 8104:1992 [*1*] already exists in this field; however, it needs to be extended so it can be applied to global weather conditions. The topic is further discussed and described in the International Energy Agency's (IEA) Annex 24, Task 2 [*2*].

Data about other External Environment than the Outdoor Air

The condition of other exterior boundary conditions than the ambient air sometimes needs to be known. Examples of such conditions are the hygrothermal condition on the exterior side of building structures that are in contact with the ground. Another example is the hygrothermal condition behind exterior ventilated cladding such as in a ventilated wall system or under a tiled roof.

It is anticipated that some guidance will be developed on how to estimate the hygrothermal conditions in these places from standard weather data. This requires quite some correlation with conditions measured in practice for different configurations of the building parts, and for different climates. Only some of this knowledge already exists. It is therefore necessary first to gather a large amount of information in a systematical way. While it is anticipated that some common consensus and guidance will be developed in this field, it is also quite certain that it will take some time and resources to develop these special exterior environment descriptions.

Moisture Design Reference Years

Today, weather data are most often chosen such that they describe the weather in a way that is statistically correct with respect to the average value, and deviation from the average, but mainly what concerns the air temperature and solar radiation data. In the future, weather data will exist in a form that is optimized for the purpose of moisture analysis, that is, weather data for moisture calculations will be optimized with respect to the data most relevant for the movement of moisture.

Furthermore, one has to decide whether an average weather situation should be represented or whether in some cases it is better to use some weather data that are somewhat extreme in terms of the impact on the moisture performance of building construction. This has been analyzed within IEA Annex 24 in an effort to generate so-called Moisture Design Reference Years [*2*] and in the work by Geving [*3*]. It is anticipated that the future will bring more weather data aimed specifically at analyzing the moisture conditions of building structures.

MATERIAL DATA

Databases of Material Properties

A much-quoted collection of material data is a catalogue by Hansen [*4*], although it is restricted to sorption curves. In this catalogue Hansen presents no measurements of his own, but simply has the strong quality of collecting data from other investigators. Such collections are very useful. Other catalogues are the material data catalogues by IEA Annex 14 [*5*] and Annex 24, Task 3 [*5,6*], and the material lists by ASTM [*7*] and ASHRAE [*8*]. The catalogues by Hansen and

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the IEA show the material properties as functions of, e.g., humidity level or temperature, but they are limited by the somewhat arbitrary selection of which properties are reported in the literature, or which measurements have been made available by researchers or manufacturers for representation in the catalogues. The lists by ASTM and ASHRAE and by many textbooks are probably more complete in the selection of materials, but each property of a material is simply registered as a single number without its functional dependency. Most catalogues have the drawback that they seldom indicate the variation that may exist of a material specified just by a single name.

The future will probably see some electronic databases in which manufacturers and researchers have admitted their data about common building materials. The databases will be overviewed by impartial organizations such as ASTM to ensure that the content is of high quality, i.e., the data are measured according to current standards and representative of the material being represented. The databases should be able to convert between the different formats common to represent the data and between different common units for these.

Furthermore, since all the different properties relevant for one material are probably not always measured for exactly the same material, the database should help the user to find the right properties for representative materials, e.g., if vapor permeability is measured for one variant of a material, but the thermal conductivity is not measured for that variant, the database should help the user to find the most identical material for which the thermal conductivity is known. For instance, it could be another manufacturer's variant of the same material with the same density and same composition of raw materials—or it could be a variant originating from another geographical location or from another period of production.

Formats and Conversion of Properties

A lot of units for the same properties are available when dealing with moisture transfer, e.g., for pressure. Sometimes a conversion is also necessary between quantities that, although not being exactly identical, represent almost similar quantities, e.g., vapor pressure can be translated to vapor concentration. Sometimes an extra parameter, e.g., the temperature, needs to be known in order to make an exact conversion. Tools will be developed that can take care of conversion of units for material properties, both when properties are similar, such as for the different variants of pressure, and when they have to be translated.

New Measurement Techniques and Properties

Different driving potentials have been proposed to model the moisture performance of building materials (e.g., IEA Annex 24, Task 1 [9]). Examples of driving potentials are: relative humidity, moisture content, temperature in combination with one of the other potentials, vapor pressure, vapor concentration, and liquid pressure. It is possible to convert between the different potentials if the sorption curve and the liquid pressure/moisture content relation (or perhaps the pore size distribution) are known. One can usually convert between the potentials if any two of them are known [*10*]. Physically, vapor pressure (Fick's law) and liquid pressure (Darcy's law) are the driving potentials. The other driving potentials, e.g., moisture content, are derived from the basic potentials using some assumptions, e.g., isothermal conditions.

The future will see a need to know the liquid pressure/moisture content relation. Since the pore water in a building material is usually at a negative pressure—tension or suction—it is common to describe the relationship in the form of a suction curve. It will be used as a supplement to the sorption curve. Where the sorption curve describes the moisture content of a material when in contact with humid air, the suction curve will describe the moisture content of a material in contact with liquid water—or with another moist material.

For the thermal conductivity of materials there exists a standard to determine the thermal conductivity of wet materials [*11*]. However, in most cases for building applications, materials are only hygroscopically moist. There is a need to standardize a method to determine the thermal conductivity at moisture contents corresponding to moderate relative humidities in the environment. This problem has been outlined in a technical report for the European Committee for Standardization [*12*].

FAILURE CRITERIA

Database of Moisture Performance Criteria

Different materials have different thresholds to govern their risk of degradation, e.g., in the form of critical moisture content or relative humidity, and probably with some influence of the temperature level. Such performance criteria are often used to compare against model predictions and measurements from practice to deem whether a material or a construction is safe from degradation due to moisture. However, it is believed that there is a need to gather, standardize, and expand on the information that is available. It is therefore anticipated that the future will see the development of databases that contain approved knowledge of moisture degradation criteria for most common building materials.

Stochastic Modeling

As models for analyzing combined heat, air, and moisture transport are becoming common to use and stronger in their capabilities, it will become common in these models to utilize the increasing knowledge of the diversity of the materials' properties. In the future, the properties of materials will be known with their statistical distribution and the models will be able to utilize this knowledge. The result of executing the models will no longer be single moisture content profiles over time but distributions of probable profiles over time. With such profiles the user can make a much better judgment of whether a proposed construction is sound. Examples of using stochastic analysis have been shown by Hokoi and Matsumoto [*13*], and by Salonvaara and Karagiozis [*14*].

Risk Analysis

The result of moisture models that operate with consideration of the stochastic distribution of properties will be probability profiles for moisture content or relative humidity. It will be natural to compare such profiles against criteria for negative impact of the presence and migration of moisture. The results are risk assessments of the adverse effect of moisture. An example of research leading to such risk assessment is shown by Harderup [*15*]. The method is also published in a Swedish moisture tutorial by Nevander and Elmarsson [*16*]. The method to estimate a risk potential is outlined in Fig. 1.

Moisture and Durability in a Life Cycle Perspective

Today, a lot of attention on new buildings and the choice of building material for the buildings is turned on ecological aspects and life cycle assessment (LCA). It could seem that most of the focus is concerned with the choices that affect the building process and the procurement of building materials. However, one of the most important parameters in the assessment is perhaps not offered enough attention in conventional analysis—it is the aspect of durability and specifically how it is affected by the moisture performance. Moisture plays a significant role in most degradation processes, and therefore the moisture performance of building structures should be used as one of the most important parameters also in life cycle assessment of building structures.

It is rather likely that, as moisture modeling and assessment techniques become still more common to use for building designers, these techniques will also be used more systematically in the life cycle assessment of building materials and structures.

Shift of Emphasis from Durable Construction to Focus on Indoor Climate Quality Assurance

The reason today to analyze the moisture performance of building structures is mainly to be able to predict the behavior of the structure itself, i.e., to ensure that it does not degrade excessively fast or is in other ways susceptible to adverse moisture effect. However, today this knowledge is bearing fruit—building owners and buildings codes of many countries demonstrate awareness of how to prevent improper construction techniques, while at the same time using increasingly better thermally performing construction methods. Shortly after the oil crises in the seventies, some unfortunate examples of bad-performing construction methods were seen in cold climate regions, and lessons have been learned so that today we have proper guidelines to show how to construct fail-proof, well-insulated structures.

At the same time, the knowledge of and awareness of the indoor air quality is improving. The moisture content in the building structure and in the indoor air is related to one another, and they both have significance on the processes that degrade indoor air quality. In the years to come, it is expected that more attention will be offered to the relationship between moisture condition and the quality of indoor air. It is anticipated that in the future one will be able to develop the design of building structures such that the indoor air quality, moisture performance of the building envelope, and energy quality of the building design will be optimized.

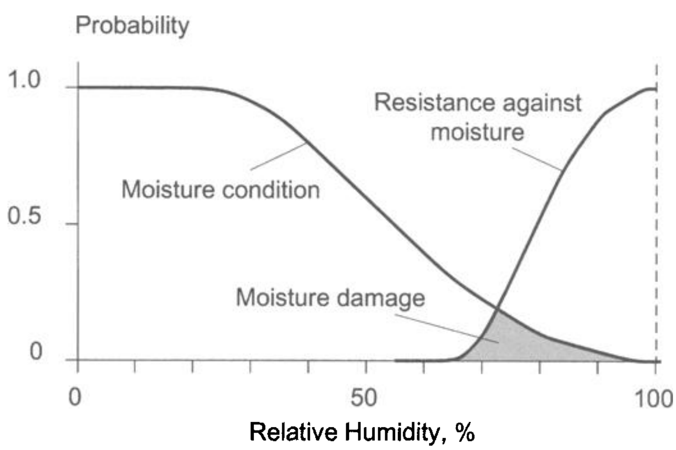

FIG. 1—Distribution curves for "moisture condition" and "resistance against moisture." The curve for moisture condition expresses the probability that the relative humidity in the environment of a material is at or above the actual level. The curve for moisture resistance expresses the probability that the material will decay if it is exposed to a certain relative humidity. Thus, the common area below the curves signifies the risk of moisture damage. After Nevander and Elmarsson [*16*].

ANALYSIS METHODS

Multidimensional Models for Heat and Moisture Transfer

Most building structures have a multidimensional nature, i.e., they are built not only of layers of homogenous materials that extend long in the directions parallel to the wall surfaces. In many cases, this geometrical composition has a significant influence on the hygrothermal performance of the building parts. For instance, it is well known that the moisture conditions can be worse around areas with cold bridges.

It poses no fundamental problem to let this geometrical feature of most building structures be reflected in the tools available to analyze the hygrothermal performance of building structures. Indeed, such multidimensional analysis tools have been available for some years among researchers, e.g., LATENITE, TCCC2D, TRATMO2, WUFIZ, DIM 3.1 and others (for a more complete list see IEA Annex 24, Task1 [*9*]). It is anticipated that these analysis methods will soon be sufficiently well validated and proper user interfaces developed so that the models can be available to design professionals as well proven analysis tools.

Convection Modeling

A lot of resources have been spent on analyzing building structures for their performance to vapor diffusion and possibly to capillary action. Analysis methods and practical guidelines exist to cope with these influences of moisture on building structures. However, from practice it is well known that especially light-weight structures are susceptible to significant impact of moisture by convection, i.e., moisture that is carried in a flow of air passing through the structure.

Today it is only possible to analyze this way of moisture impact under some simplifying assumptions. For instance, for one-dimensional modeling the analysis is limited to that of simple exfiltration or infiltration of humid air passing through a structure. In practice the airflow is most often of a multidimensional nature.

With some of the multidimensional analysis tools that are today available to researchers, it is possible to model the multidimensional nature of convective moisture transport. However, in practice the movement often takes place through non-ideal structures such as gaps and voids that were not planned or that have arisen because of a not optimal fitting of building materials, and because many building materials suffer dimensional change and bending when installed in a natural environment. Furthermore, the boundary conditions that govern the convective transport, i.e., the air pressures, cannot always be predicted with sufficient accuracy. Therefore, the analysis of convective moisture transport is today prone with some assumptions or simplifications necessary to suppose before an analysis can be carried out. The result of the analysis depends on these circumstances.

It is anticipated that in the future the multidimensional analysis methods that can predict convective moisture transport will be available to design professionals. Concurrently it will be necessary to develop guidelines on how to make proper assumptions for different non-idealities that are important to the influence of convective moisture transport. In the long perspective it might be possible to develop good models that can both predict some of the common material deflections and other factors that influence a convective moisture transport, as well as the pressure conditions that in the first place cause the air movements. The latter will require integration with tools for Computational Fluid Dynamics (CFD).

Validation and Benchmark Testing

Tools and analysis methods for moisture flow in building structures are being developed at a large pace these years, and tools are being made available to other than the research community. It is therefore necessary that the tools are well validated. The future will see guidelines or even standards on how to validate a moisture analysis methodology. Concurrently, it is anticipated that data sets for benchmark testing will become available so developers and users of analysis methods can test their method, their skills of using the method, and become aware of limitations of their analysis method.

The European Committee for Standardization, CEN, is planning to develop standards to verify the performance of analysis methods for predicting the moisture behavior of building structures [*17*].

Dissemination and Standardization of Use of Models (Design Tools)

Models to analyze the hygrothermal performance of building structures are being developed and used increasingly within the research community these years. Since the beginning of the 1990s the first of these models have also been available to design professionals and manufacturers of building components [*18*]. Today public tutorials are being held [*19*] and some analysis models are available for free to the public domain [*20*]. Thus, there is strong impetus to get these models used more in practice, and to collect and exchange users' experience with the models. It is anticipated that this will lead to the formation of user's clubs and similar organizations where guidelines for the use of the models, and exchange of experiences can be disseminated in open forums. Work is now on the way within the European Committee for Standardization (CEN) to standardize the characteristics, conditions, and necessary properties of calculation procedures for moisture transfer calculations.

Integration of Models

There is today a strong motion towards integrating the different tools available to design and analyze a building in the planning phase, as well as to operate the building when it is in service. Standardization such as ISO 10303, STEP—Standard for the Exchange of Product Model Data [*21*], and industry-driven organizations such as IAI, Industry Alliance for Interoperability [*22*] are working hard to develop common platforms for exchange of building information. This information spans from building geometry and topology information from CAD tools, over engineering design information for structural and thermal analyses, to information needed for facilities management during operation of the building.

Today, there exists some feasible techniques and platforms to exchange data between the various design tools. The research and development is mainly on procuring one or more data models that can encompass all relevant information about building structures during their life cycle. The information needed for moisture analysis of buildings will certainly be future parts of these data models, but have not been implemented yet, and will most likely be seen as an appendix to the thermal aspect of buildings.

Whole Building Modeling

The amount of, availability of, and common use of building design and analysis tools have been ever increasing since the advent of personal computers, network technology, and user-friendly computer interfaces. Models for whole building thermal analysis, e.g., DOE-2 [*23*] and BLAST [*24*] are today commonly used in building design practices to analyze the thermal performance of building structures. These models are steadily being expanded, e.g., to consider daylighting conditions of buildings and other factors, but they still most often have only a very simple steady state evaluation of the indoor humidity level, neglecting the interaction with the building envelope and the furnishing. However, DOE-2 and BLAST are now being merged as "EnergyPlus" [*25*], and the plans are that the merged model will also be able to consider moisture adsorption and desorption in building elements. A similar development is carried out in Denmark to expand an existing design tool for thermal building simulation with a moisture balance model for the whole building considering the indoor climate, the building envelope, and furnishing [*26*].

Today's moisture analysis tools are still only prepared to analyze the performance of *one* building envelope component given *prescribed* climates on the exterior and interior side of the structure.

It is foreseen that in the future existing modeling capabilities will be integrated further, such that it becomes possible to make an integral analysis of the hygrothermal performance of a whole building. This means that both the thermal and the moisture conditions of the building envelope, internal structures and furnishing, and the indoor climate are predicted concurrently for all elements.

With current and future computational capability it will be possible to analyze all the hygrothermal aspects of a building concurrently. It is anticipated that the building designer will soon have much more capable prediction tools available in normal design practices.

PRACTICE

Knowledge Systems and Design Aids on Contemporary Media

Information technology keeps providing new technology which also the users are increasingly becoming accustomed to take advantage of. Examples of information technologies that are today in common use are the Internet, CD-ROMs, and IT aids are coming in on the construction site with onsite building information.

In this setting, it is anticipated that building designers, constructors, and end-users will have new possibilities available that help them do things right in terms of moisture performance of the building structures. It has already been mentioned how new design tools will further the possibilities for building designers. On-site information technology will increase the builders' awareness of correct construction details and knowledge of which problems to look out for to help future constructions to be fail-proof.

Indoor Climate Types, Ventilation Strategy

One of the most important influences on the building shell to cause moisture problems is the influence from the indoor humidity. It is therefore important to be able to know sufficient about the indoor humidity and to take appropriate steps to make the building envelope able to sustain this influence (or to reduce the humidity level indoors).

As part of this awareness it is anticipated that methods to categorize the humidity level of the indoor environment will be developed and that building structures will be designed accordingly. It is then the responsibility of the building user to keep within the planned humidity levels. Examples of such categorization of the indoor climate humidity level have been shown in IEA Annex 24, Task 2 [*2*], where the indoor climate is categorized in four classes depending on the risk that condensation will form in different types of constructions.

Furthermore, it is anticipated that when choosing a ventilation strategy of a building, it will become more common to optimize the indoor climate's humidity level for the aspects of the well being of the building shell and of the occupants.

Equipment for In-Situ Measurements

For practical conditions there is a need to be able to measure the moisture content of a building material that is installed in a construction under field conditions. Today one typically uses electrical sensors, e.g., electrical resistance gages that are calibrated to indicate the moisture content of a material. However, the calibrations are not always accurate, or limited to some moisture content ranges, and one has to prepare the construction by building in the moisture gages from the beginning or by inserting them into the structure after its erection. Furthermore, the moisture gages are not suited for all kinds of building materials—for instance it makes no sense to use the electrical resistance as a measure of the moisture content if there are salts in the material, e.g., for silicate materials, such as brick and concrete.

There are some non-intrusive techniques available such as for measuring the electrical capacitance or measuring the neutron density. These techniques are mainly used to gage the moisture content of a roof or to estimate the moisture content of a specific material, e.g., a piece of lumber or a silicate material, and to follow relative changes or the moisture conditions over time. The measuring techniques have the drawback that they are not very accurate, they require some experience of the measuring conditions, and are mainly suited for relative measurement (e.g., "dry" or "wet").

Thus, there is a need for, and hopefully the future will bring, some well-calibrated, new and non-intrusive techniques for measuring the moisture content of a material or a structure. There exists a significant commercial potential to further develop such measuring techniques, and therefore there should be good possibilities that the future will see such developments.

Moisture Alert Systems

It is anticipated that future buildings, or renovated existing ones, will have built-in moisture alert systems. This is a direct consequence of the improved possibilities for field monitoring of the moisture condition of the building envelope and the anticipated information systems that can guide the building user or the building service technician. The purpose is that in the future it will be possible to repair and limit damages from the intrusion of moisture before it becomes too dangerous for the building shell. As information technology and automation systems become relatively cheaper, and as it will probably remain expensive to repair after moisture damages, the economic advantages are obvious.

New Techniques for Building Renovation and Retrofit, and Dissemination of Knowledge About Existing Techniques

For many reasons there will remain a desire to preserve existing buildings—especially in specific areas. Therefore, there will remain an impetus to repair, renovate and improve existing building constructions. However, it is not always sufficiently economical to renovate existing buildings. It is therefore anticipated that, just as for constructing new buildings, new techniques, prefabricated systems and knowledge systems will be developed to improve and make the building renovation process cheaper.

Not the least, this is the case when renovating after moisture damages. Here the problem is that the consultant does not always know exactly which way to renovate is the safest and at the same time the most economical. There is a great need for guidelines, information systems and diagnostic techniques that can assist the consultant in these situations. It is anticipated that such possibilities will be further developed in the future.

"Self-Drying" Concepts

So far, it has been common in many cases, for instance for flat roofs, to use tight membranes as the way to ensure constructions that can endure the influence of moisture from the outdoor weather and from the indoor influence. For many years, this may work well, but when moisture intrudes into the construction, as somehow it often does in practice, it cannot escape, and still the user might not notice that the construction is damaged by moisture as long as the membranes hold tight. All along, the materials and the thermal performance of the structure are degrading.

Both for new construction and for renovation it is therefore anticipated that a shift towards self-drying construction principles will be seen where otherwise moisture tight construction has been used. In self-drying constructions at least one of the tight membranes is replaced by another material, or a combination of materials, that will allow a possible accumulation of moisture to escape from the construction under some seasonal conditions. A pre-requisite is that constructions are designed such that the annual possibility of drying is larger than the annual accumulation of moisture. Examples of self-drying construction are being developed by Kyle and Desjarlais [27], and examples of materials for such constructions are the water permeable vapor retarder (Hygrodiode) of Korsgaard [8], and the "Feuchteadaptive Dampfbremse" of Künzel and Kaufmann [28]. Another construction type, utilizing both a moisture detection mechanism and the possibility of drying even impermeable insulation materials by mechanical ventilation, has been developed by Rudbeck [29].

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Appendix 1—Computer Models

CONTENTS

This Appendix is part of "Advanced Numerical Models for Hygrothermal Research," Chapter 6, authored by Achilles N. Karagiozis. In the Appendices, numbered from A to K, 11 advanced hygrothermal models are presented. Each author of the model was contacted to provide specific information. The models are first described, followed by details on boundary conditions and limitations. A demonstration case was included to display an example on how the model was used to examine an advanced hygrothermal issue.

APPENDIX A

Model Name: WUFI
Author: Hartwig Kuenzel[1]

Model Description:
WUFI [1] is a menu-driven PC program that allows realistic calculation of the transient hygrothermal behavior of multi-layer building components exposed to natural climatic conditions. It is based on the newest findings regarding vapor diffusion and liquid transport in building materials. WUFI requires only standard material properties and easy-to-determine moisture storage and liquid transport functions. The program can be used for assessing the drying time of masonry with trapped construction moisture, the danger of interstitial condensation or the influence of driving rain on exterior building components. It can help to analyze the effect of repair and retrofit measures or the hygrothermal performance of roof and wall assemblies under unanticipated use or in different climate zones. It is a tool for developing and optimizing building materials and components, e.g., WUFI simulations have led to the development of a smart vapor retarder [2].

Equations of State:

Moisture balance

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot (D_\phi \nabla \phi + \delta_p \nabla(\phi\, p_{sat})) \qquad (1)$$

Energy balance

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla(\phi\, p_{sat})) \qquad (2)$$

where ϕ = relative humidity, t = time, T = temperature, c = specific heat, w = moisture content, p_{sat} = saturation vapor pressure, λ = thermal conductivity, H = total enthalpy, D_ϕ = liquid conduction coefficient, δ_p = vapor permeability, h_v = latent heat of phase change.

[1] Director, Hygrothermics, Fraunhofer Institute in Bauphysics, Holzkirchen, Germany.

Boundary Conditions: Indoor and outdoor air temperature, relative humidity; direct and diffuse solar radiation; precipitation, wind speed and direction (opt.: clear sky radiation, driving rain).

Limitations:
Hysteresis of the moisture retention curve is not taken into account. Airflow by total pressure differences is not included. The influence of ice formation on enthalpy and liquid transport is accounted for but not its effect on thermal conductivity.

Application Example:
The program was validated with experimental results in many cases. An example of the one-dimensional validation is shown in Fig. A-1 examining the moisture behavior of an exposed natural stone wall. The course of the total water content after exposition of the initially dry wall samples (left) and the moisture profiles in the wall sample 2 (right) at two distinct points in time (measured by NMR scanning) show good agreement between experiment and calculation. Climate conditions recorded as hourly values during the experiment and material properties determined by laboratory tests before exposure to the natural climate were used for the WUFI simulation.

As an example for a two-dimensional calculation Fig. A-2 (left) shows the moisture distribution in the vicinity of a mortar joint between two differently orientated anisotropic sand stones (layer structure results in directionally different water absorption) of an exposed masonry wall. The results show the rapid water absorption of the mortar during driv-

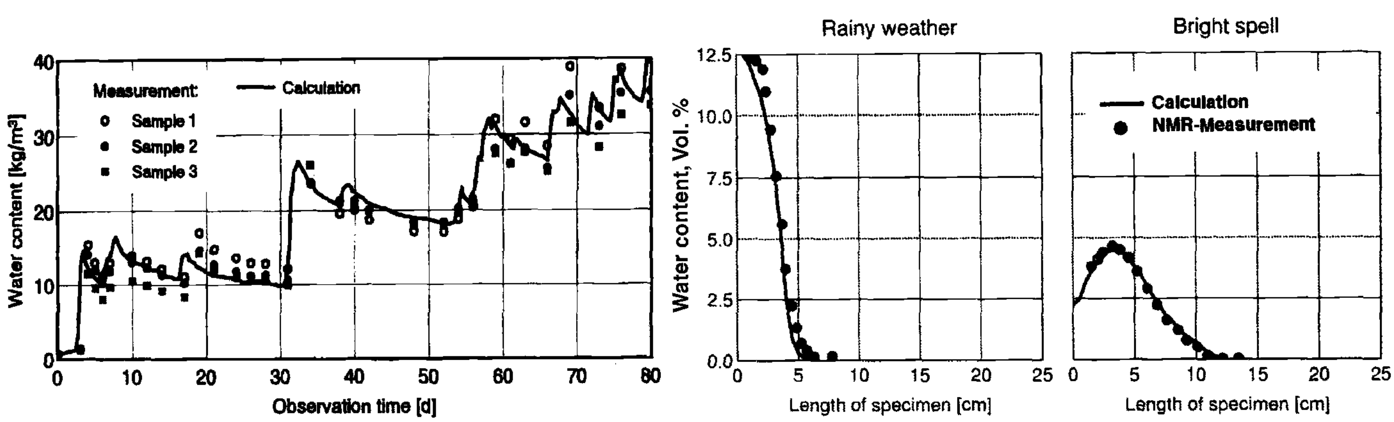

FIG. A-1.

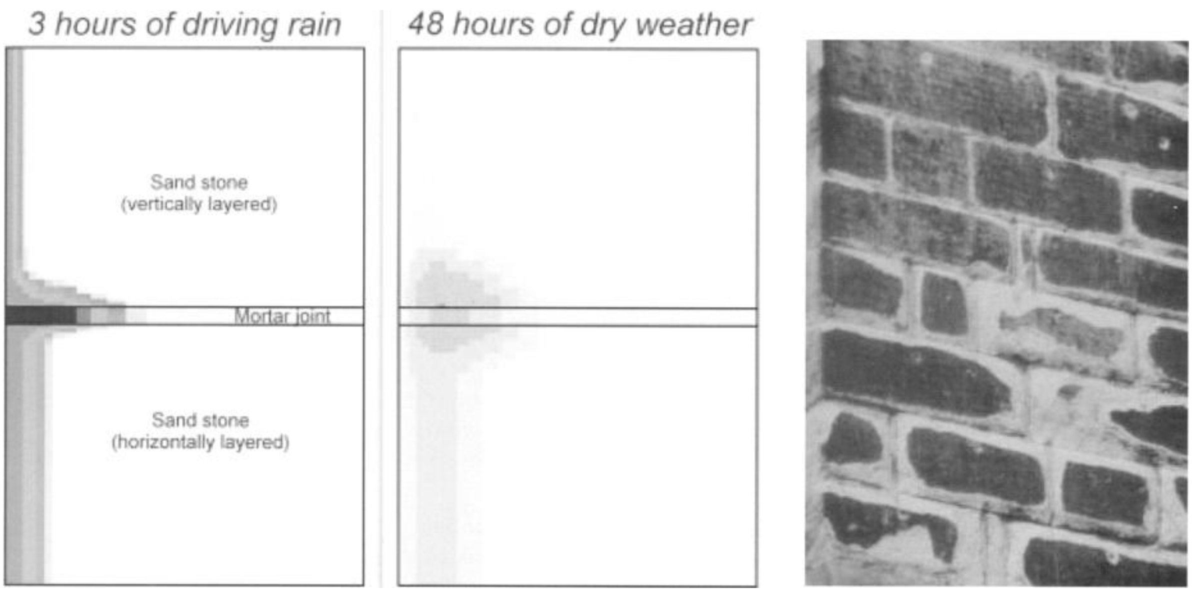

FIG. A-2.

ing rain impact. This is due to the higher porosity of the mortar compared to the sand stone, which facilitates water infiltration but also drying by vapor diffusion. Therefore, the mortar dries faster than the adjacent stone, which retains moisture spots at its flanks even after long periods without rain. It is exactly at these locations that frost or salt-induced damage is observed in practice, as for example at the Cologne Cathedral in the photograph next to the 2D calculation results.

In addition to these application examples, WUFI has been benchmarked for exposed brick walls, masonry with exterior insulation, cathedral ceilings, aerated concrete roofs, inverted roofs with greenery, etc. Some benchmark tests have been carried out by independent specialists from universities and research institutions. WUFI has been continuously upgraded since it has been made public in 1994. Currently there are one- and two-dimensional professional PC versions available. Special versions of WUFI designed for research and teaching purposes are distributed free of charge for noncommercial applications. For further information please refer to http://www.wufi.de.

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APPENDIX B

Model Name: MOISTURE-EXPERT

Author: Achilles Karagiozis[1]

Model Description:
MOISTURE-EXPERT [*1*] is a Fortran program that allows the 2-D calculation of the transient hygrothermal behavior of multi-layer building components and is customized for climatic conditions in North America. The uniqueness of the model is the inclusion of temperature-dependent sorption isotherm, and capability to handle wind-driven rain. The model was developed to evaluate the performance of any wall, roof, and basement configuration. Two systems of transport equations have been employed, one based on vapor pressure and capillary pressure and the other based on vapor pressure and relative humidity. This model is a research model and has capabilities to model complete buildings by including each wall assembly, roof and basement, and coupling an indoor air quality model. The model can also incorporate system and sub-system effects, such as those determined by experimental means. Moisture sinks and sources can be easily introduced to any building envelope assembly.

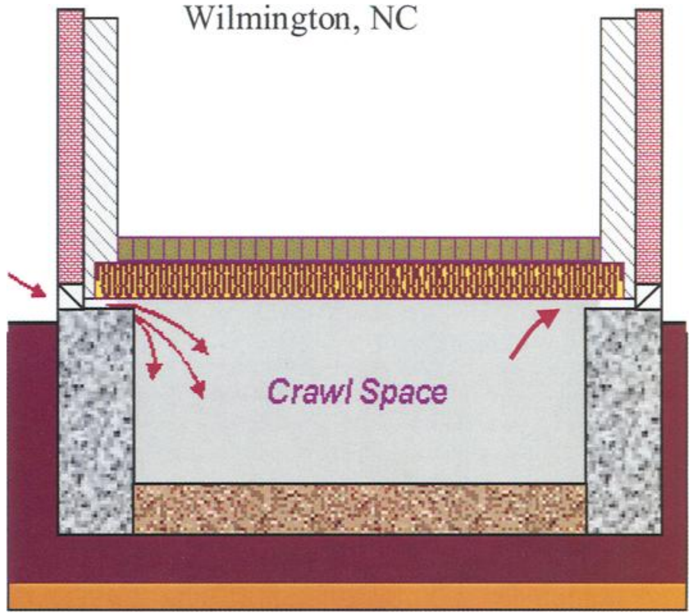

FIG. B-1—Crawl-space geometry.

Equations of State:

Moisture balance

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot (D_{\phi} \nabla \phi + \delta_P \nabla(\phi\, p_{\text{sat}}) - u\, \rho_v) \tag{1}$$

Energy balance

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot (\delta_p \nabla(\phi\, p_{\text{sat}})) - \rho_a u c_p \nabla T + S \tag{2}$$

Airflow

$$\frac{\partial(\rho u)}{\partial t} = -\nabla \rho u \cdot u - \nabla P - \eta \nabla^2 u + F$$

where ϕ = relative humidity, t = time, T = temperature, c = specific heat, w = moisture content, p_{sat} = saturation vapor pressure, λ = thermal conductivity, H = total enthalpy, D_{ϕ} = liquid conduction coefficient, δ_p = vapor permeability, h_v = latent heat of phase change, cp = specific heat of fluid, ρ_a = density of fluid, where u is the velocity vector (m/s), P is pressure (Pa), η is the dynamic viscosity (s · Pa), and F is the body force per unit volume (N/m^3); ρ_v = vapor density and S = volumetric heat source or sink.

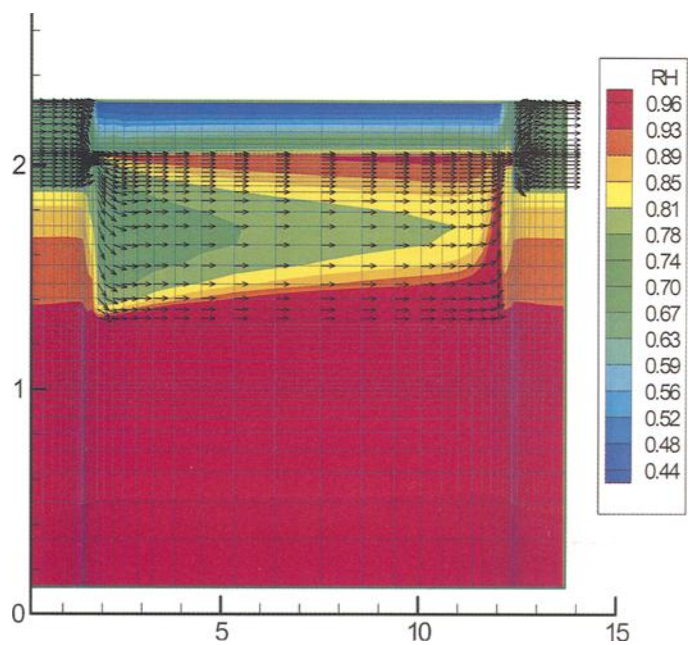

FIG. B-2—2-D relative humidity distribution.

Boundary Conditions: Indoor and outdoor air temperature on any time interval, relative humidity; direct and diffuse solar radiation; precipitation, wind speed and direction,

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pressure differences or prescribed mass flows (opt.: clear sky radiation, driving rain). Moisture-Expert version 1.0 incorporates an indoor environment model that includes moisture generation rates by inhabitants, interior pressure schedules, ventilation exchange rates, sorption and moisture release from interior finishing.

Limitations:
The model is not user friendly, an interface does not exist, and the model is a research model. Hysteresis of the moisture retention curve is not taken into account. The model is computationally very slow, as it includes the convective and diffusion resistances when the full Navier Stokes equations are solved. Darcy's equations can also be used. Limited material properties are currently available. Validation on a array of test cases of varying complexities are being performed.

Application Example:
Many design guidelines have been generated from the use of MOISTURE-EXPERT for stucco-clad wall systems (city of Seattle), retrofitting masonry wall systems (Boston), and currently in the investigation of the ventilation effectiveness in crawlspaces. For an application case of the model, the complex moisture transport in crawlspaces in Wilmington, NC (Karagiozis 2001) was chosen [2]. The model simulates the effect of air openings in a crawlspace and evaluates the option of closing these vents. Climate conditions used were hourly temperatures, relative humidities, solar radiation, and wind-driven rain on the ground surface as well as on the walls of the crawlspace. For each orientation, the values of solar radiation and air pressure were accounted for. Full functional form of the material properties were used in the application example.

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APPENDIX C

Model Name: SIMPLE FULUV
Author: Øyvind Økland[1]

Model Description:
The hygrothermal computer model SIMPLE-FULUV was developed to investigate natural and forced convection in timber frame walls. The work was part of a doctoral thesis project[2]. The model is now strictly a research tool. The simulation model is capable of solving two-dimensional heat, air, and moisture problems. Both vapor and liquid moisture transport are included. The material properties are changing with the moisture content and temperature. The model uses the SIMPLE algorithm developed by Patankar to solve the equation of state.

In the SIMPLE algorithm the momentum, energy, continuity, and moisture conservation equation is expressed in one equation. When the momentum equation is solved, the pressure gradient is included and treated specially. SIMPLE-FULUV is based on a finite difference method. The calculation area is divided in control volumes. The correct convergence is guaranteed by averaging neighboring velocities.

Equation of State:

Moisture balance

$$\xi_U \cdot \frac{\partial(\rho_\phi)}{\partial t} + \frac{\partial}{\partial x}(\rho u X_v) + \frac{\partial}{\partial y}(\rho v X_v) = \frac{\partial}{\partial x}\left(D_v \cdot \rho \frac{\partial X_v}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_v \cdot \rho \frac{\partial X_v}{\partial y}\right) + S \quad (1)$$

Energy balance

$$c_m \frac{\partial \rho_m T}{\partial t} + c_a \frac{\partial}{\partial x}(\rho u\ T) + c_a \frac{\partial}{\partial y}(\rho v T) = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + S \quad (2)$$

Momentum in v-direction

$$\frac{\partial \rho v}{\partial t} + \frac{\partial}{\partial x}(\rho u v) + \frac{\partial}{\partial y}(\rho v v) = \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) - v \frac{\mu}{B_{oy}} - \frac{\partial P}{\partial y} + \rho g_o \quad (3)$$

Continuity of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) = 0 \quad (4)$$

where B_o = specific permeability, c = heat capacity, D = diffusion coefficient, g_o = acceleration of gravity, P = pressure, S = source term (includes condensation and evaporation), T = absolute temperature, t = time, X_v = moisture content, v and u = velocity, ξ_U = moisture capacity, λ =

[1]The Research foundation POLYTEC, Smedasundet 77, 5527 Haugesund, Norway.
[2]Publication: Økland, 1998, *Convection in Highly-Insulated Building Structures*, NTNU, Trondheim, Doctoral thesis, ISBN 82-471-0292-7, ISSN 0802-3271.

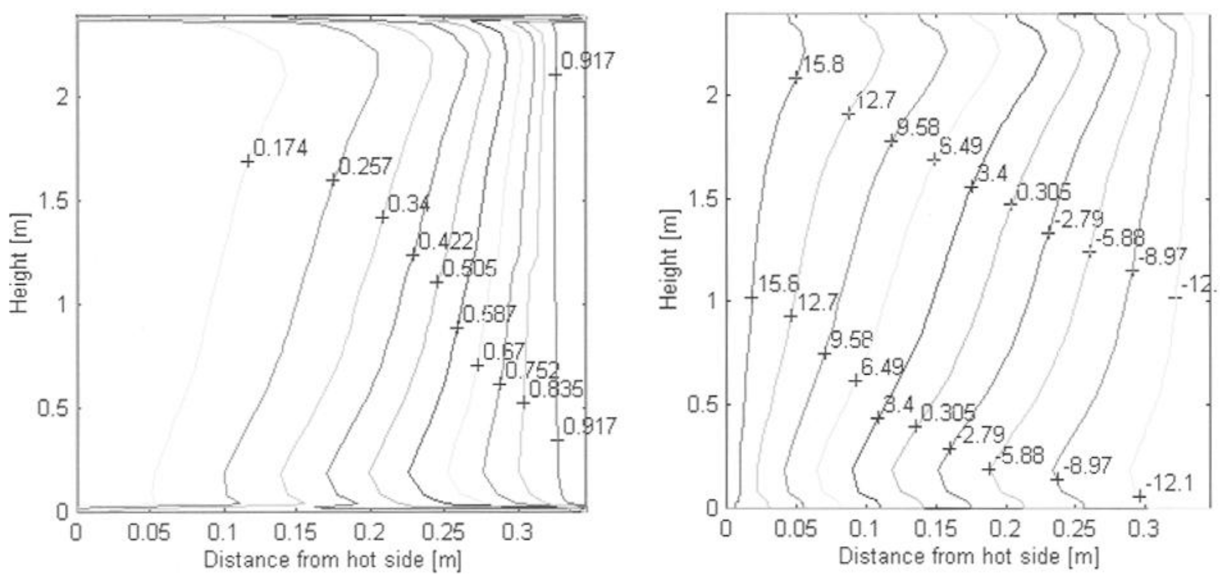


FIG. C-1—The relative humidity (%/100) and temperature (°C) for a timber frame wall influenced by natural convection.

thermal conductivity, ρ = density, μ = dynamic viscosity, x and y = the coordinate directions.

Boundary Conditions: Interior and exterior temperature, relative humidity, wind speed.

Limitations: Deformation of the porous structure caused by the ice content changes is neglected. Hysteresis of sorption material properties and over-cooling is not taken into account.

Verification: Climate chamber measurements with highly insulated walls have been conducted to verify the model. The walls were timber frame walls of wood with permeable glass fiber insulation. Air gap defects have been placed in different parts of the insulation. The walls had airtight boundary materials with a cold and hot side to study natural convection effects in the wall cavity. The simulations were in reasonable agreement with the measurements considering the difficulties to measure all the physical effects that occurred in real walls.

APPENDIX D

Model Name: TRATMO2 (Transient Analysis of Thermal and Moisture behavior of 2D-structures)

Author: Mikael H. Salonvaara[1]

Model Description:
The program calculates numerically the transient heat and moisture transfer in one- or two-dimensional building structures. The mechanisms by which heat are transferred in materials are conduction, convection in porous materials and cracks, radiation through transparent insulation, phase changes of moisture, and phase change materials. Moisture can be transferred by diffusion and convection in the gas phase and by liquid flow.

Equations of State:

Moisture balance

$$\rho_0 \frac{\partial u}{\partial t} = - \nabla \cdot q_m$$

$$q_m = - \rho_0 D_w \nabla u - \lambda_D \nabla p_v + v\rho_v$$

Energy balance

$$q = -\lambda \cdot \nabla T + \rho v c_{pa} T$$

$$C''' \frac{\partial T}{\partial t} = - \nabla \cdot q + S$$

[1] Research scientist, VTT Building Technology, Espoo, Finland.

$$S = \begin{cases} -\nabla q_{mv,\Lambda}, \text{ moisture condensation/vaporization} \\ -\rho\Lambda_{sl} \dfrac{\partial f_l}{\partial t}, \text{ solid/liquid phase change (ice, PCM)} \end{cases}$$

Phase changes in materials are handled using a method that has its origin in the so-called enthalpy method [2,3].

Mass balance for air

$$\text{(Darcy) } \nabla \cdot \vec{v} = 0; \cdots \vec{v} = - \frac{K}{\mu} (\nabla p + \rho g \vec{k})$$

(Navier-Stokes)

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} + \frac{\mu}{K} u = - \frac{\partial p}{\partial x} + \mu' \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \rho g \vec{k}$$

$$\rho \frac{\partial v}{\partial t} + \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} + \frac{\mu}{K} v = - \frac{\partial p}{\partial y} + \mu' \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \rho g \vec{k}$$

Solution method for NS-equations is a non-iterative PISO-method [1] that maintains mass balance by coupling it together with pressure equations.

Boundary Conditions:
Ambient temperature (interior and exterior), vapor pressure or relative humidity, solar and sky radiation: direct, diffuse,

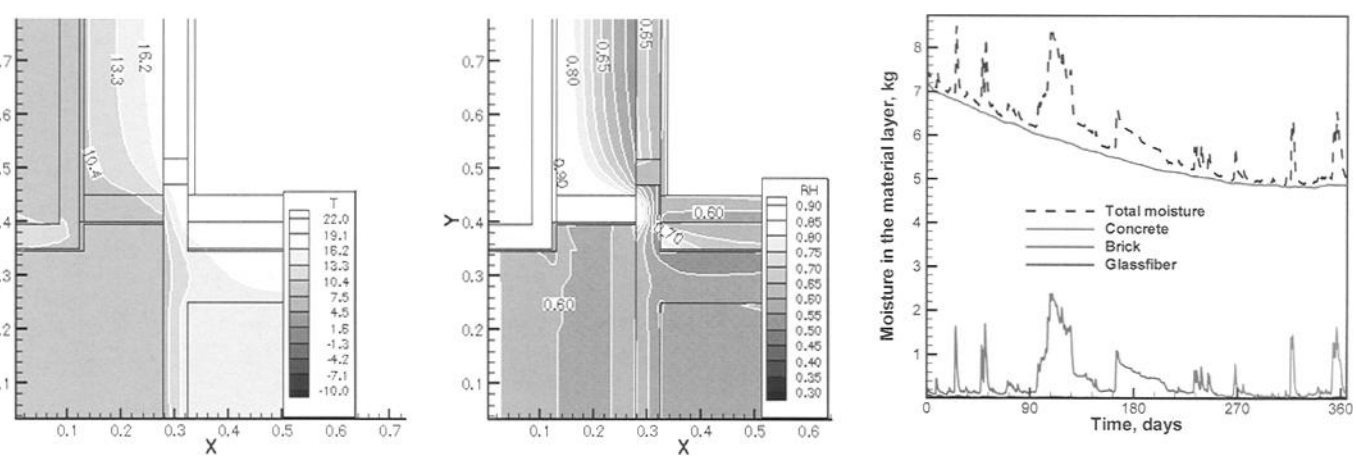


FIG. D-1—Simulated relative humidity in a wall/floor detail (a) and the amount of moisture in different material layers as a function of time (b).

and reflected, wind velocity and direction, precipitation, pressure (including stack effect).

Limitations:
No hysteresis, no gravity-induced liquid flow, lumped characteristics for transparent insulations. No user-friendly interface for inputting data.

Application Example (floor and exterior wall detail): The model has been used for research purposes only. The example demonstrates yearly hygrothermal analysis of a wall and floor detail.

References

[1] Issa, R. I., "Solution of the Implicitly Discretized Fluid Flow Equations by Operator-Splitting," *Journal of Computational Physics*, Vol. 62, 1985, pp. 40–62.
[2] Voller V. R., "Fast Implicit Finite-Difference Method for the Analysis of Phase Change Problems," *Numer. Heat Transfer, Part B*, Vol. 17, 1990, pp. 155–169.
[3] Ojanen, T. and Salonvaara, M., *Numerical Simulation of Structures with Transparent Thermal Insulations and Phase Change Materials*, Espoo. VTT, 1992, ETRR-Report 14, 70 p., + app. 10 p. Laboratory of Heating and Ventilation.

APPENDIX E

Model Name: TCCC2D (Transient Coupled Convection and Conduction in 2D structures)

Author: Tuomo Ojanen[1]

Model Description:
The first version of this program was presented in 1988 and has been improved since then continuously. This model calculates two-dimensional heat, air, and moisture transfer in multi-layer building structures. The material properties are functions of temperature and moisture content. Phase change of moisture (and also in general) is taken into account. The model solves mold growth index developed by Viitanen [*1*], which shows the risks for mold growth on material surfaces and can be used as one criteria for the moisture-caused risks. The model is described in detail by Ojanen [*2*].

Equations of State:

Darcy flow equation

$$\vec{v} = -\frac{K}{\mu}(\nabla p + \rho g \vec{k})$$

Moisture balance equations

conservation $\rho_0 \frac{\partial u}{\partial t} = -\nabla q_m,$ and

moisture transfer $q_m = -\delta_p \nabla p_v + v_f \rho_v$

Energy balance

$$C''' \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) - (\rho v c_p)_f \nabla T + S$$

where ρ = density, v = air flow velocity, K = air permeability (m^2), u = moisture content (kg/kg), q_m = moisture mass flow rate (kg/s m^2), δ_p = moisture diffusivity (kg/s m^2 Pa), C''' = volumetric thermal capacity (J/K m^3), λ = thermal conductivity (W/Km), T = temperature (K), S = source term (W/m^3), subscript f refers to fluid (air) flow and 0 to solid material.

Boundary Conditions: Interior and exterior temperature, relative humidity, solar radiation, cloud cover, stack effect, wind speed, wind orientation, pressure difference over the structure.

Limitations:
Moisture flow is presented by diffusion-type equation, where the total moisture diffusivity includes also liquid flow driven by partial vapor pressure difference. Pure capillary moisture flow and hysteresis are not taken into account. Wind-driven rain is an approximation of surface wetting.

Application Example—Analysis of Mold Growth During Air Exfiltration:
This model was applied in a case with continuous indoor air flow (exfiltration) through a timber frame wall (Fig. E-1). The inside air had constant temperature, +22 °C, and moisture load caused constant + 4 g/m^3 increase compared to outdoor air conditions. The outdoor climate conditions were hourly values of Jyväskylä in Central Finland.

Cases with two air flow rates (0.1 and 0.01 L/sm) and two different exterior boards (plywood 9 mm or porous woodfiber board 12 mm) were analyzed. In one case the plywood sheathing had open, 30 mm thick exterior mineral wool insulation layer. The analysis was done for a 480-day period starting from Sept. 1. The numerically predicted mass of moisture in the wall structure (per area unit, kg/m^2) is presented in Fig. E-2, and the local maximum mold growth index on the warm surface of the exterior boards is presented in Fig. E-3. The index can have values between 0 to 6, where 6 indicates to maximum mold growth on a surface, Index 1 is the limit for first microscopical signs for biological growth, and Index 3 is the lower limit value for visible mold growth.

Exterior insulation improved the drying of the wall with plywood sheathing, but only in the case with porous woodfiber board, and 0.01 L/(sm) airflow rate the mold growth index stayed in a safe level.

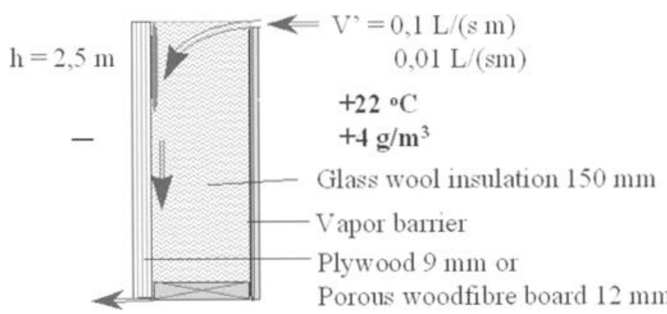


FIG. E-1—Wall section with continuous and constant air exfiltration used in the numerical analysis.

[1] Senior research scientist, VTT Building Technology, Building Physics, Finland.

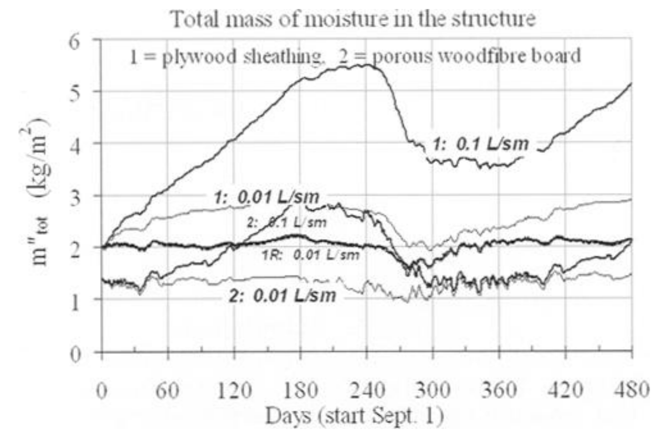


FIG. E-2—Numerically predicted total mass of moisture in the analyzed wall structure (mass per unit area) during 480 days of air exfiltration. The exterior sheathing was either plywood or porous woodfibre board and the airflow rates were 0.1 or 0.01 L/(sm). In case IR, the wall had plywood sheathing with 30 mm thick exterior insulation layer.

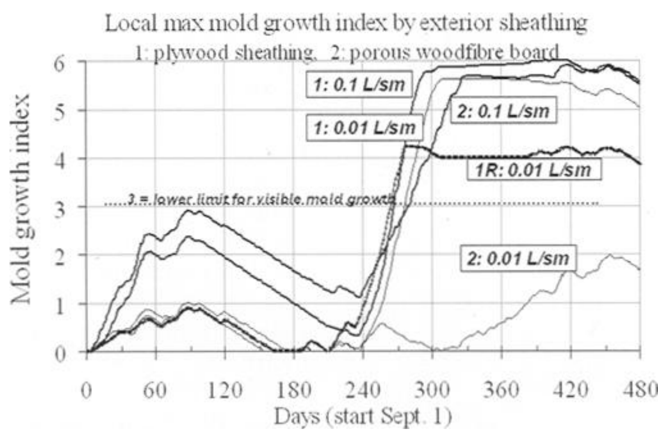


FIG. E-3—Numerically predicted mold growth index during 480 days of air exfiltration. The exterior sheathing was either plywood or porous woodfiber board and the air flow rates were 0.1 or 0.01 L/(sm). In case IR the wall had plywood sheathing with 30 mm thick exterior insulation layer.

References

[1] Viitanen, H., "Factors Affecting the Development of Mould and Brown Rot Decay in Wooden Material and Wooden Structures. Effect of Humidity, Temperature and Exposure Time," The Swedish University of Agricultural Sciences, Uppsala, 1996.

[2] Ojanen, T., Kohonen, R., and Kumaran, M. K., "Modeling Heat, Air and Moisture Transport through Building Materials and Components," *ASTM Manual Series MNL 18, Moisture Control in Buildings*, H. R. Trechsel, Ed., Philadelphia, 1994, pp. 18–34.

APPENDIX F

Model Name: HMTRA (Heat Mass Transient Analysis)
Authors: D. Gawin[1] and B. A. Schrefler[2]

Model Description:

This program calculates two-dimensional heat and moisture transfer in deformable soils and building elements, including also high-temperature regimes for concrete. Hygro-thermal and mechanical processes are considered as a three-phase system including gaseous, liquid, and solid phases. Full coupling between hygro-thermal (i.e., capillary and gas pressure temperature) and mechanical (i.e., stress tensor) fields is taken into account by means of the effective stress principle. Material damaging effects arising from the coupled hygro-thermal and mechanical interaction are regarded by use of the isotropic non-local damage theory. An effect of damage (material cracking) on material permeability and sorption isotherms hysteresis is taken into account. The model is described in detail in the following publications by Gawin and Schrefler[3] and Gawin et al.[4] and is a mechanistic model.

Governing equations:

Dry air mass balance: $$\frac{\partial}{\partial t}[\phi(1 - S)\rho_{ga}] + \nabla \cdot (\rho_{ga} v_g) - \nabla \cdot (\rho_g v^d_{gw}) = 0$$

Moisture mass balance: $$\frac{\partial}{\partial t}[\phi(1 - S)\rho_{gw}] + \nabla \cdot (\rho_{gw} v_g) + \nabla \cdot (\rho_g v^d_{gw}) = -\frac{\partial}{\partial t}[\phi S \rho_1] - \nabla \cdot (\rho_1 v_1) - \dot{m}_d$$

Energy balance: $$\rho C_p \frac{\partial T}{\partial t} + [C_{pw}\rho_w v_1 + C_{pg}\rho_{gw} v_g]\nabla T - \nabla \cdot (\lambda_{\text{eff}} \nabla T) = \Delta h_{\text{vap}} \left[\frac{\partial(\phi \rho_1 S)}{\partial t} - \nabla \cdot (\rho_1 v_1) - \dot{m}_d\right] + \Delta h_d \dot{m}_d,$$

Linear momentum balance: $$\nabla \cdot [\sigma'' - \alpha(S p_1 + (1 - S)p_g)I] + \rho g = 0$$

where ρ = density, t = time, T = absolute temperature, Φ = porosity, S = saturation, C_p = isobaric specific heat, v = velocity, $\dot{m}_d$ = dehydration mass source, λ = thermal conductivity, Δh = enthalpy of phase change, $g\pi$ = acceleration of gravity, α = Biot's constant, σ'' = effective stress tensor, suffices: l = liquid water, g = gas, s = solid skeleton, gw = water vapor, ga = dry air, eff = effective (for the whole medium), vap = evaporation, d = dehydration.

Boundary Conditions: Interior and exterior temperature, radiation, relative humidity, gas pressure and mechanical load or mechanical constraints.

Limitations:

Freezing is not regarded, only elastic material with isotropic damaging is considered.

Application Example (analysis of concrete heating during fire):

This model is a research model and has been used mainly for R&D purposes. Model was validated for several building and geo-materials. The material parameters for various types of HP and UHP concrete were measured in several European laboratories participating in the BRITE EURAM III "HITECO" project. The code was also calibrated with some experimental data concerning high temperature behavior of concrete walls, columns, and special structures, e.g., tunnel sectors and nuclear waste containers. Below are presented results concerning temperature, relative humidity and damage distribution in a cylindric sample after 10 min of heating during fire. They are used for predicting of an explosive spalling phenomenon.

[1] Associated professor, Department of Building Physics, Technical University of Lodz, Poland, D.Sc. Eng.
[2] Professor, Department of Structural and Transportation Engineering, Unviersity of Padua, Italy, D.Sc. Eng.
[3] Publication 1996: Thermo-Hydro-Mechanical Analysis of Partially Saturated Porous Materials, *Engineering Computations*, Vol. 13, No. 7, pp. 113–143.
[4] Publication 1999. "Numerical Analysis of Hygro-Thermic Behaviour and Damage of Concrete at High Temperature," *Mech. Cohes. Frict. Mater.*, Vol. 4, pp. 37–74.

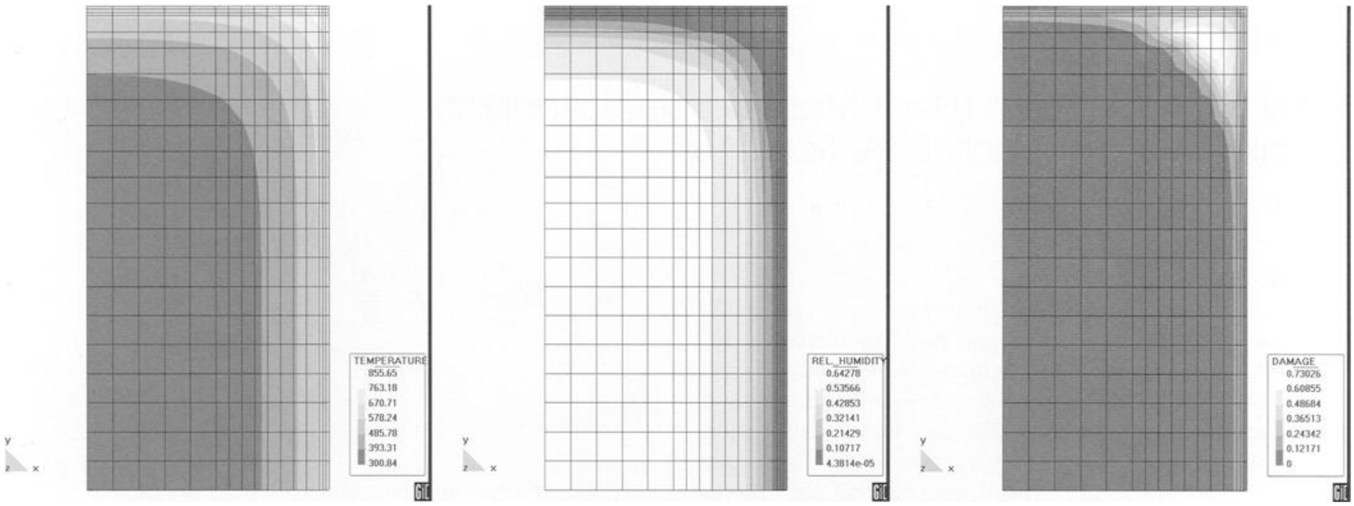

TEMPERATURE
855.65
763.18
670.71
578.24
485.78
393.31
300.84
REL._HUMIDITY
0.64278
0.53566
0.42853
0.32141
0.21429
0.10717
4.3814e-05
DAMAGE
0.73026
0.60855
0.48684
0.36513
0.24342
0.12171
0

FIG. F-1.

APPENDIX G

Model Name: DIM3.1

Author: John Grunewald[1]

Model Description:
DELPHIN.4 calculates two-dimensional transient heat, air, and moisture transfer in porous materials. The physical model below is described in [*1*] and the usage of the program is documented in [*2*]. A download of the program-inclusive documents is possible from ftp://141.30.41.194.

Equations of State:

Moisture mass balance

$$\frac{\partial}{\partial t}[\rho_w\theta_1 + \rho_v\theta_g] = -\frac{\partial}{\partial x_k}[(\rho_w v_k^{m_1} - j_{k,\mathrm{disp}}^{m_s} - j_{k,\mathrm{diff}}^{m_s})\theta_1 + (\rho_v v_k^{m_s} + j_{k,\mathrm{diff}}^{m_v})\theta_g] \quad (1)$$

Air mass balance

$$\frac{\partial}{\partial t}[\rho_a\theta_g] = \frac{\partial}{\partial x_k}[(\rho_a v_k^{m_s} - j_{k,\mathrm{diff}}^{m_v})\theta_g] \quad (2)$$

Energy balance

$$\frac{\partial}{\partial t}[\rho_m u_m + \rho_p u_p\theta_p + \rho_l u_l\theta_l + (\rho_v u_v + \rho_a u_a)\theta_g] = -\frac{\partial}{\partial x_k}[\rho_l u_l v_k^{m_1}\theta_1 + (\rho_v u_v + \rho_a u_a)v_k^{m_s}\theta_g] - \frac{\partial}{\partial x_k} \times [j_{k,\mathrm{diff}}^{Q} + (h_s - h_w)(j_{k,\mathrm{disp}}^{m_s} + j_{k,\mathrm{diff}}^{m_s})\theta_1 + (h_v - h_a)j_{k,\mathrm{diff}}^{m_v}\theta_g] \quad (3)$$

[1] Institute of Building Climatology, University of Technology Dresden, Germany, Dr.-Ing, e-mail:grunewald@ibk.arch.tu-dresden.de

where:

Advective flux of the liquid phase

$$\rho_l v_k^{m_1} = -K_l\left[\frac{\partial p_l}{\partial x_k} + \rho_l g_k\right]$$

Water vapor diffusion

$$j_{k,\mathrm{diff}}^{m_v} = -\rho_g D_{vn}\frac{\partial c_v}{\partial x_k} - \frac{D_{vp}}{R_g T}\frac{\partial p_g}{\partial x_k}$$

Advective flux of the gaseous phase

$$\rho_g v_k^{m_s} = -K_g\left[\frac{\partial p_g}{\partial x_k} + \rho_g g_k\right]$$

Reduced heat flux

$$j_{k,\mathrm{diff}}^{Q} = -\gamma\frac{\partial T}{\partial x_k}$$

Boundary Conditions:
Temperature, relative humidity, wind velocity, wind direction, air pressure, long wave and short wave solar radiation, driving rain, water contact, ground water pressure.

Limitations:
The deformation of the porous structure caused by the salt crystallization is neglected, influence of salt on hygric material properties is not included. Hysteresis is not taken into

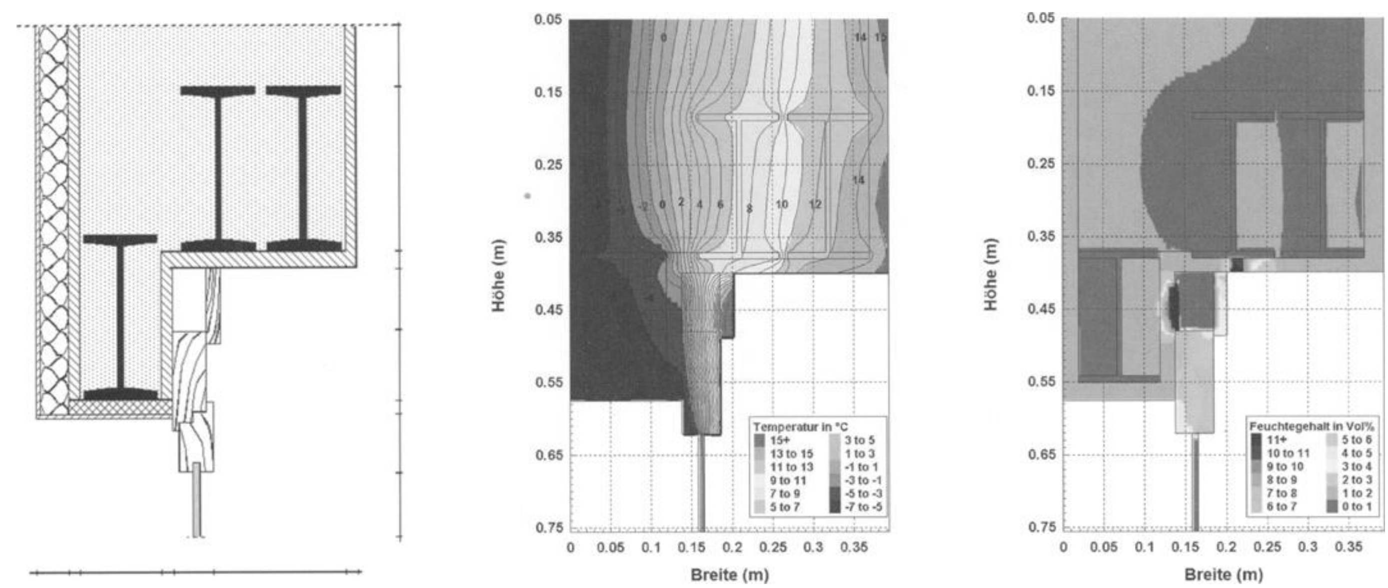


FIG. G-1.

account. Non-equilibrium moisture distributions in the pore space are also not accounted for.

Application Example (condensation problem, coupled heat and moisture calculation):
DELPHIN4.1 has been used mainly for R&D purposes but also for practical applications. The figures demonstrate the moisture accumulation in the area of a window lintel. The ambient air of temperature 20°C and R.H. of 60%, with exterior conditions of −10°C and R.H. of 80%. Results show the temperature and the moisture distribution after 60 days.

References

[*1*] Grunewald, J., Plagge, R., and Houvenaghel, G., *Modelling of Coupled of Coupled Heat, Air, Moisture and Salt Transfer in Porous Building Materials*, Vol. 2 of the final report of the Brite-Euram Project BRPR-96-0229: Development of a New Methodology to Analyse the Durability of Facade Repair and Retrofitting Systems, Technical University of Dresden, Germany, 1998.

[*2*] Grunewald, J, Plagg, R., and Roels, S., *Full Documentation of the Numerical Simulation Program DIM3.1*, Vol. 5 of the final report of the Brite-Euram Project BRPR-96-0229, Development of a New Methodology to Analyse the Durability of Facade Repair and Retrofitting Systems, Technical University of Dresden, Germany, 1999.

APPENDIX H

Model Name: 2DHAV
Author: Arnold Janssens[1]

Model Description:[1]
The model is a two-dimensional calculation tool to predict the effects of air movement on the thermal and moisture performance of multi-layered building components. The model describes a building component as a general two-dimensional assembly of continuous porous materials and discrete air channels, which are interconnected and saturated by humid air (Fig. H-1). It allows specification of complex airflow paths consisting of cracks, gaps, and permeable materials. The numerical calculation method provides the airflow rates, temperatures, relative humidities, moisture content, and condensation flow rates at a finite number of control volumes in the calculation domain.

Equations of State (Porous domain):

AIR:
$$\frac{k_x}{\eta}\frac{\partial}{\partial x}\left[\rho_a\left(\frac{\partial p_a}{\partial x}-\rho_a g_x\right)\right]+\frac{k_y}{\eta}\frac{\partial}{\partial y}\left[\rho_a\left(\frac{\partial p_a}{\partial y}-\rho_a g_y\right)\right]=0$$

HEAT:
$$\frac{\partial}{\partial t}[(\rho c_d+c_w w)\theta]+\frac{\partial}{\partial x}\left[-\lambda_x\frac{\partial\theta}{\partial x}+\rho_a c_a u_P\theta\right]+\frac{\partial}{\partial y}\left[-\lambda_y\frac{\partial\theta}{\partial y}+\rho_a c_a v_P\theta\right]+h_e div g_v=0$$

VAPOR:
$$\rho\xi_\phi(\phi)\frac{\partial}{\partial t}\left[\frac{p_v}{p_{\rm sat}(\theta)}\right]+\frac{\partial}{\partial x}\left[-\delta(\phi)\frac{\partial p_v}{\partial x}+\rho_a\xi_a u_P p_v\right]+\frac{\partial}{\partial y}\left[-\delta(\phi)\frac{\partial p_v}{\partial y}+\rho_a\xi_a v_P p_v\right]=0$$

Air, heat, and vapor flow in the air channels is modeled assuming unidirectional, fully developed, laminar flow between parallel plates. Radiative heat exchange between air channel walls is described assuming isothermal parallel surfaces.

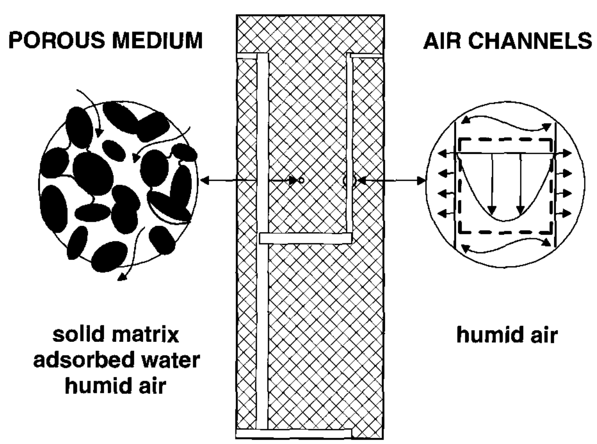


FIG. H-1—Two-domain building-component model.

[1]Assistant professor, Building Physics, Faculty of Applied Sciences, University Gent, Belgium.

Boundary Conditions:
Temperature, surface heat flux, vapor pressure, air pressure, transfer coefficients, neutral pressure level.

Limitations:
Liquid water transfer and ice formation are not included. The model is thus restricted to rectangular building components with low-capillary-active materials and shallow air enclosures in moderate climates. The model has been used for R&D purposes and for the development of design tools for condensation control.

Application Examples:
Steady-state condensation due to air leakage: Figure H-2 shows the velocity and temperature distribution in a 60° sloping cathedral ceiling roof with air gaps around the fibre glass insulation and a 1 mm crack in the internal lining: global velocity field (left), porous field (middle, scale *X*15), condensation location and profile (right).
Dynamic simulation of condensation due to air leakage: Figure H-3 gives an illustration of the predicted evolution in time of the moisture content and condensation profile along the hygroscopic underroof of a 30° sloping cathedral ceiling roof. The roof consists of four layers: a vented tile-layer, fiber cement underroof boards (1 cm), fiber glass thermal insulation (12 cm), and a vapor retarding gypsum board containing a 1 mm crack near the ridge. The moisture contents are mean values over the thickness of the underroof boards. The outside boundary conditions are specified by the TRY weather data file for Belgium with hourly mean values. The simulation does not account for redistribution of condensate by gravity drainage along the underroof surface.

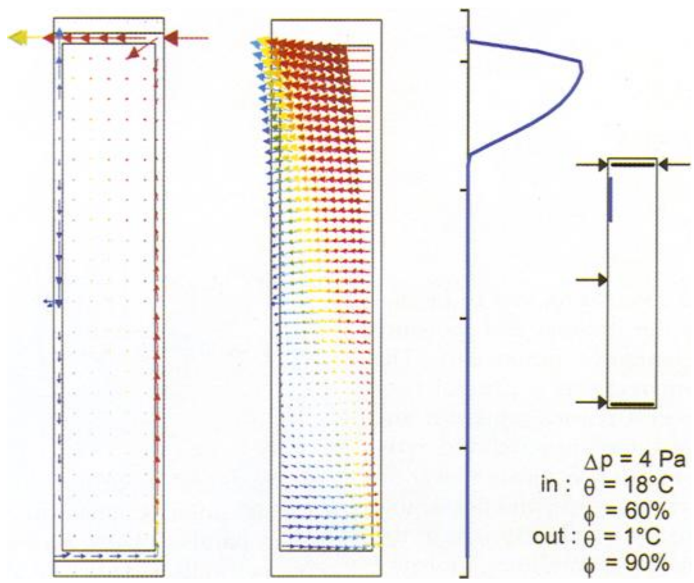


FIG. H-2—Velocity and temperature distribution in a 60° sloping cathedral ceiling roof with air gaps around the fiber glass insulation and a 1 mm crack in the internal lining: global velocity field (left), porous field (middle, scale ×15), condensation profile (right).

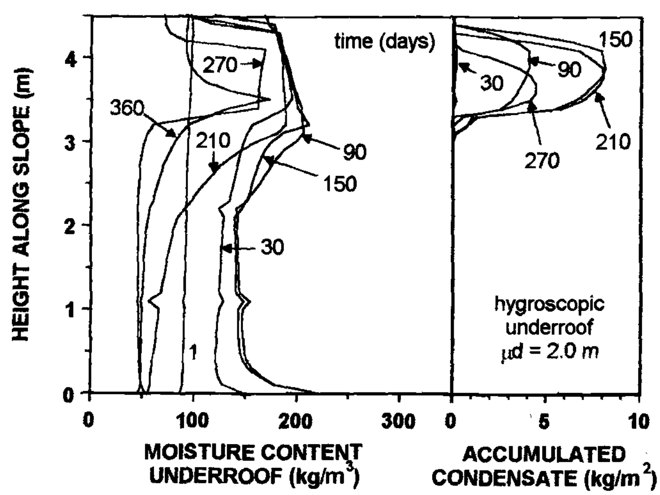


FIG. H-3—Dynamic simulation of condensation due to air leakage: evolution of the moisture content and condensation profiles as a function of height along the underroof. The time indication starts at October 1.

Reference

[1] Janssens, A., 1998, *Reliable Control of Interstitial Condensation in Lightweight Roof Systems: Calculation and Assessment Methods*, Doctoral dissertation, (promotor H. Hens), Laboratory of Building Physics, K. U. Leuven, Belgium, 217 pp. ISBN 90-5682-148-2.

APPENDIX I

Model Name: LATENITE

Authors: Achilles N. Karagiozis[1] and Mikael H. Salonvaara[2]

Model Description:
This model calculates the two-dimensional heat, air, and moisture transfer (HAM) in building envelope systems. A three-dimensional version also exists. Evaporation-condensation and freezing-thawing processes are also treated. The model incorporates innovative mathematical and theoretical developments from the author's previous models such as LIDCAV,[1] TRATMO,[2] and TRATMO2.[2] The model is described in detail in the publications by Karagiozis [*2*], Salonvaara and Karagiozis [*1*], and Salonvaara et al. [*3*]. The model is formulated to be both deterministic (1992) and stochastic (1995).

The LATENITE-VTT version also includes a whole building simulation model that can be used to calculate the heat and mass transfer between the building envelope and indoor air. Heating and ventilation systems are combined with the building envelope performance in order to analyze the indoor climate, thermal and hygric comfort, and indoor air quality instead of assuming interior conditions as known boundary values.

Equations of State:

Moisture balance:
$$\rho_0 \frac{\partial u}{\partial t} = \nabla \cdot (\delta_p \nabla P_v) + \nabla \cdot (\rho_0 D_w \nabla u) - \nabla \nu \rho_v \quad (1)$$

Energy balance:
$$c\rho_{\text{eff}} \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + L_v \{\nabla \cdot (\delta_p \nabla P_v)\} - \nabla \cdot (\rho \nu c T) \quad (2)$$

Mass balance:
$$\nabla \cdot (\rho_a \vec{v}) = 0 \quad (3)$$

$$\vec{v} = -\frac{K}{\eta} (\nabla P - \rho_a g) \quad (4)$$

[1]Senior research engineer, Hygrothermal Project Manager, Oak Ridge National Laboratory, Bldg 3147, Oak Ridge Tennessee. (During 1991–1998 the author was a research officer at the National Research Council, Canada.).
[2]Building scientist, VTT, Espoo, Finland.

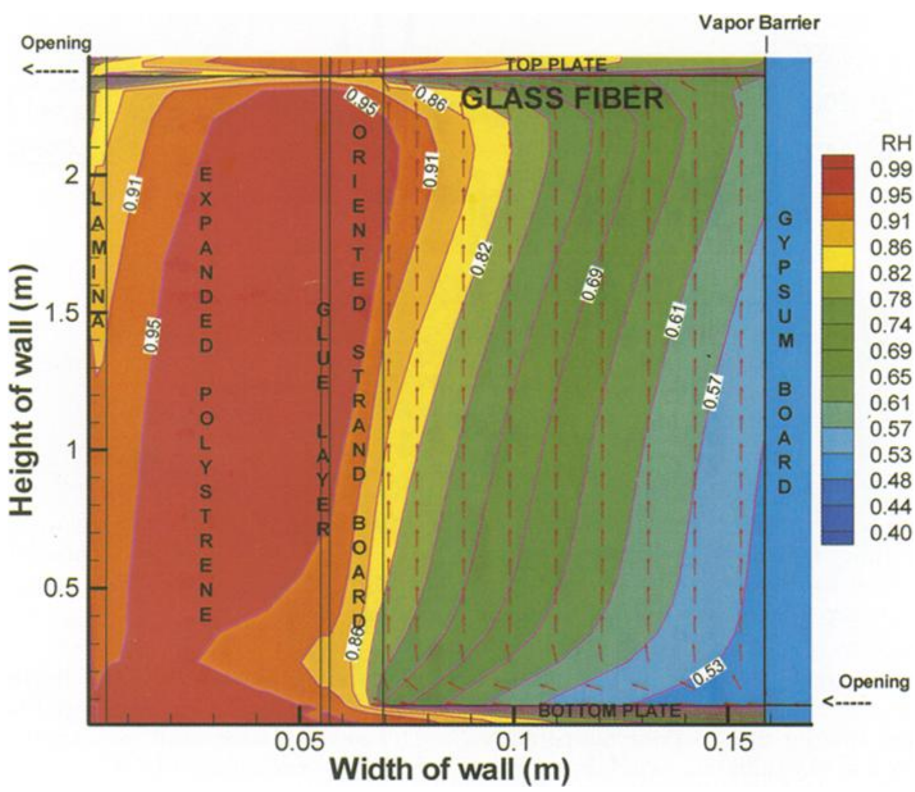


FIG. I-1—Simulated relative humidity in EIFS wall cross section (Wilmington, NC).

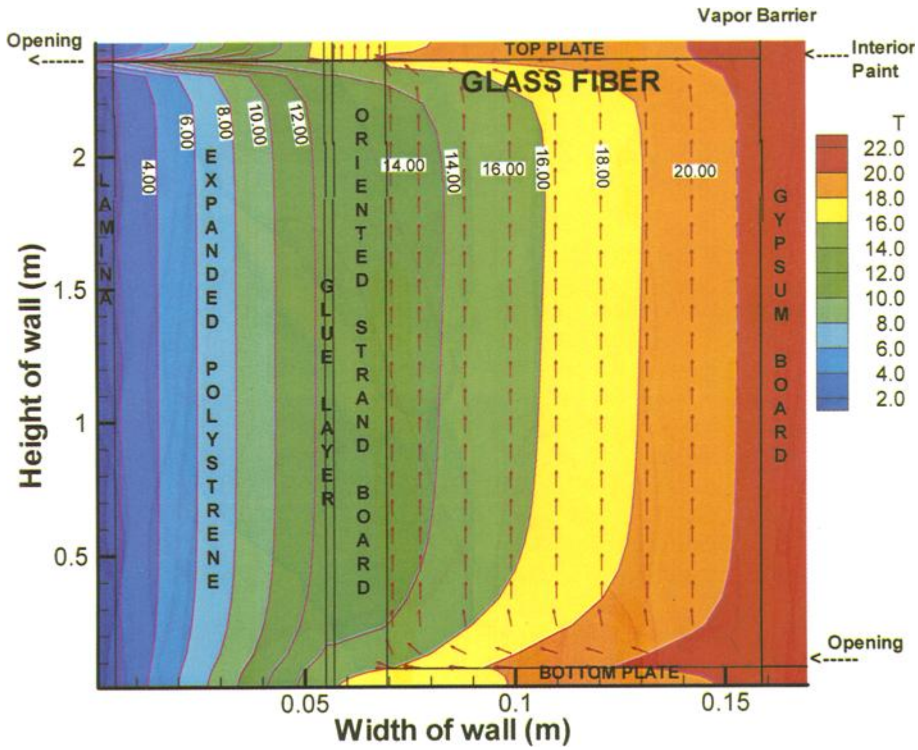


FIG. I-2—Simulated temperature distribution in EIFS wall cross section (Wilmington, NC).

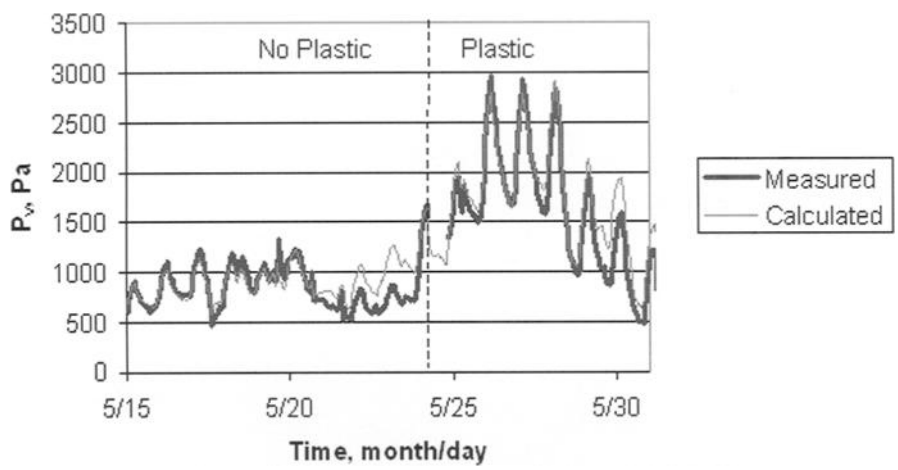


FIG. I-3.

where: ρ_α = air density, $c\rho_{eff}$ = the volumetic heat capacity of moist porous materials, ρ_0 = density of solid material, u = moisture content, t = time, T = absolute temperature, c = specific heat, λ = thermal conductivity, L_v = latent heat of vapor phase change, δ_p = vapor permeability, D_w = the liquid diffusivity, V = volume, $\vec{v}$ = velocity vector, K = air permeability, η = dynamic viscosity, P = pressure.

Boundary Conditions: Interior and exterior temperature, relative humidity, solar and sky radiation, wind-driven rain, pressure difference, and stack effect.

Limitations:
Deformation of the porous structure, hysterisis, material aging are not accounted for. A limited number of laboratory benchmarking tests have been performed, none with field data.

Application Examples (EIFS Drying and Building Envelope Effects on Indoor Air Humidity)
This model is a research model and has been used solely for R&D purposes. Recently, it has been used for commercial applications. Figures I-1 and I-2 demonstrate the effects of

moisture accumulation and drying due to air leakage on wall RH and T, respectively. Details are presented in an *ASTM STP1352* paper by the authors [4]. Figure I-3 presents measured and calculated indoor air humidity as a function of wall surface and ventilation rate (permeable vs. impermeable to moisture). More details on the effect of hygroscopic materials in building envelopes on indoor air quality has been presented in Salonvaara et al. [5]

References

[1] Salonvaara, M. and Karagiozis, A., "Moisture Transport in Building Envelopes using Approximate Factorization Solution Method," CFD Society of Canada, Toronto, 1–3 June 1994.

[2] Karagiozis, A., "Moisture Engineering," 7^{th} *Conference on Building Science and Technology*, 1997, pp. 93–112.

[3] Salonvaara, M. and Karagiozis, A., *1999 Proceedings, Performance of Exterior Envelopes of Buildings*, Thermal VII, pp. 179–188.

[4] Karagiozis, A. and Salonvaara, M., "Hygrothermal Performance of EIFS Clad Walls: Effect of Vapor Diffusion and Air Leakage on Drying on Construction Moisture," *ASTM STP 1352*, pp. 32–51.

[5] Salonvaara, M. and Simonson, C., "Mass Transfer Between Indoor Air and a Porous Building Envelope: Part II—Validation and Numerical Studies," *Healthy Buildings 2000*, Espoo, Finland, 6–10 Aug. 2000, O. Seppänen and J. Säteri, Eds., Vol. 3: *Microbes, Moisture, and Building Physics*, Finnish Society of Indoor Air Quality and Climate (FiSIAQ) (2000), pp. 123–128.

APPENDIX J

Model Name: FRET (A simulation program for FREezing-Thawing processes)

Authors: M. Matsumoto,[1] S. Hokoi,[2] and M. Hatano[3]

Model Description:
This program developed in 1992 calculates two-dimensional heat and moisture transfer in building walls, including freezing regimes. Freezing-thawing processes are dealt with as a three-phase system including gaseous, liquid, and solid phases. The model is described in detail in the following publication by Hokoi [*1*] and is a deterministic model.

Equations of State:

Moisture balance

$$\frac{\partial \rho_w \psi_w}{\partial t} = \nabla \cdot (\lambda'_{Tg}\, \nabla T) + \nabla \cdot \{(\lambda'_{\mu g} + \lambda'_{\mu l}) \nabla \mu \qquad (1)$$

Energy balance

$$c\rho\psi \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + H_{gl}\{\nabla \cdot (\lambda'_{Tg}\, \nabla T) + \nabla \cdot (\lambda'_{\mu g}\, \nabla_{\mu})\} + H_h \frac{\partial \rho_i \psi_i}{\partial t} \qquad (2)$$

Freezing Point Depression and Equilibrium Liquid Moisture Content

$$\mu = H_{li} \log_e(T/T_o) \qquad (3)$$

where:
ρ = density , ψ = volume fraction, t = time, T = absolute temperature, c = specific heat, μ = chemical potential of water relative to free water, λ = thermal conductivity, H = heat of phase change, $\lambda'_{\mu\gamma}$, $\lambda'_{\mu l}$, λ'_{μ} = moisture conductivities in gaseous, liquid, and total phase related to water chemical potential gradient, $\lambda'_{\mu\gamma}$, $\lambda'_{\mu l}$, λ'_{μ} = moisture conductivities in gaseous, liquid and total phase related to temperature gradient, T_o = freezing temperature of free water = 273.16 [K]. Suffix w = water, g = gas, l = liquid, I = ice, s = solid skeleton.

[1] Professor, Faculty of Engineering, Osaka Sangyo University, Japan.
[2] Professor, Graduate School of Engineering, Kyoto University, Japan.
[3] Government of Housing Loan Corporation, Japan.

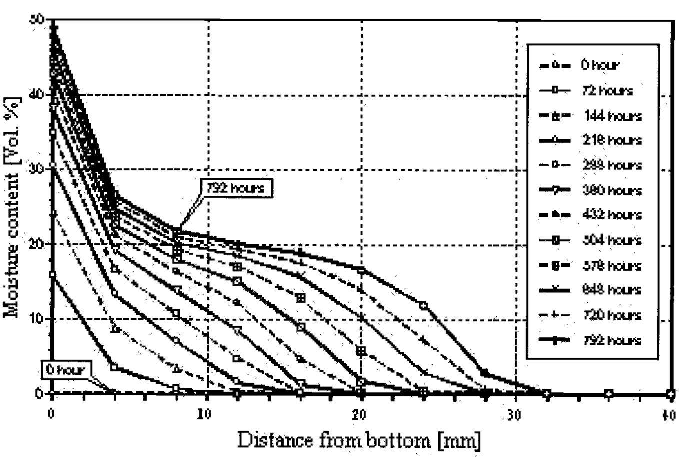


FIG. J-1—Calculated total moisture (liquid water + ice) content distribution during feezing process.

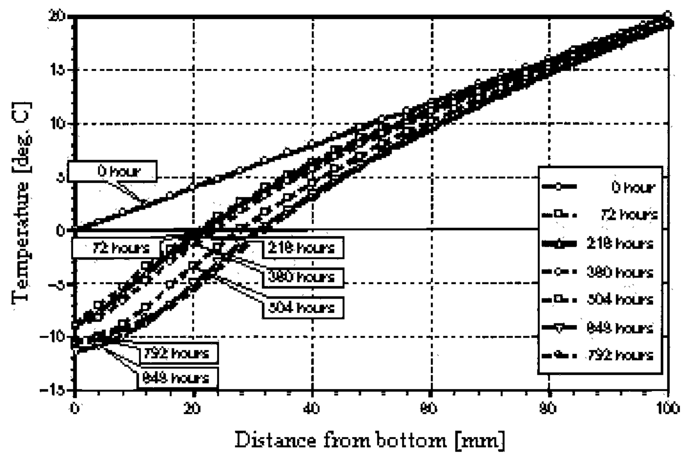


FIG. J-2—Calculated temperature distribution during freezing process.

Boundary Conditions: Interior and exterior temperature, relative humidity, solar radiation.

Limitations:
The deformation of the porous structure caused by the ice content change is neglected, all variables are single valued; hysteresis and over-cooling are not taken into account, wind-driven rain is not included. Air flow is also not accounted for.

Application Example (analysis of freezing process):
This model is a research model and has been used solely for R&D purposes. It has not been benchmarked for commercial applications. Below demonstrates the moisture accumulation of a fiberglass specimen 10 cm × 10 cm × 10 cm glass fiber board (density of 48 [kg/m^3]) due to moisture accumulation in a freeezing experiment. The ambient air of temperature 20°C and RH 60%, with exterior conditions of −10°C. Results show the moisture content (Fig. J-1), and the temperature distribution (Fig. J-2).

Reference

[*1*] *Journal of Thermal Env. & Bldg. Sci.*, Vol. 24, July 2000, pp. 42–60.

APPENDIX K

Model Name: FSEC 3.0

Authors: Muthusamy V. Swami, Lixing Gu, and Philip W. Fairey

Model Description:

FSEC 3.0 is a general building simulation program, developed by the Florida Solar Energy Center [*1*]. The program provides detailed simulation of whole building system problems, including simultaneous solution of energy, moisture, and contaminant transport, including the interactive impacts of pressures and airflows within forced air distribution systems and the building zones. The program has been selected by ASHRAE TC 6.3 as the simulation tool of choice for air distribution system analysis [*3*]. Its current capabilities consists of zone thermal and moisture balances, zone contaminant balance, including radon and VOC, heat and moisture transfer in building envelope, airflows in multiple zones and air distribution systems, zone and air distribution system pressures, HVAC system models, duct heat and moisture exchanges, radon transport in soil and slab, and contaminant sources and sinks.

FSEC 3.0 consists primarily of three main sections. The first section is the heart of the program, which calculates temperatures, air pressures, and moisture levels in the envelope. Users have a choice of either finite element or conduction transfer function methods. The second section is the building program that calculates zone balances for heat, moisture, and contaminants. The third section is the HVAC and airflow program that calculates airflows, pressures, contaminant concentrations, temperatures, and humidity ratios in the building and distribution system. All three sections are fully coupled in an iterative loop and simulations are run until overall convergence tolerance is attained.

FSEC 3.0 is able to simulate coupled heat, air and moisture transfer in 1-D, 2-D, and 3-D geometry in the hygroscopic region in the building envelope using the finite element method. The detailed model description may be found in references [*2*,*4*].

Boundary Conditions:

Outdoor temperature and humidity, pressure, wind speed, and wind direction.

Limitations:

Liquid water transfer in building envelope is not included.

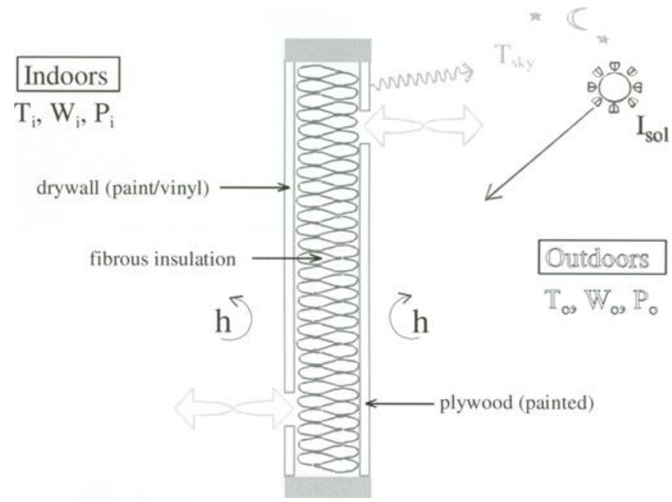


FIG. K-1—Combined heat, airflow, and moisture transport across an external wall.

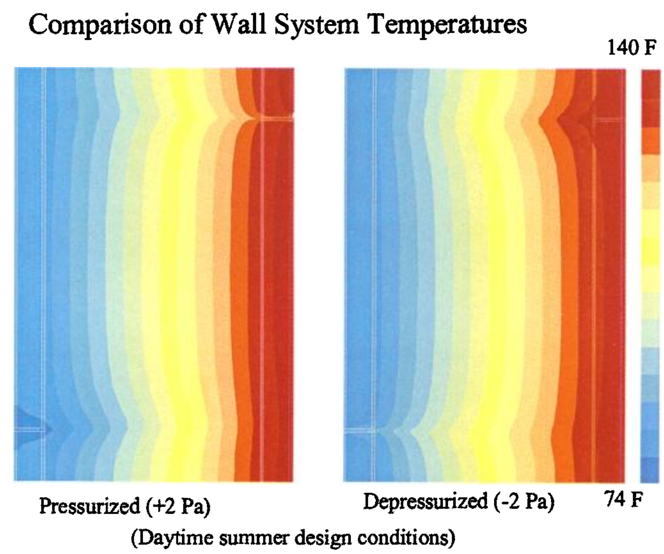


FIG. K-2—Steady-state temperature gradients.

Application Example (Air Pressure Impact)

The following example is used to show the impact of air pressure on temperature and moisture distribution in a frame wall in a hot, humid climate under steady state equilibrium condition. The frame wall is 8 ft high as shown in Fig. K-1, composed of ½-in. plywood on the exterior with a ½-in. hole above the middle of the wall, 2.25-in. fiberglass insulation and ½-in. gypsum drywall on the interior with a ½-in. hole below the middle of the wall. Indoor conditions are 23.3°C and 60% RH, while outdoor conditions are 30°C and 90% RH with 300 W/m^2 solar radiation in daytime and 25.6°C and 100% at night.

Figure K-2 shows temperature distribution in the wall in the daytime. The left figure is temperature distribution at +2 Pa indoor pressure with respect to outdoors, while the right figure is at −2 Pa indoor pressure with respect to outdoors. Even though air is flowing through the wall, temperature distributions are only slightly affected. Figure K-3 shows RH

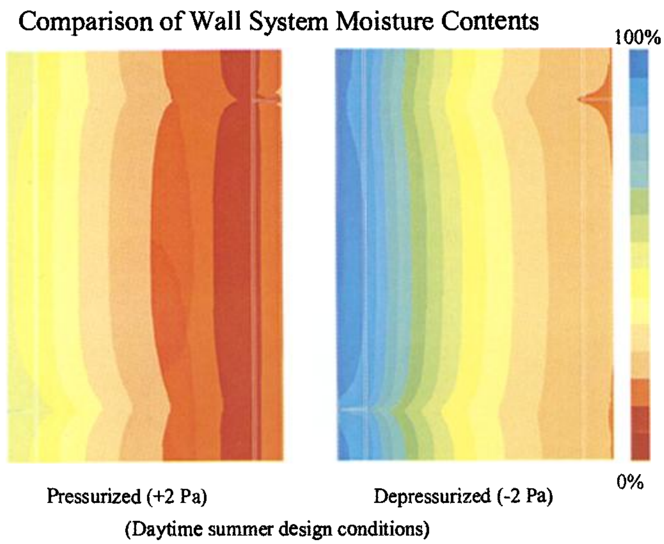


FIG. K-3—Steady-state equilibrium relative humidity.

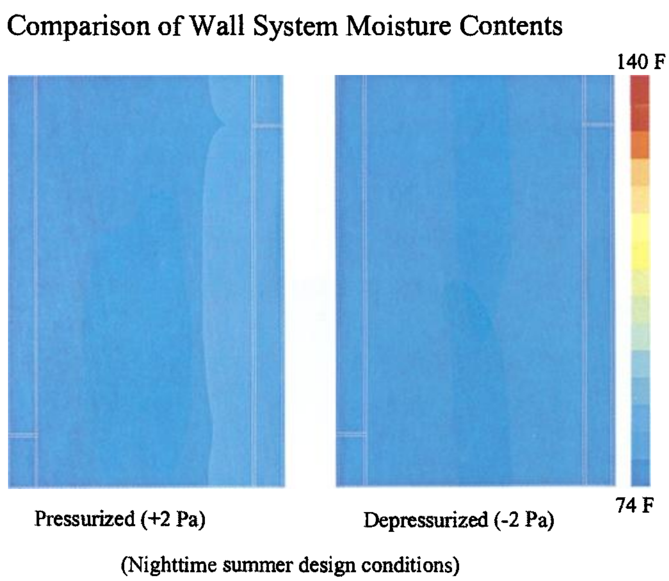


FIG. K-4—Steady-state temperature gradients.

distribution in the wall. When indoor pressure is positive (+2 Pa), the RH level in the wall is less than 60%, as shown in the left figure, because dry indoor air flows through the wall. However, when the pressure is negative (−2 Pa), the

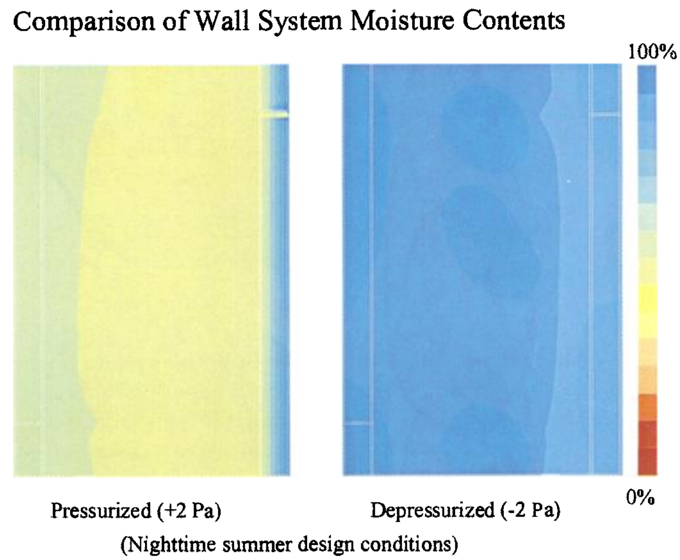


FIG. K-5—Steady-state equilibrium relative humidity.

RH level in the gypsum drywall is above 95%, because humid outdoor air flows through the wall.

Figure K-4 shows temperature distributions in the wall at night. The pressure differential across the wall only slightly affects the temperature distribution. Figure K-5 shows RH distributions in the wall at night. When the indoors is pressurized, the humidity in the almost the entire wall (excepting the outmost portion of exterior plywood) is below 60% RH However, when the indoor pressure is negative, the RH level in almost the entire wall is above 95%.

References

[*1*] Florida Solar Energy Center, 1992, "FSEC 3.0: Florida Software for Environmental Computation," Version 3.0, FSEC-GP-47-92.

[*2*] Gu, L., Swami, M., and Fairey, P., "Generalized Theoretical Model of Combined Heat, Air and Moisture Transfer in Porous Media," *FED-Vol. 173/HTD-Vol. 265, Multiphase Transport in Porous Media in 1993, ASME Winter Annual Meeting,* New Orleans, LA, Nov. 28-Dec. 3, 1993, pp. 47–55.

[*3*] Gu., L., Cummings, J. E., Swami M. V., and Fairey, P. W., "Comparison of Duct System Computer Models That Could Provide Input to the Thermal Distribution Standard Method of Test (SPC152P)," *1998 ASHRAE Winter Annual Meeting,* San Francisco, 1998.

[*4*] Kerestecioglu, A. and Gu, L., "Theoretical and Computational Investigation of Heat and Moisture Transfer in Buildings: Evaporative and Condensation Theory," *ASHRAE Transactions,* Vol. 96, Part 1, 1990, pp. 455–464.

Appendix 2—CD-ROM: Content, Installation, and Information

CONTENT

The enclosed CD ROM includes four programs, two moist air conversion programs and two moisture analysis models:

- Trane Engineers Toolbox, a program for converting moist air properties in inch/pound units.
- Moist Air Unit Conversion (MAC), a program for converting moist air properties in SI (metric) and in inch/pound units.
- MOIST, NIST developed hygrothermal model for moisture analysis of walls and roofs, and
- WUFI ORNL/IBP, hygrothermal model developed by the Fraunhofer Institute für Bauphysik and Oak Ridge National Laboratory.

SYSTEM REQUIREMENTS

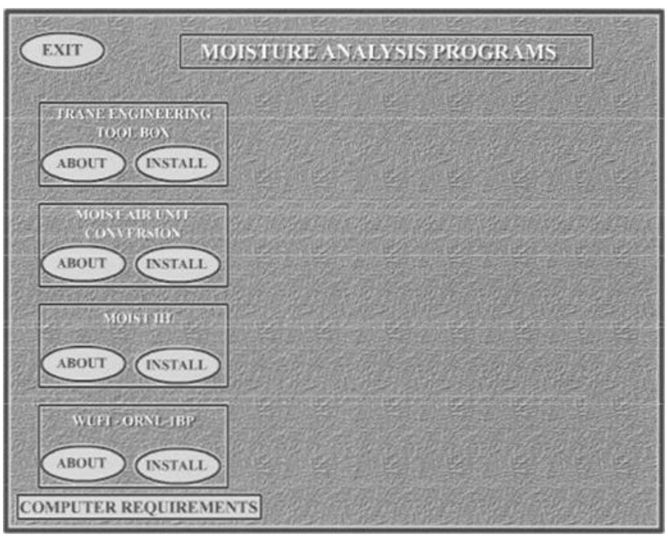
- IBM or IBM-compatible machine
- Pentium processor or higher
- At least 100 megabytes of hard disk space
- At least 32 megabytes of memory (RAM)
- Windows 95/98 or Windows NT/2000

Additional requirements for WUFI ORNL/IBP:

- Under Windows NT: Service Pack
- Under Windows 95/98: IE 4.01
- Microsoft Data Access MDAC 2.5

INSTALLATION

To install the programs, place the CD ROM into the CD ROM drive. The disk will install itself and the opening screen as shown below will appear with the four programs and for each a choice of "About" and "Install."



Please read the About file first by clicking on the "About" button.

The installation process can be started for each of the three programs by clicking on the "Install" button. Continue by following the directions on screen. However, before attempting to run any of the programs, it is strongly recommended that the user read the instructions, manuals, help files, and read-me first documents provided on the disk. At the end of the installation of each program, the opening/installation screen reappears. You can then either install the next program or exit to run the program.

PROGRAM SPECIFIC COMMENTS

Toolbox

When installing Toolbox, you need to provide your name and company name and a Serial Number. For owners of MNL 40, the Serial Number is "ASTM". This will provide free access to two programs: "Properties of Air" and "Mixed Air Properties." At the end of the installation routine, you will have the choice of either:

- Restart your Computer now or
- Restart your computer later.

If you click on "Now," you will get back to the windows opening screen; If you click on "Later," you will get back to the Moisture Analysis Programs opening screen.

Additional engineering tools are part of the Trane supplied program but access to them has to be purchased separately from the Trane Company. The purchase is convenient through a hot link provided in the installation routine. The additional tools are:

- Power Factor Correction,
- Fluid Properties,
- Refrigerant Properties,
- Refrigerant Line Sizing, and
- Ductulator.

Additional engineering tools for HVAC Engineers published by the Trane Company and not included are listed on the CD ROM in a file C.D.S. Electronic Catalog.

To run Toolbox, go to Explorer, Programs, and C.D.S. Applications and click on Toolbox.

To run "Properties of Air," insert altitude (sea level is default) and two values, click on calculate, and read the eight other values.

To run "Mixed Air Properties," insert properties of the two constituent air masses, altitude (sea level is default). Click on "calculate", and read the ten properties of the mixed air.

Moist Air Unit Conversion (MAC)

The Moist Air Unit (MAC) Conversion program was developed by Dr. Carsten Rode of the Technical University of Denmark. It is based on SI/Metric units, but also allows the use of inch/pound units. To change units, press the PGUP and PGDN keys.

To read the instructions and user's guide for the program, in Explorer go to Programs, MAC Program, and MAC Instructions. To run the program, also under Explorer and MAC Program, click on Moist Air Unit Conversion.

MOIST Hygrothermal Model for Moisture Analysis of Walls and Roofs

MOIST was developed by Douglas M. Burch at the National Institute of Standards and Technology (NIST). To read the user's manual for MOIST, with the CD ROM in the drive, find the drive where the CD ROM is located and click on

MOIST Install. The User's Manual is located in the Folder "Manual."

To run MOIST, go to Explorer, Programs, find NIST MOIST 3.0 Programs, and click on "Moist Release 3.0." At opening screen it is highly recommended that the user read the help file first. This provides a tutorial and line-by-line instructions for conducting a moisture analysis.

Note that MOIST 3.0 includes initially only weather data for six cities. To install the weather data for any of another 45 cities in the United States and Canada, follow the instructions given in the "About" screen. The data are in WY Format with the following convention: The first two letters are the WY (for Weather Year), next is a three-letter City code, followed by the two-letter code for the State (in the U.S.) or the single letter "C" for Canada.

The WYEC Weather data on the disk are published with the permission of the American Society of Heating, Refrigerating and Air Conditioning Engineers Inc. (ASHRAE). A newer set of hourly weather data WYEC2 has been prepared by ASHRAE and is available from the Society. However, WYEC data are not compatible with MOIST 3.0.

The results of the analysis are a graphic depiction of the moisture/RH/etc. levels. The numeric values, in default settings as weekly averages, can be obtained by accessing the "results" files in the MOIST directory. The two most frequently used result files are those for Moisture Content (file Result.mc) and Surface Relative Humidity (file Result.srh).

WUFI ORNL/IBP Hygrothermal Model for Architects and Engineers

WUFI ORNL/IBP was developed by Hartwig Kuenzel at the Fraunhofer Institute für Bauphysik and Achilles Karagiozis at the Oak Ridge National Laboratory. To read the instructions and a detailed User's Manual, go to Explorer to the drive where the CD ROM is located and click on "wufi install." The manual is in a file "Wufi ORNL-IBP Manual-Guide.pdf." A very useful "Help" file is located in a Folder called Wufi30. This can be accessed after installation by going to "Start," "Programs," "Wufi30," to "Wufi30 Help."

Before installing WUFI ORNL-IBP, you must first obtain a password/Serial Number. The password/number is free for owners of MNL 40. To obtain the number/password, send an E-mail to Dr. Karagiozis at the web-site: *http://www.ornl.gov/btc/moisture,* and provide the following information:

Legal name
Company or University
Address
Telephone
Zip Code
Fax
E-mail

You will receive your three-line password by E-mail within a short time. When prompted, enter the three-line password *exactly* as received from ORNL on the three lines on the screen. To run WUFI ORNL/IBP after the installation is complete, go to "Start," "Programs," and "Wufi30."

TECHNICAL SUPPORT

- *Trane Engineering Toolbox:*
  Mr. Rob Davidson
  The Trane Company
  3600 Pammel Creek Rd.
  LaCrosse, WI
  rdavidson@trane.com
  Telephone: 608-787-3926
- *Moist Air Unit Conversion (MAC):*
  Dr. Carston Rode
  Technical University of Denmark
  Dept. of Civil Engineering
  Lyngby, Denmark
  car@byg.dtu.dk
- *MOIST*
  The program MOIST, developed by Douglas M. Burch at the National Institute of Standards and Technology (NIST), was one of the earliest hygrothermal models for building walls and roofs published in the United States and designed for use by building practitioners and building researchers. Since it is no longer maintained by NIST, technical support is no longer available. However, the program is still very useful to evaluate the propensity of wall and roof designs to condensation damage, and the documentation provided is very complete so that the reader should not have any difficulty in using the program.
- *WUFI-ORNL/IBP:*
  Dr. Achilles N. Karagiozis
  Oak Ridge National Laboratory
  1 Bethel Valley Road
  Oak Ridge, TN
  ank_hammodel@ornl.gov
  Telephone: 865-576-3924

For information on the original version of WUFI (Europe), contact:

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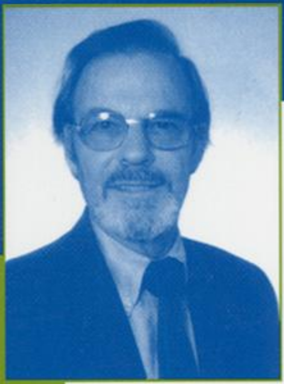
ABOUT THE EDITOR



HEINZ R. TRECHSEL is a graduate architect of the Swiss Federal Institute of Technology in Zürich and is a registered architect in the state of New York. As an independent consultant, he is investigating and consulting on moisture problems in buildings, develops remedial measures, and serves as an expert witness in cases related to moisture problems in buildings.

Trechsel also is a staff architect with the Engineering Field Activity Chesapeake of the Naval Facilities Engineering Command. He was previously employed by the National Bureau of Standards (now National Institute of Standards and Technology), the Applied Research Laboratory of United States Steel Corporation, and various architectural firms in New York and in Europe.

He has been a member of ASTM Committee E06 on Performance of Buildings since 1961 and was a member of Committee C16, Thermal Insulation, and D20, Plastics.

Mr. Trechsel has published extensively on moisture control in buildings, energy conservation, and on building diagnostics. He most recently edited *Moisture Control in Buildings, MNL 18* and was co-editor of *Water Vapor Transmission Through Building Materials and Systems: Mechanisms and Measurement, STP 1039; Measured Air Leakage in Buildings, STP 904,* with Peter Lagus and Mark Bomberg; *Moisture Migration in Buildings, STP 779,* with Morris Lieff; and *Building Air Change Rate and Infiltration Measurements, STP 719,* with John King and Max Hunt.

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