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Researching Complex Heat, Air and Moisture Interactions for a Wide-Range of Building Envelope Systems and Environmental Loads

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ABSTRACT

This document serves as the final report documenting work completed by Oak Ridge National Laboratory (ORNL) and the Fraunhofer Institute in Building Physics (Holzkirchen, Germany) under an international CRADA No. 0575 with Fraunhofer Institute of Bauphysics of the Federal Republic of Germany for Researching Complex Heat, Air and Moisture Interactions for a Wide-Range of Building Envelope Systems and Environmental Loads.

The purpose of this Cooperative Research and Development Agreement (CRADA,) between UT-Battelle (Contractor) and the Fraunhofer Institute of Bauphysics (Participant,) was to develop energy efficient and durability strategies of key building envelope components and systems. The Contractor and the Participant are hereinafter referred to jointly as the "Parties."

This CRADA required a multi-faceted approach to building envelope research that included a moisture engineering approach by blending extensive material property analysis, laboratory system and sub-system thermal and moisture testing, and advanced moisture analysis prediction performance. The Participant's Institute for Building Physics (IBP) and the Contractor's Buildings Technology Center (BTC) identified potential research projects and activities capable of accelerating and advancing the development of innovative, low energy and durable building envelope systems in diverse climates. This allowed a major leverage of the limited resources available to ORNL to execute the required Department of Energy (DOE) directives in the area of moisture engineering. A joint working group (ORNL and Fraunhofer IBP) was assembled and a research plan was executed from May 2000 to May 2005.

A number of key deliverables were produced such as adoption of North American loading into the WUFI-software. In addition the ORNL WeatherFileAnalyzer was created and this has been used to address environmental loading for a variety of US climates. At least 4 papers have been co-written with the CRADA partners, and a chapter in the ASTM Manual 40 on Moisture Analysis and Condensation Control.

During the project period ORNL constructed two test facilities (one in Charleston SC and the other one in Puyallup WA) which provide a number of wall benchmark data for the goals of the international CRADA.

Finally, all deliverables and goals were met and exceeded making this collaboration a success to all parties involved.

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Additionally, we would like to thank all individuals that assisted development of the CRADA (in the construction and instrumentation of the Natural Exposure Test Facilities, and the detailed work required to assemble the test walls:

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Florian Antretter, Fraunhofer Institute in Building Physics

Statement of Objectives

The purpose of this Cooperative Research and Development Agreement (CRADA) between UT-Battelle and the Fraunhofer Institute of Bauphysics (Participant,) was to employ state-of-the-art research to develop energy efficient and durability strategies of key building envelope components and systems. The main objective of the work effort was to make available design tools to accomplish this activity. The objective of this project was to develop tools to allow building envelope designers and architects to design for moisture control.

This required a multi-faceted approach to building envelope research, that includes a moisture engineering approach by blending extensive material property analysis, laboratory system and sub-system thermal and moisture testing, and advanced moisture analysis prediction performance. To achieve such an ambitious undertaking required a significant amount of financial and scientific resource leveraging. During the CRADA period (2000-2005) ORNL budget was severely cut, but the enthusiasm and individual efforts did not take the toll.

The Participant's Institute for Building Physics (IBP) and the Contractor's Buildings Technology Center (BTC) identified a number of potential research projects and activities capable of accelerating and advancing the development of innovative, low energy and durable building envelope systems in diverse climates. Effort was co-assigned to develop new or enhance existing tools that architects and engineers could use to analyze the complex heat, air and moisture transport in building envelope systems. Two such tools that have become available to USA designers are the WUFI-ORNL software and the WeatherFileAnalyzer.

A number of major advances have been made by the CRADA research teams in the field of moisture engineering. Significant progress developing understanding of the varying exterior and interior climates in terms of loading was achieved. These conditions are very critical in developing the needed boundary conditions for accurate design considerations by hygrothermal modeling. Another is the introduction of hygrothermal material properties for USA constructions.

INTRODUCTION

The purpose of this Cooperative Research and Development Agreement (CRADA,) between UT-Battelle and the Fraunhofer Institute of Bauphysics (Participant,) was to employ state-of-the-art research to develop energy efficient and durability strategies of key building envelope components and systems.

This required a multi-faceted approach to building envelope research, that includes a moisture engineering approach by blending extensive material property analysis, laboratory system and sub-system thermal and moisture testing, and advanced moisture analysis prediction performance. To achieve such an ambitious undertaking required a significant amount of financial and scientific resource leveraging.

The Participant's Institute for Building Physics (IBP) and the Contractor's Buildings Technology Center (BTC) identified a number of potential research projects and activities capable of accelerating and advancing the development of innovative, low energy and durable building envelope systems in diverse climates. A joint working group was assembled and meet at least twice a year to chart the joint research activities.

The success of this CRADA is well recognized by the construction industry, architects and building envelope designer. In 2000, less than 5 individuals were employing vapor and liquid transport in moisture designs in the USA. In the short period of 5 years (2000-2005), this number has grown exponentially that by the end of 2005, more than 3200 licensed WUFI-ORNL users existed. By May 2007 this number has grown to 6600 licensed WUFI-users. This presents 99 % of all US building and architecture firms designers that are employing WUFI/WUFI-ORNL in North America for moisture design purposes.

Scope of CRADA Work

The Parties jointly performed a number of research activities aimed at developing the scientific and technological basis for understanding the complex interactions involved in heat, air and moisture transport for a wide range of building envelope systems and environmental loads. The joint activities involved developing new tools such as the WEATHERFILEANALYZER (ORNL) or upgrading existing ones such as WUFI to WUFI-ORNL (Participant's WUFI model (Fraunhofer)) and development of experimental data (field, laboratory and material properties) for energy efficient and durable building envelope materials and systems (such as walls, roofs, and basements).

Three main tasks were identified that require varying levels of participation by both the participant and the contractor under this CRADA.

Task 1 - Develop a simplified moisture analysis model for designers and architects

Task Objective:

The objective of this task was to make available a simple to use hygrothermal design tool that was customized for engineers and architects based on existing software (WUFI) provided by the participant. The research collaboration resulted in a product that was called WUFI ORNL/BP customized for North America allowing building envelope designers and architects to design energy efficient system that minimize the risk for moisture related problems. This software is currently labeled as WUFI-ORNL.

DOE's mandate is to assist in the development the next generation of buildings that are very energy efficient. Within the mandate, the emerging technology groups and the Building America teams are performing research into zero-net energy buildings. This major step forward makes existing material and construction technology not capable to perform satisfactory in terms of both energy and moisture performance.

As the net heat flux moving through the envelope is reduced by introducing novel energy savings technologies, energy to transport moisture is reduced. This reduction in energy required for the transport of moisture through the evaporation-condensation principles results in significant quantities of water accumulating in the wall structures. Designers have

had no way to analyze these effects, as no software existed. What was needed was a simple to use tool to assist the designer in the judicious selection of materials layers in an envelope system, or to assist the manufacturer of construction material to identify opportunities for new products. The CRADA activities were concentrated to deliver such a software tool to assist DOE to achieve the objectives of energy efficiency in building envelopes.

Special features were incorporated into the WUFI ORNL/IBP to permit minimal input and safe-proof execution. The activities during the upgrading and further development were shared by both Parties. These involved upgrading and enhancing the WUFI, translation of input dialogs and upgrade interface attributes, post-processing of data directly from IP to SI unit, enabling a graphical user interface design development and implementation for US designers, adopting an exterior environmental methodology; then analyzing existing North America climatic conditions to generate moisture design years and document, gathering, and developing material properties representative of North America construction product. These above task objectives were completed 36 months after the effective date of CRADA.

Task 2 – Develop Advanced Hygrothermal Models

As the 1-dimensional analysis does not include the thermal and moisture bridges as found in real construction applications, existing 2-D tools were identified for upgrade. The objectives of this task were to develop unique capabilities to investigate the complex heat, air and moisture transport in building envelope systems. State-of-the-art knowledge was incorporated into the model, features including 2-D thermal and moisture bridging. This activity was to be executed in parallel with Task 1 of this CRADA. However, the major effort of the CRADA was spent on the 1-D version of the WUFI software.

Task 3 – Experimental Analysis

This task deals with the development of experimental data for both material and building envelope characterization. The task involved the further development of methods for analyzing the hygric transport mechanisms in construction assemblies. Facilities at both ORNL and IBP were employed in this task. An additional task was to validate parts of the research activities of Task 1. ORNL was assisted by Fraunhofer IBP to establish its own North America capability. At the end of this CRADA, ORNL could determine all hygrothermal material properties with the exception of the liquid diffusivity, as funding for a nuclear magnetic resonance or gamma-ray spectrometric apparatus was not available. The development of a number of material property characterizations has also been achieved during this time period.

Contractor Responsibility for this Task

1. Experimental compatibility of IBP and ORNL in hygrothermal material property analysis, through the performance of a round-robin.
2. Field Testing compatibility of IBP and ORNL test huts. Currently the contractor is planning this activity and the future is dependent on securing the appropriate resources for this activity.
3. Development of the measurement capabilities and testing of North American hygrothermal material property data.

These task objectives were completed 60 months after the effective date of CRADA.

Milestones

<u>Number</u>	<u>Milestone – When Due (Months After CRADA is Effective)</u>
1.	Task1 – Environmental Loads and Material Properties (18 months)
2.	Task1a – Subtask WUFI ORNL/IBP (Development of WUFI 3.0 to 3.34) (36 months)
3.	Task2 – Subtask Advanced Model (48 months)
4.	Task3 – Subtask Experimental Analysis (60 months)

Property Considerations

The North American version of the WUFI ORNL/IBP version 1 was to be distributed freely to assist architects and engineers in design considerations. It was the intention to distribute the educational version of this software by ORNL and IBP free of charge. Both common considerations were achieved.

Benefits to DOE Mission

The Energy Efficiency and Renewable Energy Program Office, within DOE, has benefited in a major manner. The tools developed allow building envelope designers to design durable highly energy efficient building envelope systems.

Subject Inventions

No inventions were developed during the complete duration of this collaborative project.

Commercialization Possibilities

No commercial possibilities for ORNL exist for this CRADA.

Plans for Future Collaboration

Plans exist to re-enter a next phase of collaboration for extending the capabilities to analyze the multi-phase transport in porous media research for the next generation of building envelope systems.

Conclusions

A successful international CRADA-0575 between the Oak Ridge National Laboratory and the Fraunhofer Institute in Building Physics was completed. All deliverables of the project have been achieved. The WUFI-ORNL 3.3 has been upgraded and the WeatherFileAnalyzer has been developed as part of the collaborative effort. Both softwares have been distributed to North American users.

A total of 3500 users (2005) have downloaded the softwares for use for moisture control design purposes. WUFI-ORNLBP has been used extensively for research purposes as well to better understand the impact of weather resistive barriers, vapor retarders, and the impact of higher insulations in building envelope systems. The proper use of higher levels of insulation in terms of moisture control has positively contributed to DOE's directive of increasing the energy efficiency of envelopes.

APPENDIX A:

WUFI ORNL/IBP– (Up to version 3.3) a hygrothermal design tool for architects and engineers

by

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Introduction

As the number of moisture-induced damages in buildings is 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 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 a 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 ORNLMBP which 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 ORNLMBP is an easy to use, menu driven program for use on a personal computer which 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 which 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, solar radiation, are employed in the hygrothermal calculations. These data are available for a wide range of North American climate zones.

WUFI ORNL/IBP can be used to estimate the drying times of masonry and light weight 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 the 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 widely used by building envelope designers, architects, building physicists consulting bureaus and universities in Europe. In spring 2000 a special North American version was developed by 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 attached to this ASTM handbook. Future free updates will be available at the following two Internet sites:

www.oiml.gov/bld/moisture/models and www.bauphysik.de/software

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 evaporation/condensation and freeze/thawing processes. Different types and shapes of pores, exist see Figure1. 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].

where :

1 = isolated pores

2 = dead-end pores

3 = continues channel pores

Figure 1: Different pore types and shapes in porous building materials.

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. 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% - 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 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, then the material is called capillary active. In contact with water such a material may reach an intermediate state of saturation called the free water saturation or capillary saturation, w_i . 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_i may result from condensation in the presence of a temperature gradient. Insulation materials are especially prone to moisture exceeding w_i . They often are not capillary-active and have w_i near 0).

The moisture storage function of non-hygroscopic 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]

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

Table2: 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
Electrokinetics	Electric field

Moisture Transport

Table 1 and Table 2 summarize 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]

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, which is reduced in comparison to that in still air by a resistance that corresponds to the volume fraction of air-filled pores α and a tortuosity factor α . This is can be described as:

$$q_v = -\alpha \alpha D_v \frac{M}{RT} \nabla P_v$$

where

- q_v : mass flux rate of vapor flow, kg/m²s, (grains/ft² hr)
- D_v : diffusion coefficient of vapor air, m²/s, (ft²/hr)
- R : universal gas constant, 8.314 J/(mol K), (1543.3 ft-lb/lb mol R)
- P_v : partial vapor pressure, Pa (lb/ft²)
- M : molar weight of water, 0.018 kg/mol, (lb_m/mol)

In most European countries a diffusion resistance factor is introduced as $\mu=1/(\alpha a)$ leading to the following flux equation for vapor flow

$$q_v = - \frac{D_v M}{\mu RT} \nabla P_v$$

In the measurement of the water vapor permeance, or water vapor permeability (permeance multiplied by thickness) using the ASTM E96 standard or the EN 12086:1997, the factor δ_p is used, and that is equivalent to:

$$\delta_p = \frac{D_v M}{\mu RT}.$$

This is termed the water vapor permeability and has units of kg/(Pa m s) or (perm in) or (grains¹/hr ft² inHg 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 would be plastic films or coatings where the vapor permeability can increase considerably with humidity because water molecules creep between the polymers.

¹ Note 7000 grains equal 1 pound of water

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 and a state of equilibrium is difficult to define.

For capillary transport, Krischer [6] has introduced the following equation:

$$g_w = -D_w(w) \frac{dw}{dx}$$

where:

g_w : Liquid transport flow density, $\text{kg}/(\text{m}^2 \text{s})$, or $(\text{lb}/\text{ft}^2 \text{ hr})$

$D_w(w)$: Liquid transport coefficient, m^2/s or (ft^2/hr)

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-Poiseuille. This leads to the water front (see Fig. 2a, left). If the supply of water is cut off, the spread of the liquid continues (see Fig. 2b, 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 drying).

Absorption (before cutting supply)

(a)

Redistribution (after cutting supply)

(b)

Figure 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].

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, $\text{kg/m}^2\text{s}$ or $(\text{lb/ft}^2 \text{ hr})$

D_ϕ : liquid conduction coefficient, m^2/s , or (ft^2/hr)

ϕ : relative humidity

The liquid conduction coefficient is related to the liquid transport coefficient by:

$$D_\phi = D_w \cdot \frac{\partial w}{\partial \phi}$$

where:

D_w : liquid transport coefficient, m^2/s or (ft^2/hr)
 $\partial w / \partial p$: 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/hr)
 D_{wo} : Transport coefficient in the sorption moisture range, m^2/s or (ft^2/hr)

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 (hr)
 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, (inHg)
λ :	thermal conductivity, W/(mK), or (Btu/hr ft °F)
H :	total enthalpy, J/m ³ , or Btu/ ft ³
D_ϕ :	liquid conduction coefficient, kg/ms or (lb/ft hr)
δ_p :	vapor permeability, kg/(msPa) or (perm in) or (grains ¹ /hr ft ² inHg 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 are strongly depending 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 non-linearity of both transport equations a stable and efficient numerical solver had to be designed for their solution.

The discretization of the transport equations is done by a fully implicit finite volume scheme with variable grid spacing. In the one-dimensional case this leads to difference equations which can be solved efficiently by the Thomas algorithm for tridiagonal matrices. The coupling of the discretized equations is assured by iterative consecutive solution of these equations using under-relaxation factors adapted to the progress of solution. Special care had to be taken formulating the difference equations containing the vapour pressure which is a function of the two transport variables, temperature and relative humidity [2].

¹ Note 7000 grains equal 1 pound of water

Figure 3 Flow chart of the solution procedure in the WUFI ORNL/BP model

The calculation procedure including the necessary input and the obtainable results are demonstrated with the aid of Figure 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 hour is generally appropriate.

After compilation of the input data the transient calculations start from initial temperature and moisture conditions which are either based on measurements or derived from previous calculations respective 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 either without conversion to the desired output system. Material properties in this version release of the model incorporates early 2001 till 2005 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 2003, 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 have been included into the WUFI ORNL/IBP database.

The minimum material properties required for the simulation are:

- Bulk density [kg/m^3] [lb/ft^3], which serves to convert the specific heat by mass to the specific heat by volume.
- Porosity [m^3/m^3] [ft^3/ft^3], which determines the maximum water content w_{max} (by multiplication by $\rho_{\text{water}} = 1000 \text{ kg/m}^3$ or 1.940 slugs/ft^3).
- Heat capacity [kJ/kgK] [$\text{Btu/lb}^\circ\text{F}$], the specific heat capacity by mass. Rough values are 0.85 kJ/kgK ($0.203 \text{ Btu/lb}^\circ\text{F}$) for mineral materials and 1.5 kJ/kgK ($0.3583 \text{ Btu/lb}^\circ\text{F}$) for organic materials.
- Heat conductivity dry [W/mK] or [$\text{Btu/hr ft}^\circ\text{F}$] 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/m^3] or [lb_m/ft^3] that give the equilibrium moisture content of materials as function of relative humidity in both hygroscopic
- Liquid diffusivity [m^2/s] or [ft^2/s] both for uptake and redistribution of materials as a function of moisture content w .

As an example of a typical datasheet, Figure 4 displays material properties for lime silica brick, as employed by WUFI. (All values are in SI units, but are also available in I-P)

Material : lime silica brick.1900

Description :

Bulk Density	[kg/m ³]:	1900
Porosity	[m ³ /m ³]:	0.29
Heat Capacity	[kJ/kgK]:	0.85
Heat Conductivity Dry	[W/mK]:	1.0
Moisture-related Supplement	[%/M-%]:	8
Water Vapour Diffusion Resistance Factor Dry	[-]:	28
Free (Capillary) Water Saturation	[kg/m ³]:	250.0

Figure 4: Example of one complete set of material data used in WUFI ORNL/IBP

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 which has a value of about $0.13 \text{ m}^2\text{K/W}$ or $(7.374 \times 10^{-3} \text{ }^\circ\text{F hr}^2/\text{Btu})$ at the undisturbed surface and about $0.2 \text{ m}^2\text{K/W}$ ($1.1350 \times 10^{-2} \text{ }^\circ\text{F hr}^2/\text{Btu}$) 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).

Figure 5: Indoor and Outdoor boundary conditions

The situation is more complex at the outdoor surface of the building structure. Here the heat transfer by convection and radiation has 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 direction.

The vapor transfer is adequately described 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 only significant as long as the surface is wet.

The absorption of rain water at the surface can be treated similar to the solar radiation absorption as a source term at 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 drainage of water which has to be accounted for. In general no water will be absorbed below 0°C or (32 °F). 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 which govern the processes in the component, but also by the heat and moisture exchange with the surroundings. Thus there is 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 of the surroundings.

Because WUFI ORNL/BP has been developed specifically for building physics application, 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/BP 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, [8] has validated the approach. Additionally use of 3-D computational modeling has allowed the development of wind-driven rain shape factors by [11], [12] and [13]. For more information on wind-driven rain, the user should review the papers by [9] to [13].

Indoor climate

In general the interior temperature and relative humidity of different conditioned building shows 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. At present, the model is including the three indoor environmental classes in accordance to ASHRAE SPC 160P (TenWolde, 2000).

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 karagiozian@ornl.gov or holm@hki.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.

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 degree 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 which 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 only deals 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 air flows in the component, uptake of ground water under hydrostatic pressure, and gravity effects. Water and heat sources and sinks inside constructions, and 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 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. That means that for example contaminated surfaces due to exposure, 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/BP 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 mainly due to moisture induced weathering or damage processes. Therefore these facades are often treated with water repellent or reinforcing chemicals which 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 ORNLBP 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.

Figure 6. Transient behavior of a stone faced. 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 in the figures below.

Figure 7: Transient behavior of a stone facade. Measured and calculated moisture content profiles for four subsequent time periods.

This excellent agreement in total water content between experiment and calculation can be confirmed by examining the moisture profiles at certain time intervals in Figure 7 recorded for sample 2 in Figure 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 mainly used 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 they 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 dry-out to both sides. However, in this case the stucco must also have a high permeability in order to avoid excessive condensation beneath its surface which can cause frost damage.

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 a autoclaved aerated concrete (AAC) roof a vapor retarder would also prevent the construction moisture from drying out, and thereby, severely impair the thermal insulation quality of the AAC. In order 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 1960's 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 [9].

Figure 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).

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 Figure 10 that within 2 ½ years the AAC has lost most of its construction moisture and is reaching its hygroscopic

equilibrium. Because there is a 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.

Figure 9: Measured and calculated moisture distribution at the end of the first summer and in the following winter

Figure 10 Moisture performance of the AAC flat roof

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 were kept to a bare minimum without sacrificing the performance capability of the software. This was achieved by keeping the inputs that are necessary and critical to simulation. The model is equipped with both 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 begin. The calculated results can be visualized with WUFI-FILM. 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 visualisation tool.

At the end of the simulation, peripheral post-processing modules are available that further analyze and process the hygrothermal performance results of the investigated construction. These modules are 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 complete software architecture is shown in Figure 12.

Figure 11: Visualization of the calculated results with WUFI-Film

Figure 12 Software Architecture of WUFI ORNL/IBP

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, Windows NT, Windows 2000 and Windows XP. A logical set-up is followed in the design of the interface. First the user develops a Project. Within each project, the user may introduce many set 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 executing the simulation. The WUFI® ORNL/IBP interface uses three pathways that compose the input runstream file input 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 that 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 status of the simulation, view results, include measure 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 menu bar. Following the sequence order in the pathway you can successful prepare all inputs and review output results.

In Figures 13 to 18 several Menu screen shots are presented to display the user friendly design of the program.

WUFI ORNL/IBP 3

Project: Aerated Concrete Block Construction

Project Name: Aerated Concrete Block Construction

Project Number: A55-0300-JULY

Client: JBA

Contact Person: AEDROZ

Street: 110 Jane Street

City/Zip: Knoxville TN

Telephone: 865 123-3456 Fax: 865 123-3456

e-mail: jba@edro.com

Responsible: Mr. Jack Hone

Observations: Problems in wall design

Date: 15.5.00

Project Information

Figure 13 Project Definition Menu

Figure 14: Definition of Construction Component

Figure 17: Definition of Interior Environmental Loads

Figure 17: Definition of Definition of Material Properties

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