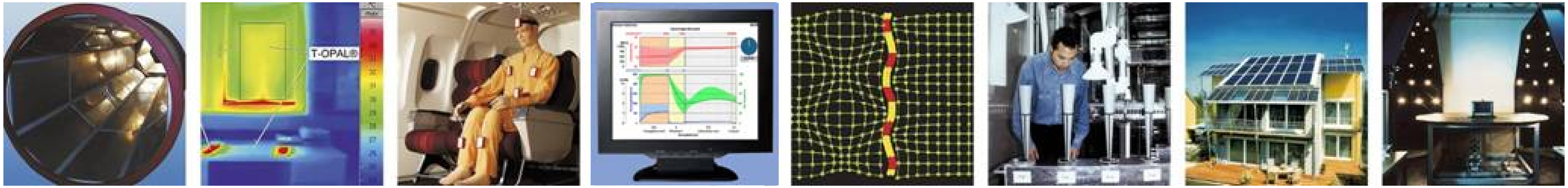


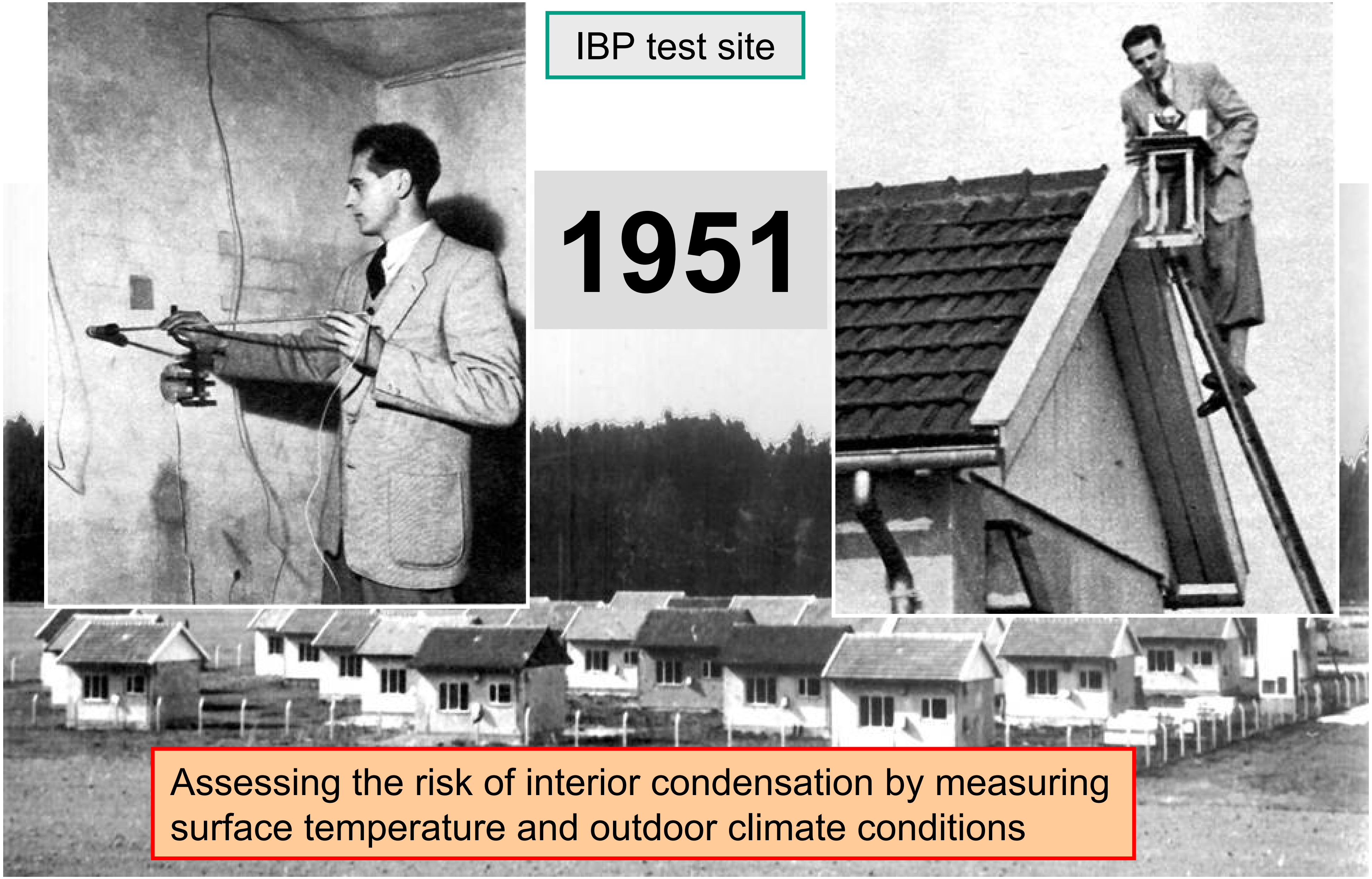
Hartwig M. Künzel
Andreas Holm
Daniel Zirkelbach

Building Envelope Design by Hygrothermal Simulations

Fraunhofer Institut Bauphysik
IBP

Contents:

Building Envelope Design by Hygrothermal Simulations



IBP test site

1951

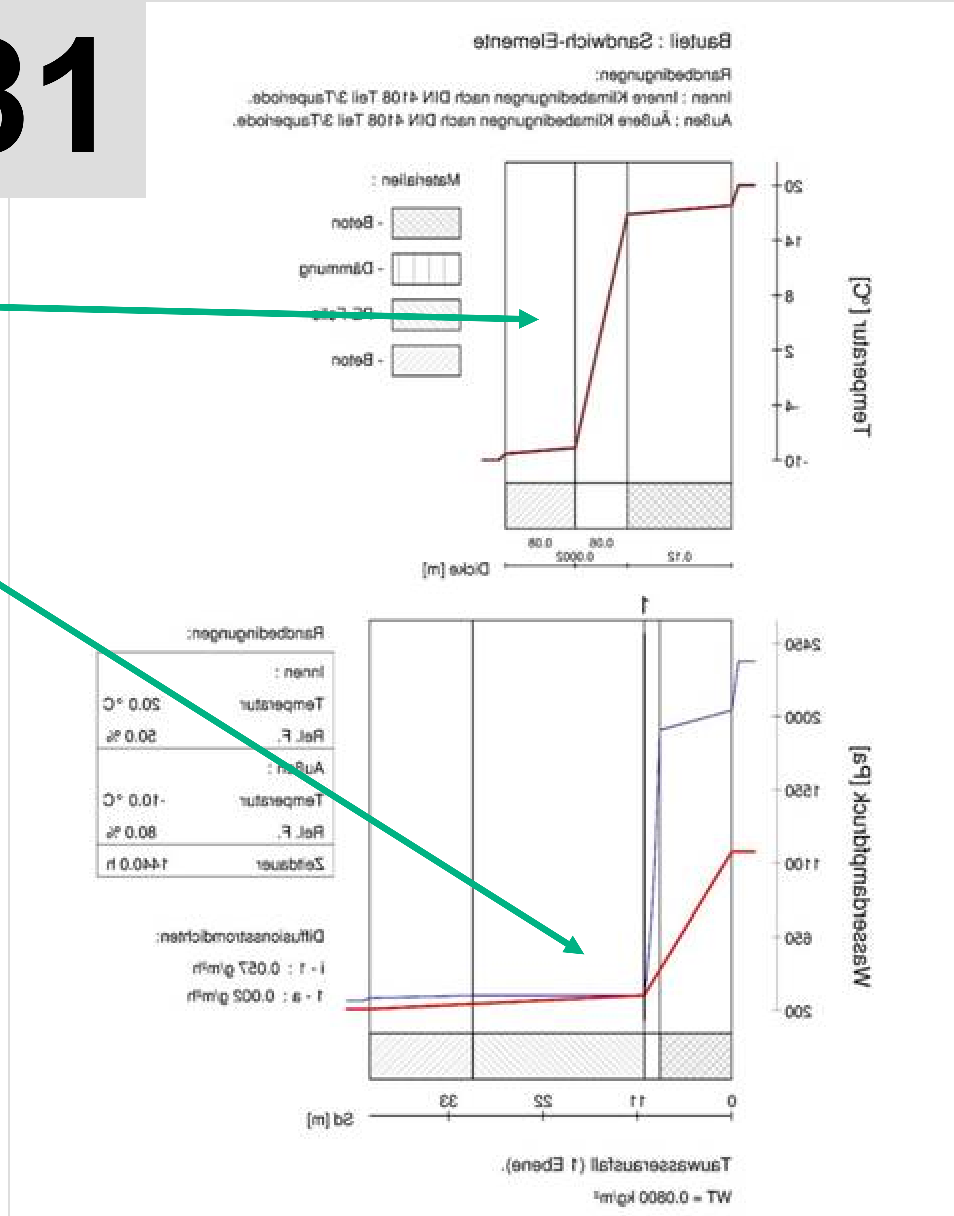
Assessing the risk of interior condensation by measuring surface temperature and outdoor climate conditions

Steady-state Calculation

1981

Glaser / Dew Point Method

- Determine temperature gradient for steady-state condensation conditions
- Plot vapour and saturation pressure gradients over diffusion resistance of building assembly to calculate the amount of condensate



Problems

- **no heat and moisture storage**
- **no liquid flow**
- **no coupling of heat and moisture transfer**

Today

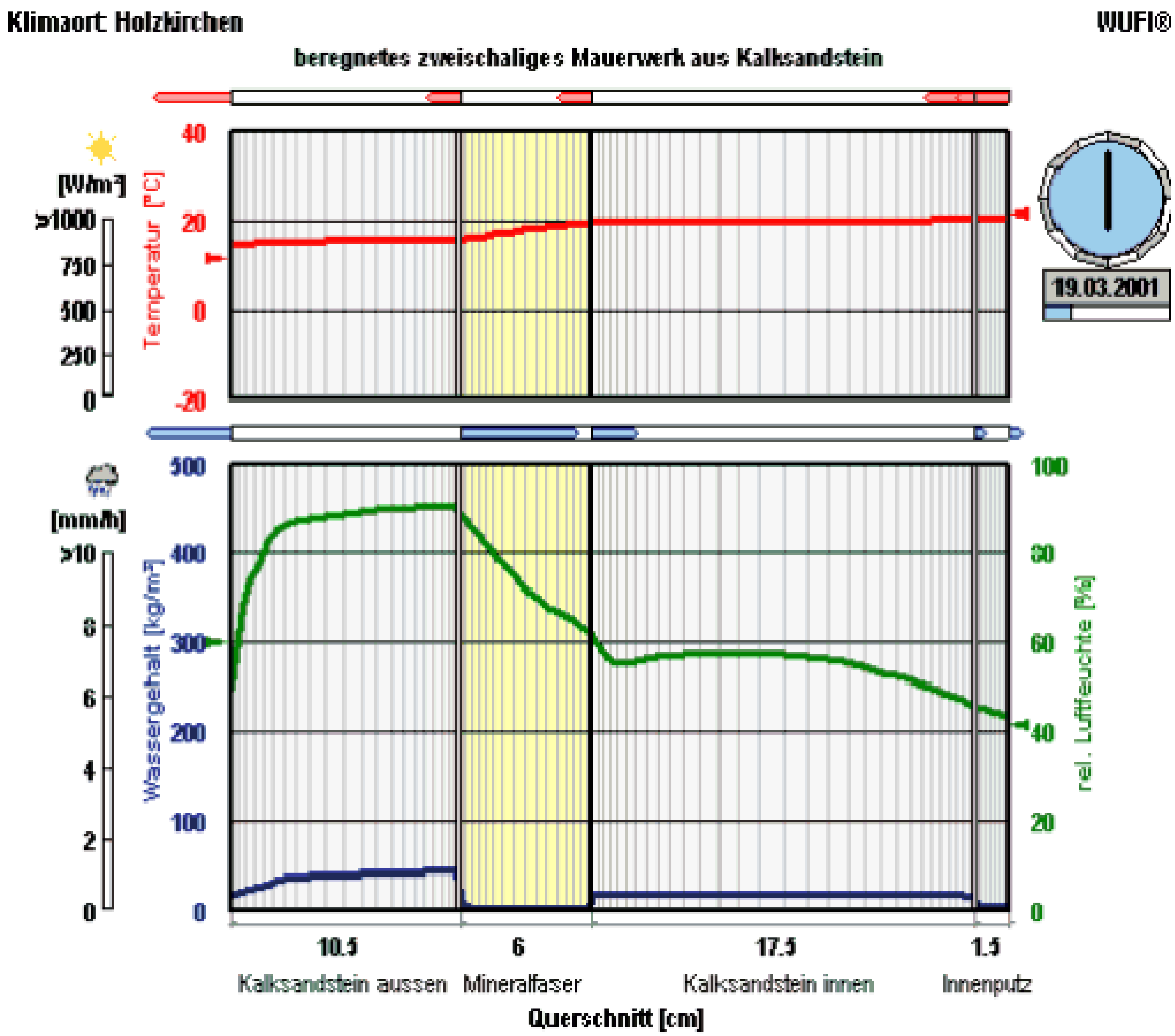
Moisture control by transient simulation according to:

prEN 15026

WTA-Guideline 6-2-01

ASHRAE 160P

ASTM MNL 40

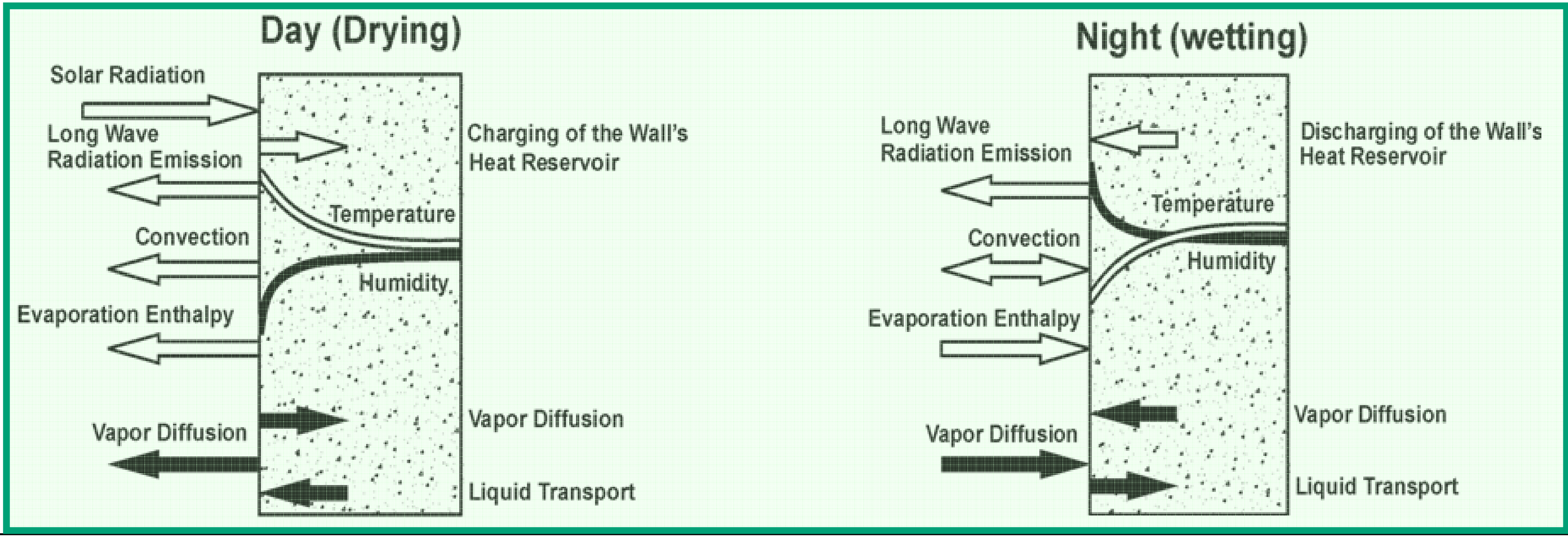


WUFI® simulation of west facing cavity wall MW insulation

Model Fundamentals

In addition to steady-state diffusion models like "Glaser" hygrothermal models must include:

- ► heat and moisture storage
- ► liquid flow
- ► coupling of heat and moisture transfer
- ► effects of radiation and rain



Model Fundamentals

Heat storage

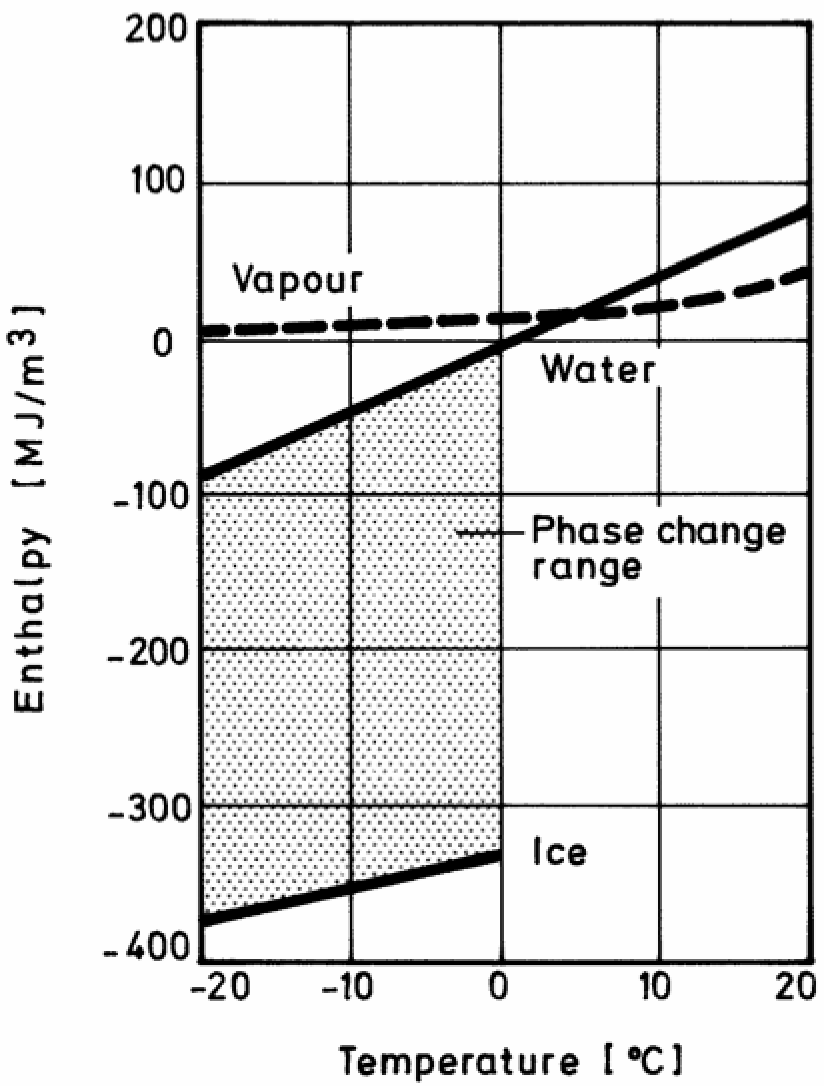
- Heat storage of dry material

$$h_d = \rho_s \cdot c_s \cdot \vartheta$$

- Heat storage wet material

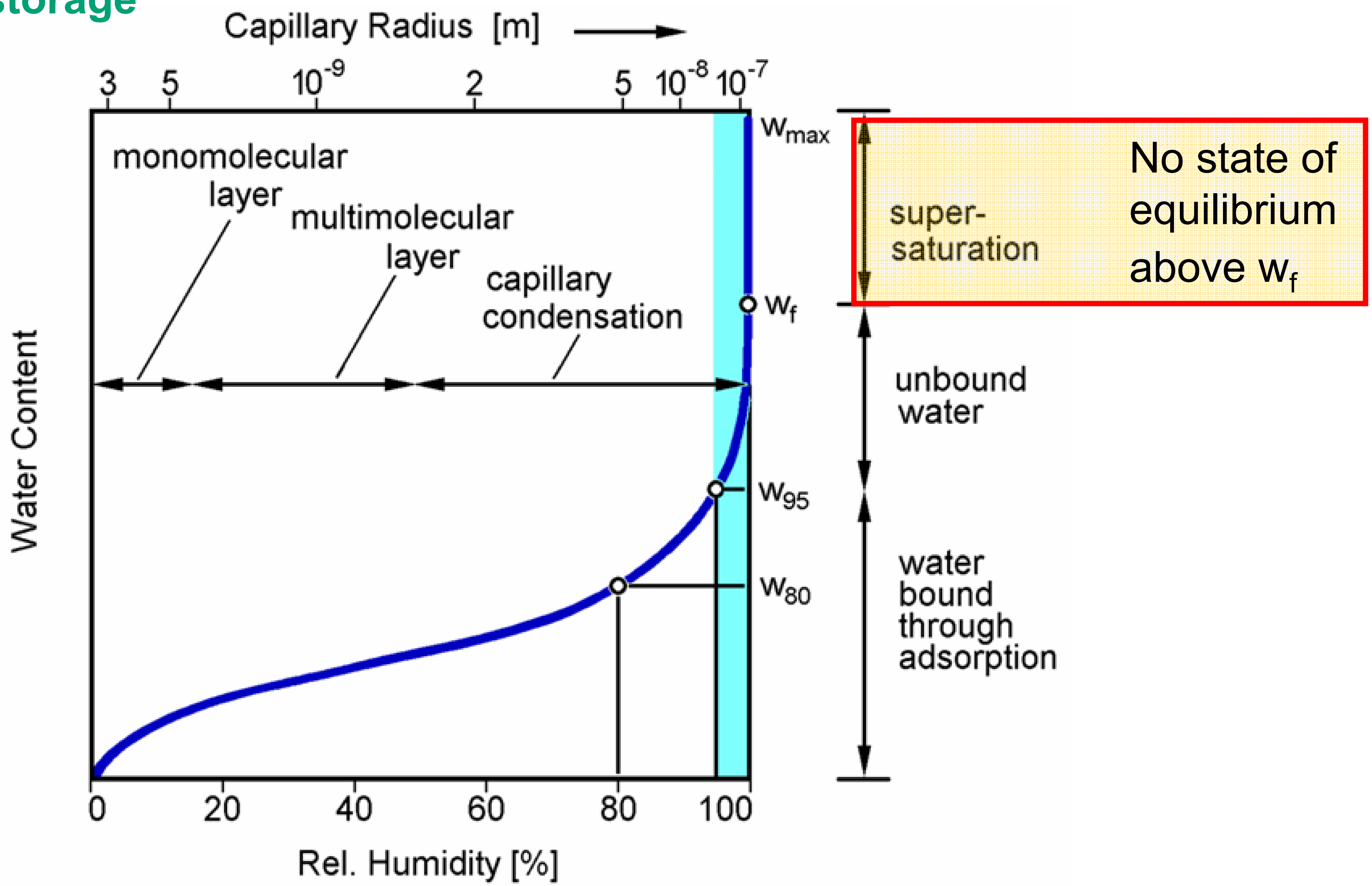
$$h_m = h_d + h_{water}$$

- Heat of fusion water (ice ↔ water)



Model Fundamentals

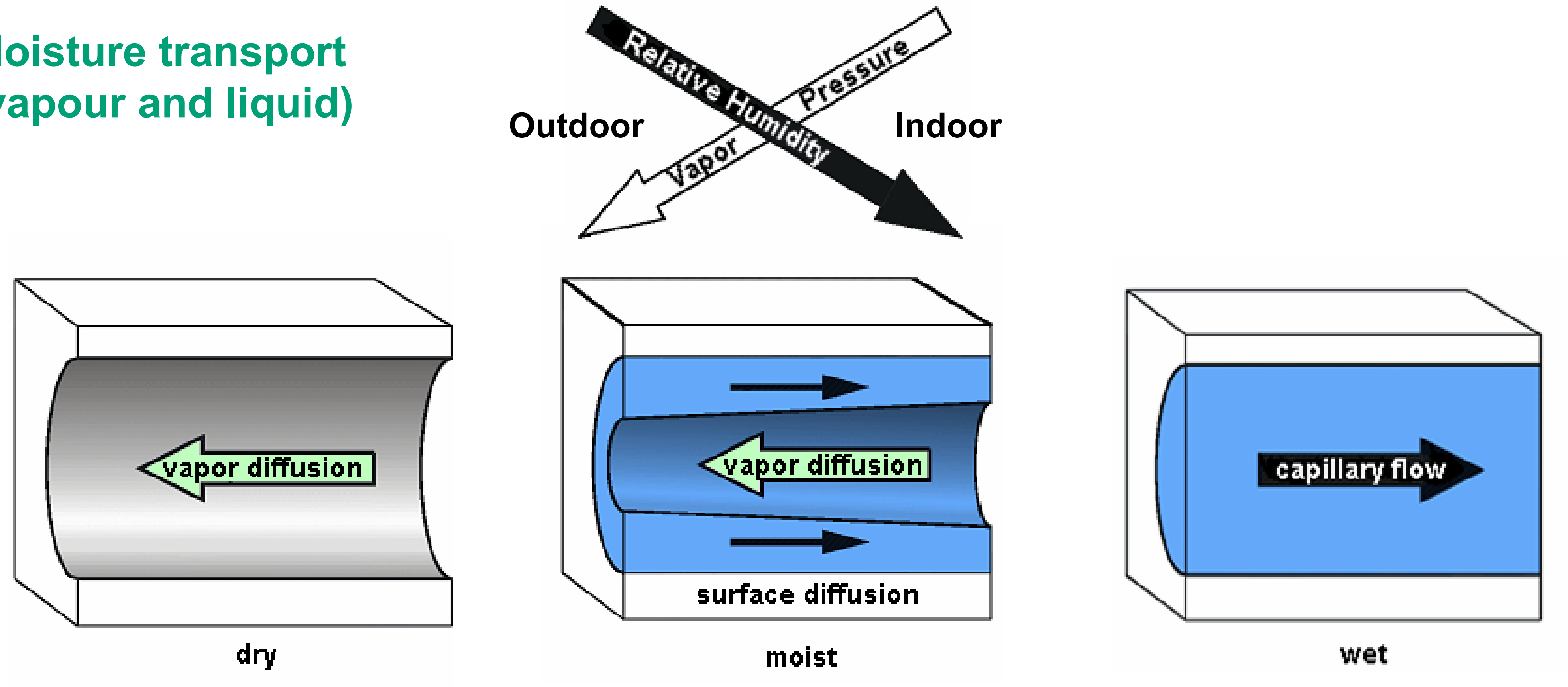
Moisture storage



Fraunhofer Institut Bauphysik

Model Fundamentals

Moisture transport (vapour and liquid)



$$g_v = -\frac{\delta}{\mu} \cdot \nabla p_v$$

$$g_l = -D_S \cdot \nabla \varphi$$

$$g_l = -D_{pc}(p_c) \cdot \nabla p_c - D_w(w) \cdot \nabla w - D_\varphi(w) \cdot \nabla \varphi$$

Model Fundamentals

Coupled transport equations

- Exponential increase of saturation pressure with temperature
- Moisture depending thermal conductivity
- Enthalpy flow by vapour diffusion with phase change

Coupled differential equations have to be solved numerically.

Heat transfer

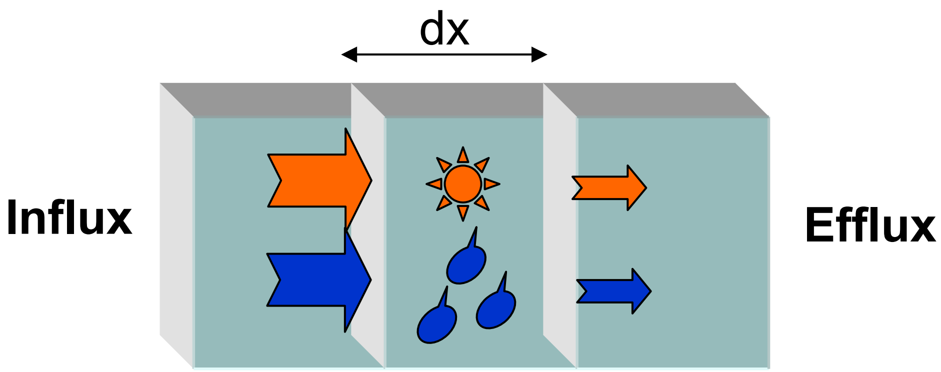
$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + h_v \nabla \cdot \left(\delta_p \nabla (\phi \, p_{sat})\right)$$

Moisture transfer

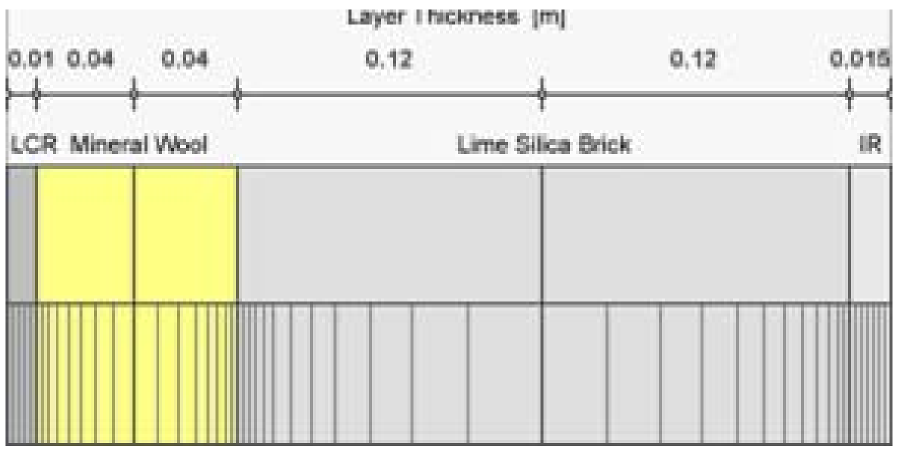
$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot \left(D_\phi \nabla \phi + \delta_p \nabla (\phi \, p_{sat})\right)$$

Model Fundamentals

- Conservative discretisation: implicit finite volumes
- Iterative coupling by subsequent solution of transfer equations with under-relaxation
- Matrix-solver: Thomas-Algorithm (1D) or ADI (2D)



$$\frac{\partial}{\partial t} A = -\vec{\nabla} \cdot \vec{a} + \text{Sources} / \text{Sinks}$$



Building Envelope Design by Hygrothermal Simulations

construction details

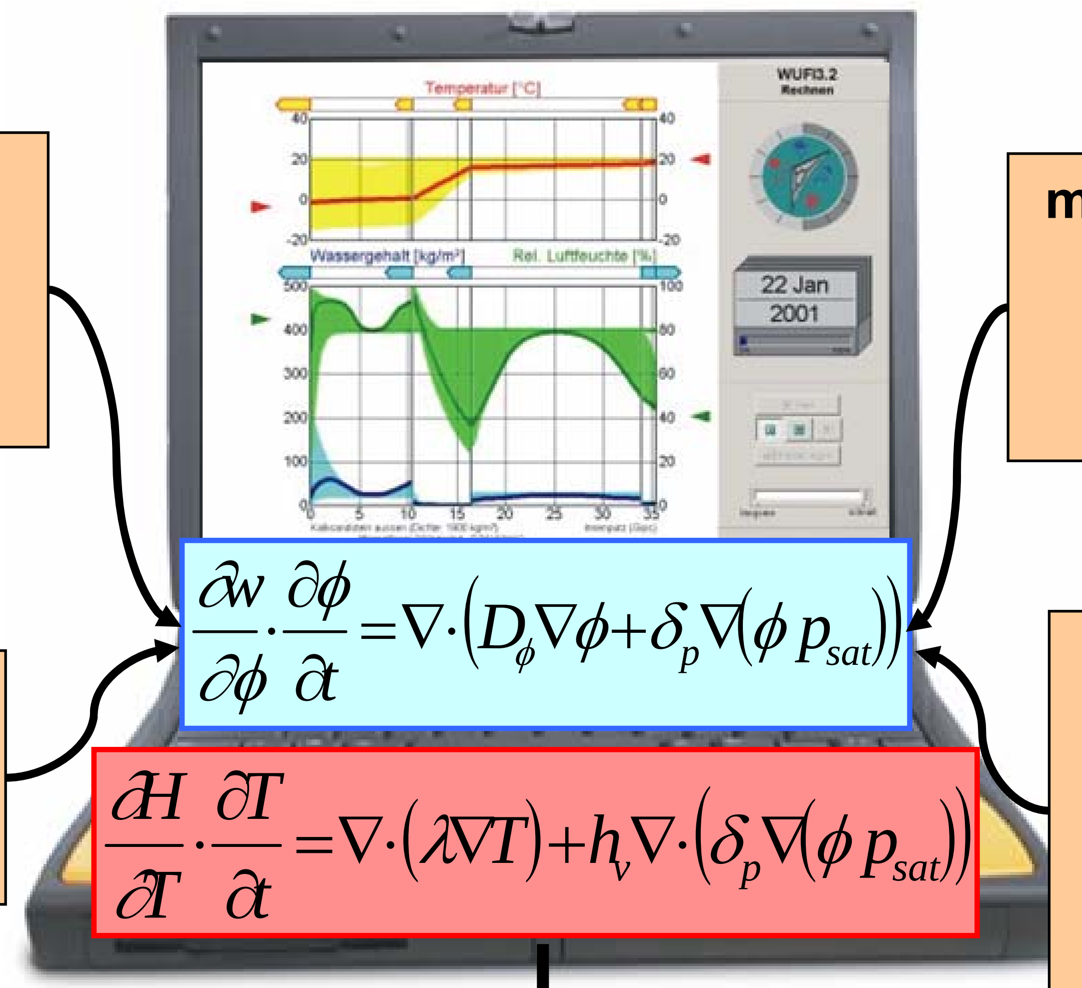
orientation inclination

material properties

ρ, c, λ, μ

$w = f(\varphi)$

$D_w = f(w)$



$$\frac{\partial w}{\partial \phi}\cdot\frac{\partial \phi}{\partial t} = \nabla\cdot\left(D_\phi \nabla\phi + \delta_p \nabla(\phi\, p_{sat})\right)$$

$$\frac{\partial H}{\partial T}\cdot\frac{\partial T}{\partial t} = \nabla\cdot(\lambda\nabla T) + h_v \nabla\cdot\left(\delta_p\nabla(\phi\, p_{sat})\right)$$

initial conditions

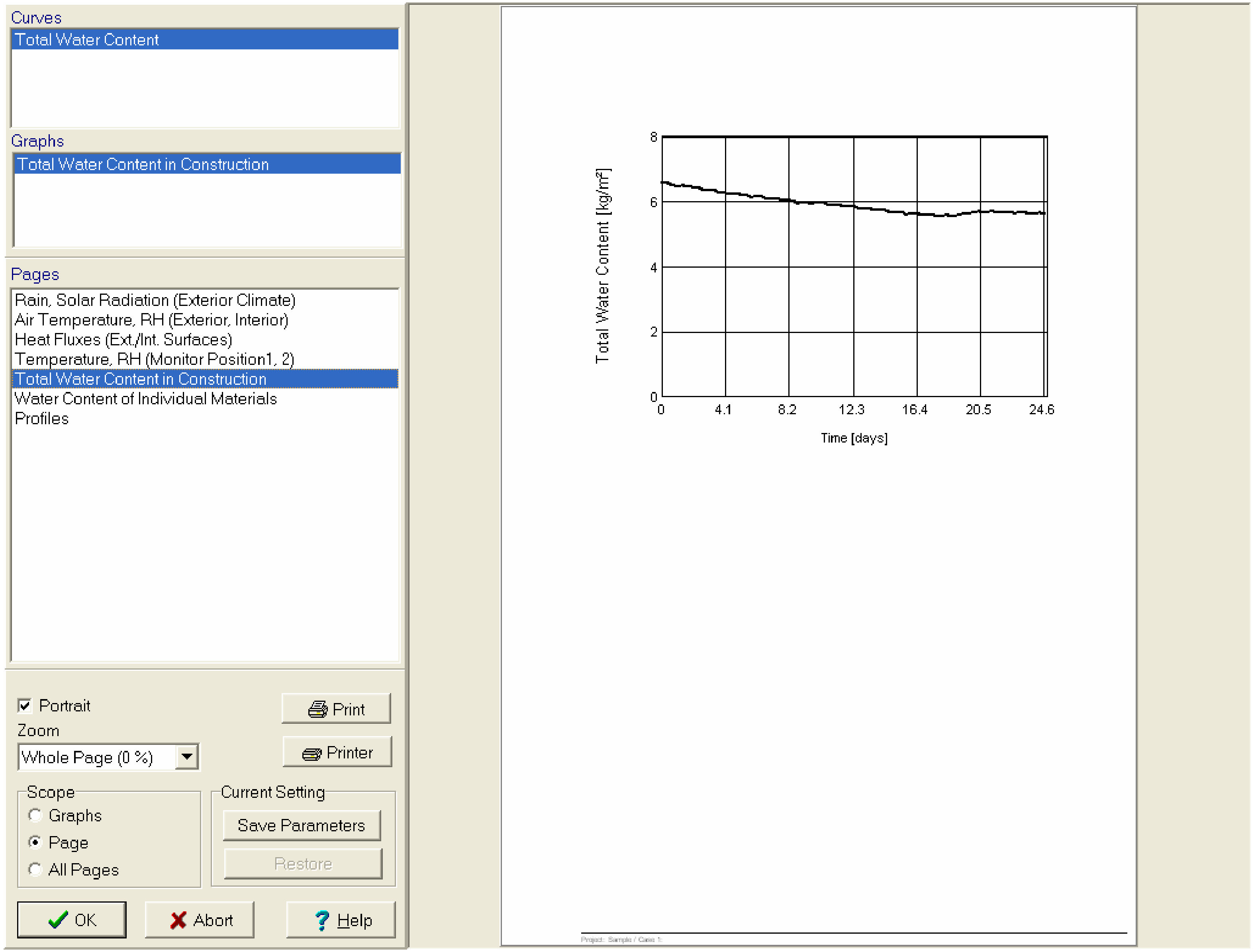
e.g. construction moisture

climate conditions

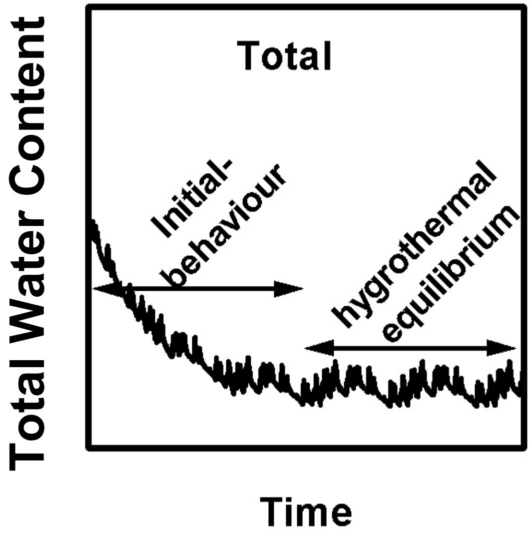
temperature, RH, radiation, precipitation, wind speed & direction

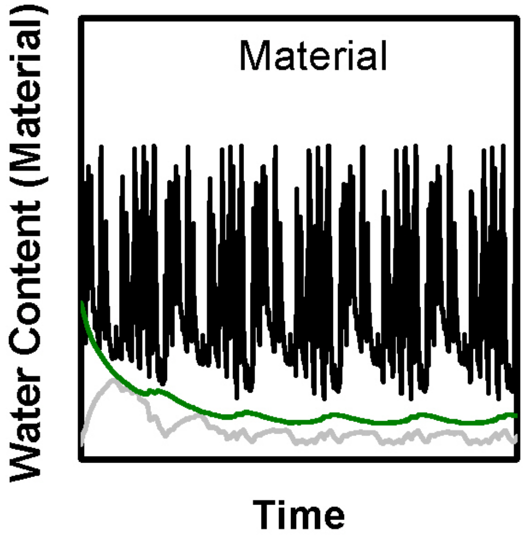
dynamic temperature and moisture profiles
heat and moisture fluxes

Building Envelope Design by Hygrothermal Simulations



Water Content





Performance Criteria:

$u_{max.}$

$u_{min.}$

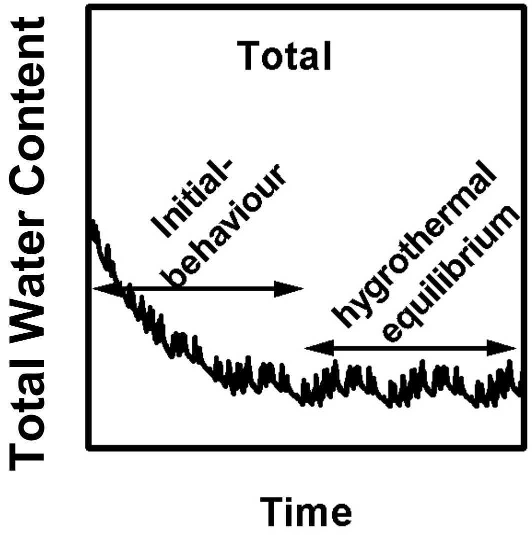
u_{End}

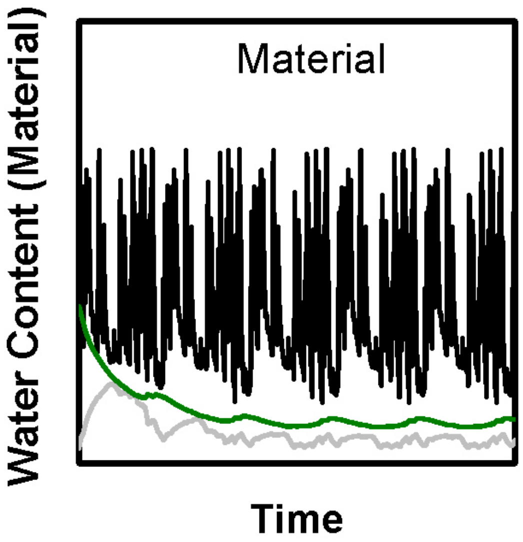
Drying-Out Time

Time with specific criteria

...

Water Content

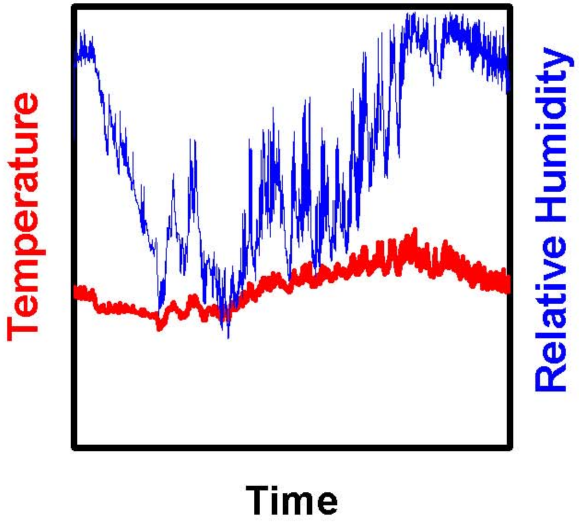


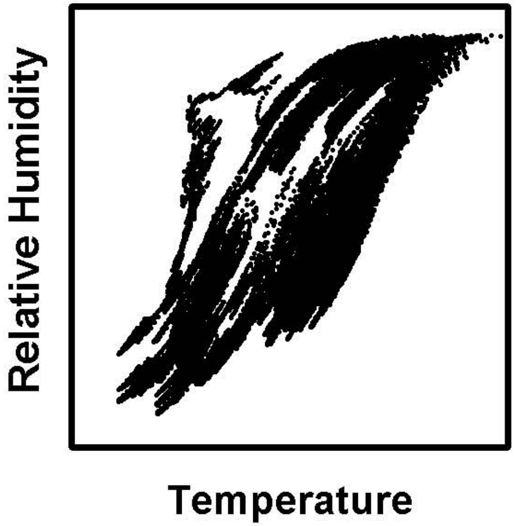


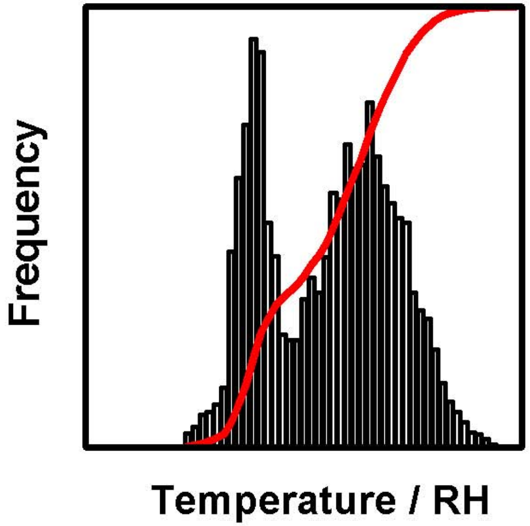
Performance Criteria:

$u_{max.}$
$u_{min.}$
u_{End}
Drying-Out Time
Time with specific criteria
…

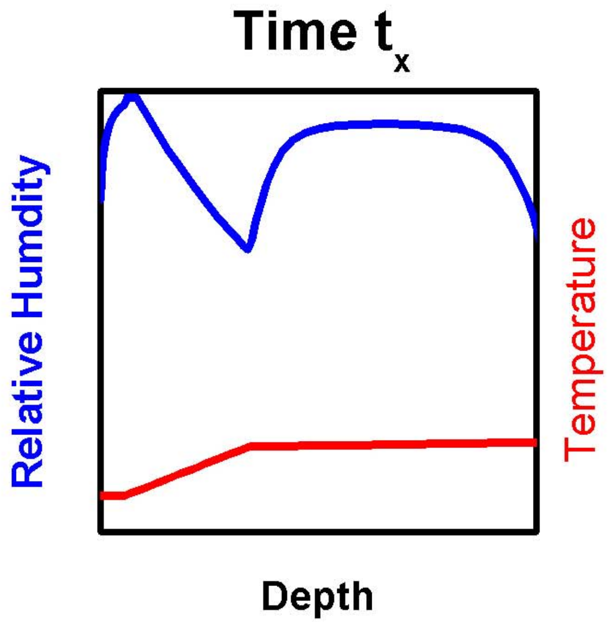
Hygrothermic Situation at Critical Points of the Construction



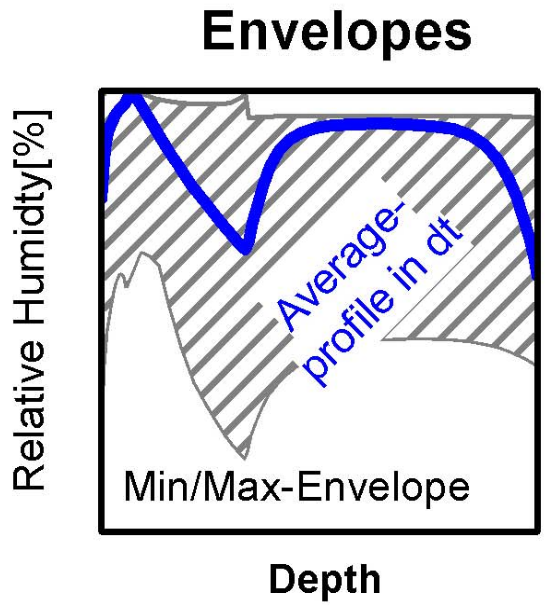




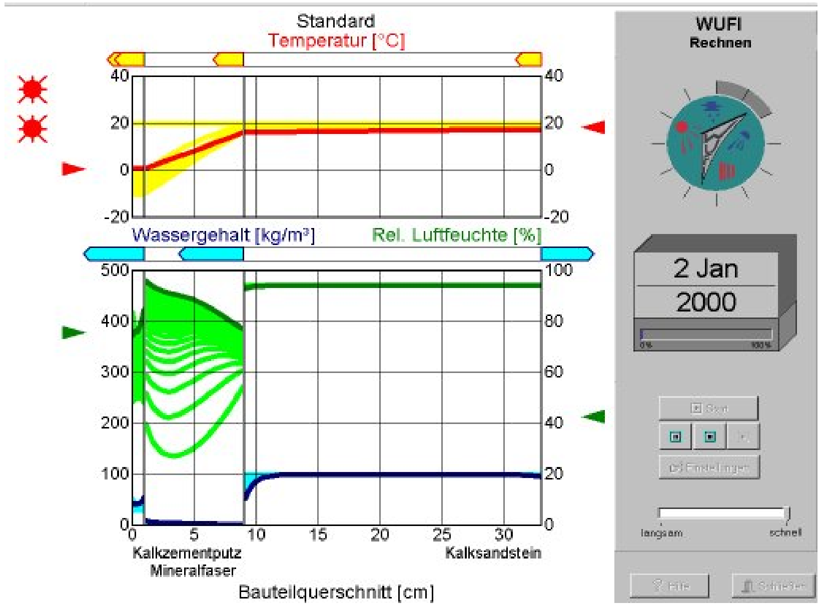
Profiles



Time t_x
Relative Humdity
Temperature
Depth



Envelopes
Relative Humidty[%]
Average-profile in dt
Min/Max-Envelope
Depth



Standard
Temperatur [°C]
Wassergehalt [kg/m³]
Rel. Luftfeuchte [%]
Kalkzementputz
Mineralfaser
Kalksandstein
Bauteilquerschnitt [cm]
WUFI
Rechnen
2 Jan
2000
langsam
schnell

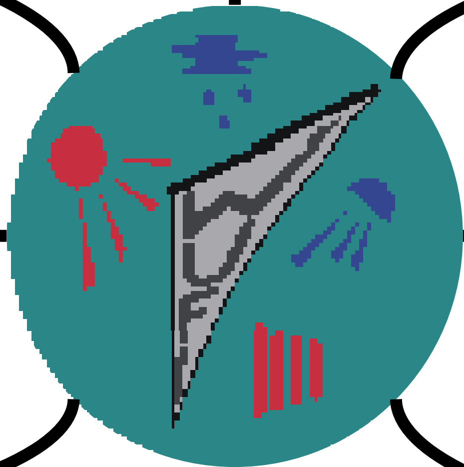
Building Envelope Design by Hygrothermal Simulations

Transfer to different climate zone

Different types of indoor environment

Extrapolation (long-term behavior)

Development and optimization of building products



Hygrothermal loads

Microbial growth (mold / algae)

Corrosion

Frost damages

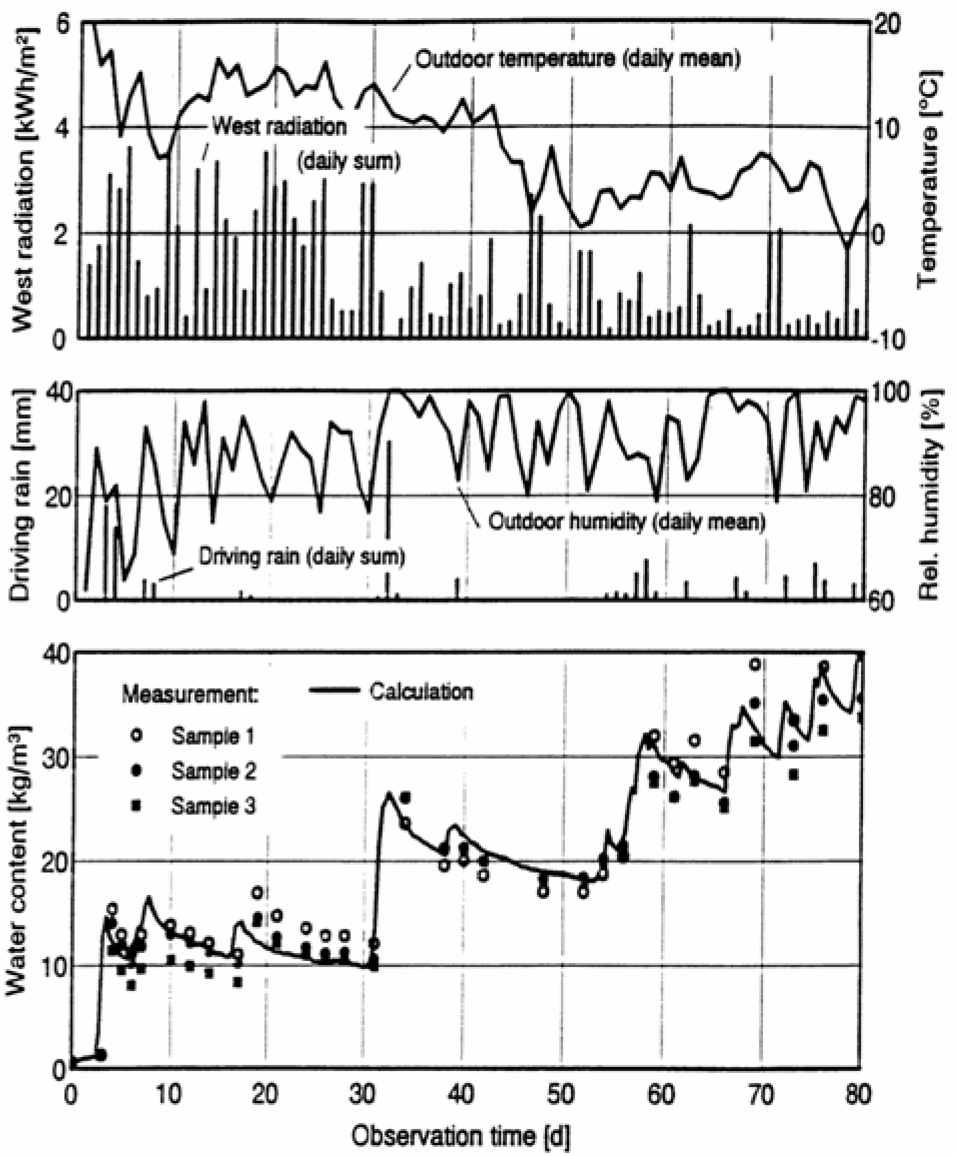
Experimental Validation

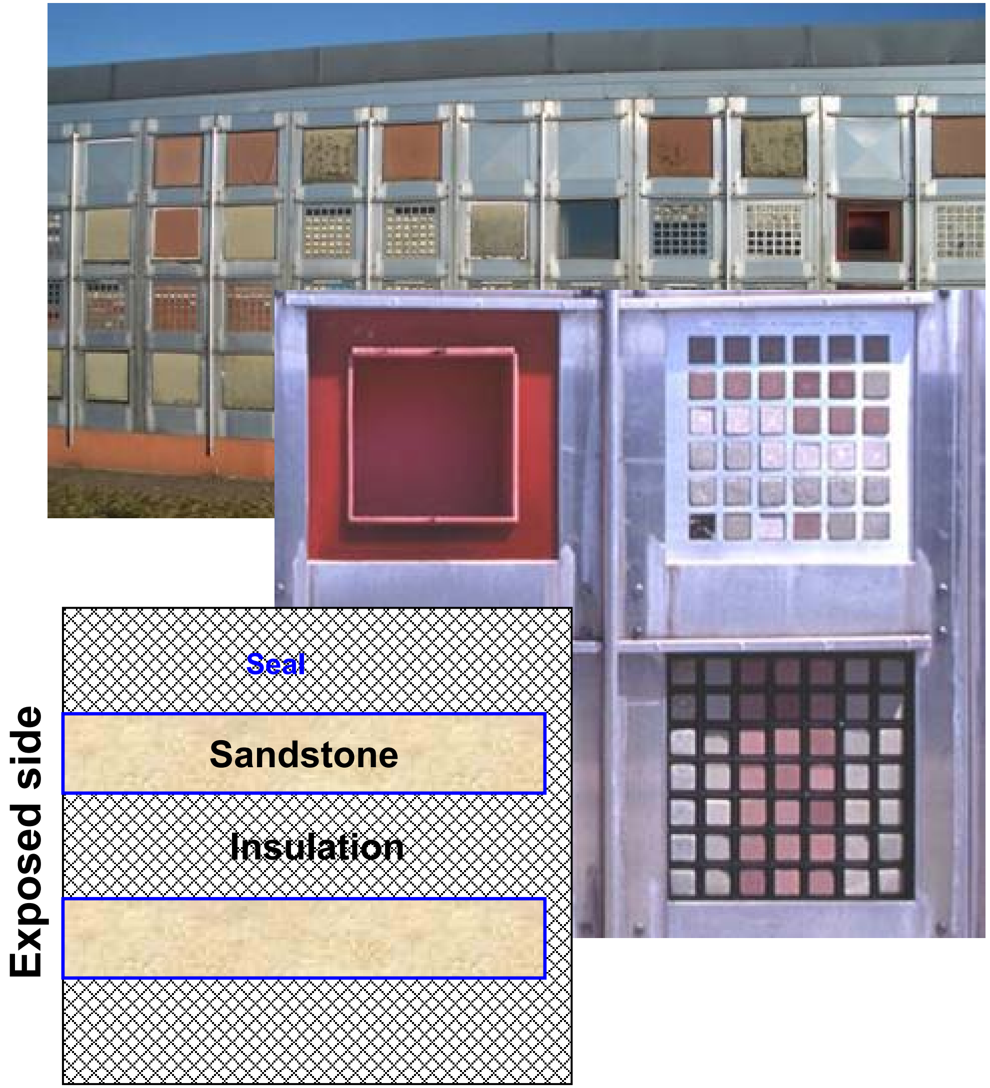
Prerequisites:

- well defined material parameters (measured for the same material)
- hourly recording of boundary conditions (natural climate)
- periodic or continuous readings of total water content (weighing) and moisture profiles (e.g. NMR- scanning)

IBP weather station

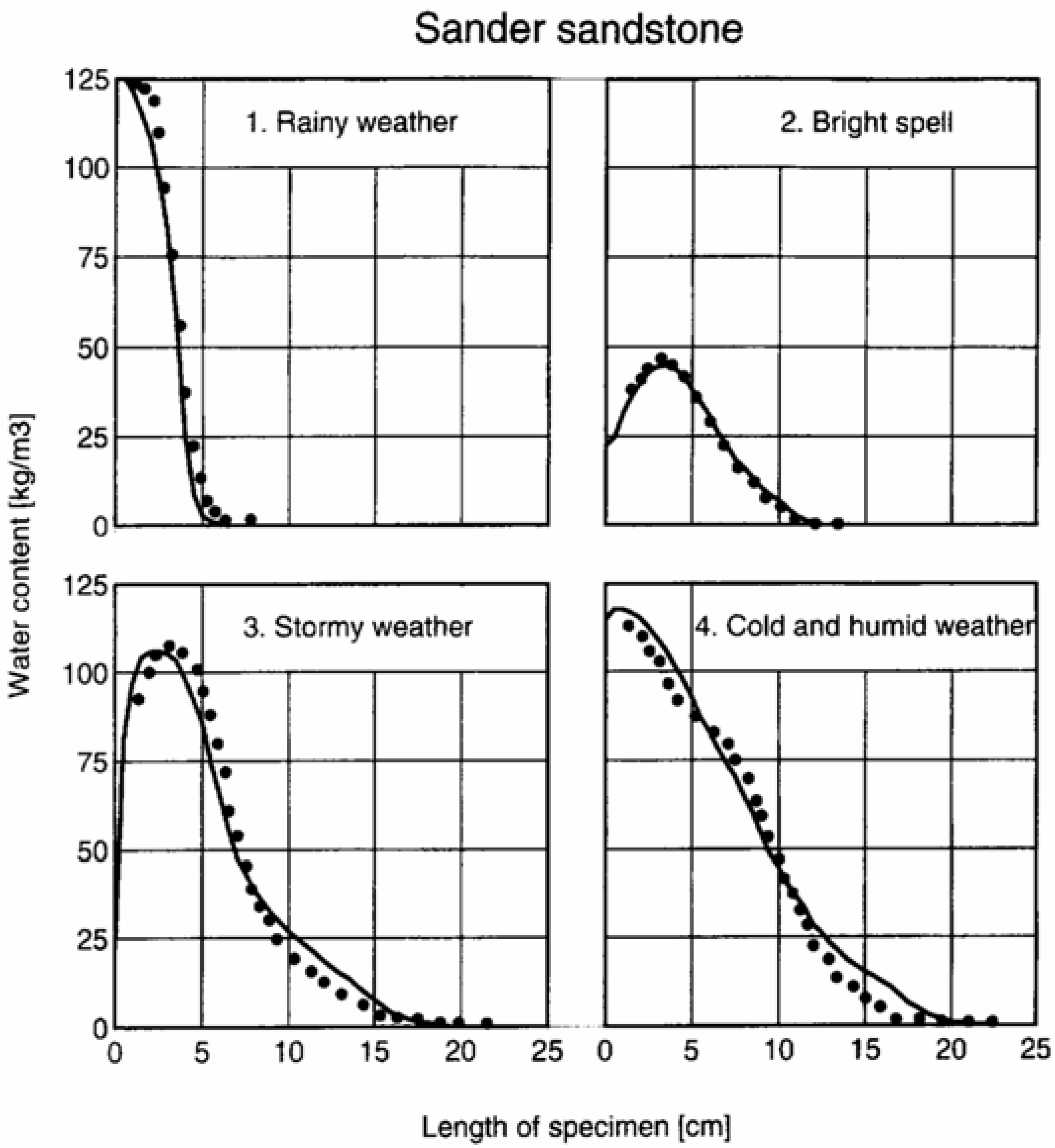
Experimental Validation





Comparison of total water content

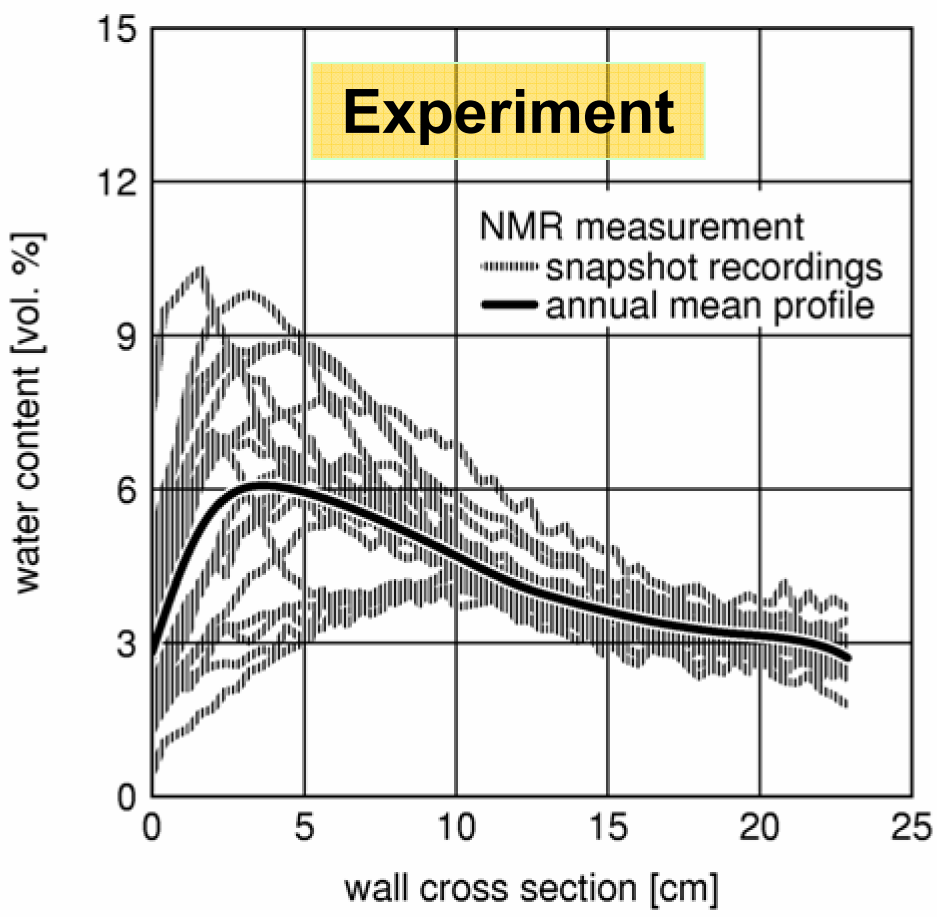
Experimental Validation

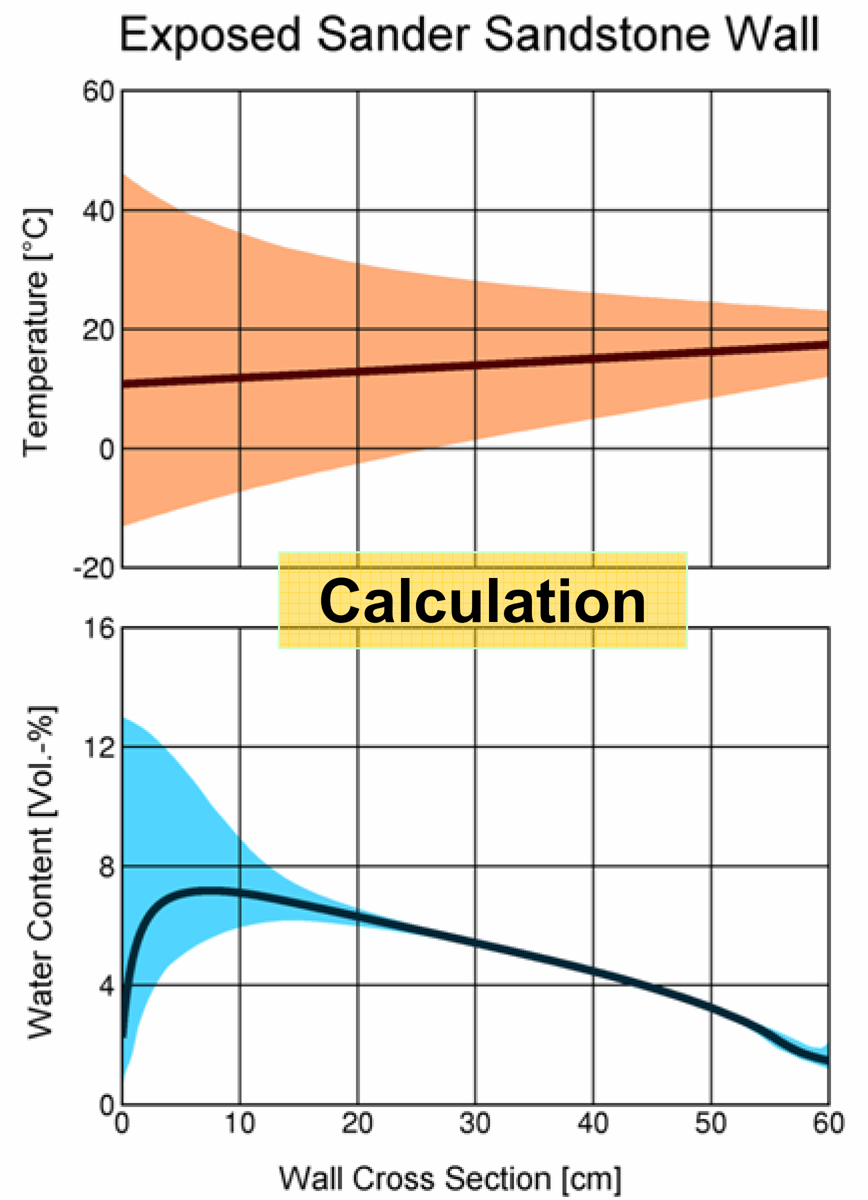


NMR-Scanner

Comparison of moisture distributions during a test period of 80 days

Experimental Validation

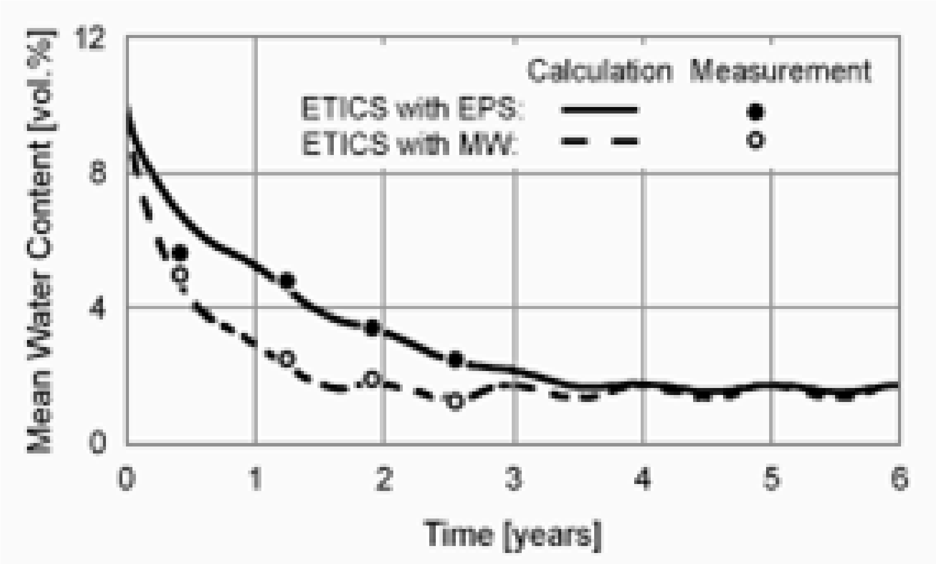


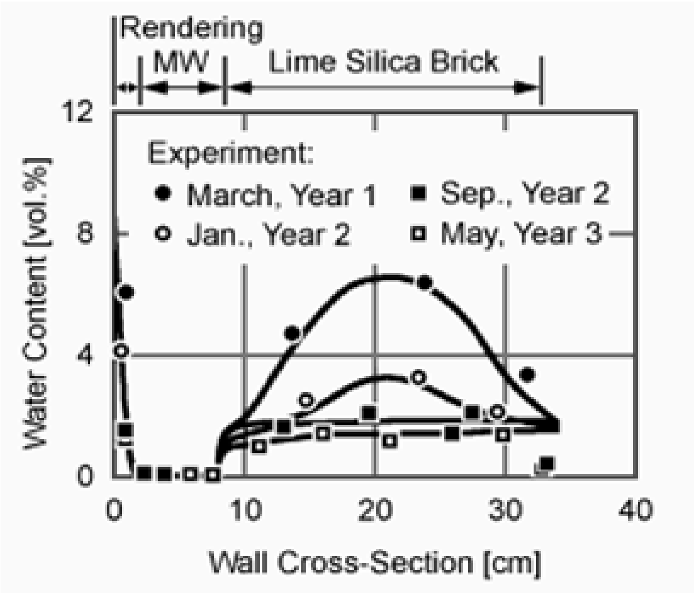


Comparison of long-term moisture profiles

Fraunhofer Institut Bauphysik

Experimental Validation



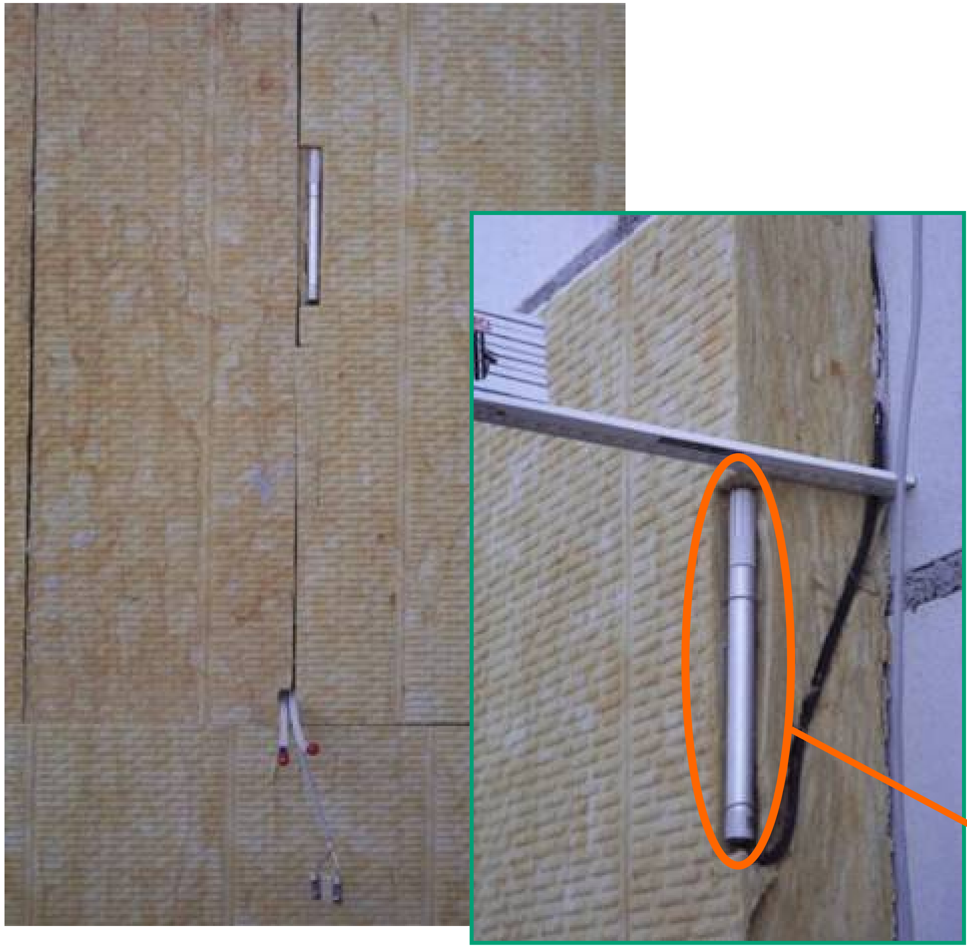


CSB wall with exterior insulation

Practice case: drying of construction moisture

Experimental Validation

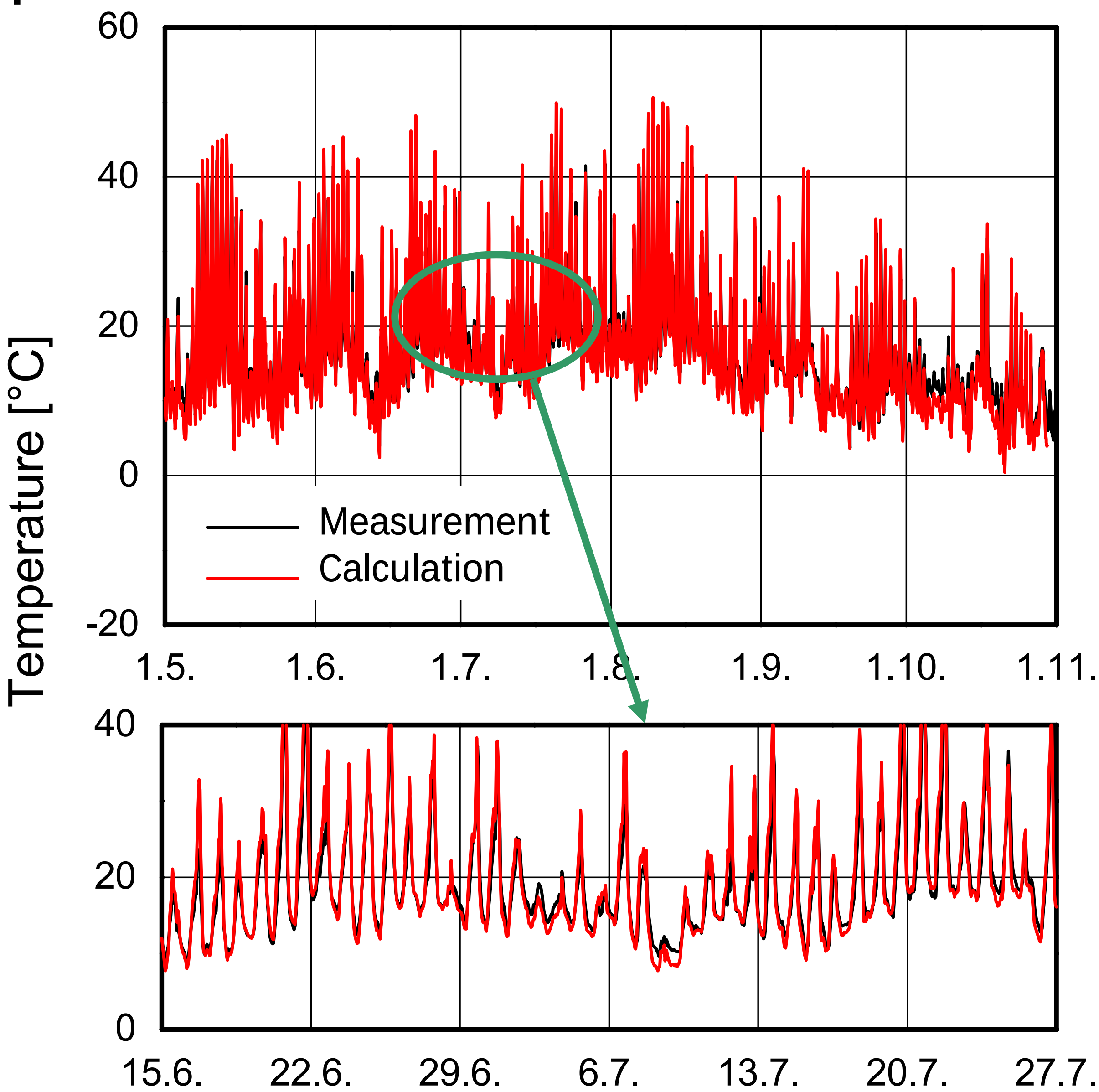
Comparison of temperature and RH fluctuations



RH (capacitive sensor)
& temperature (PT100)

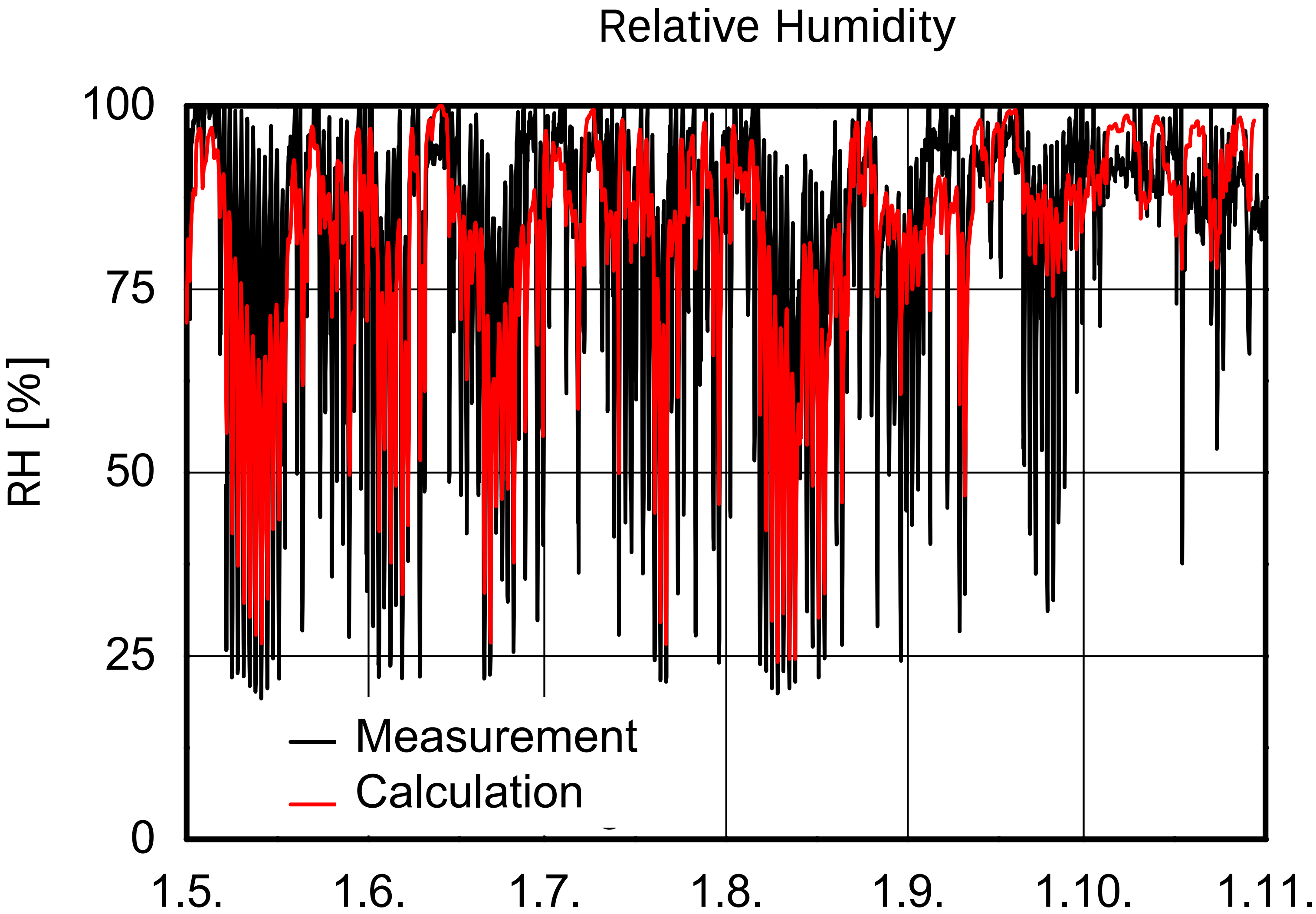
Building Envelope Design by Hygrothermal Simulations

Experimental Validation



Measured and simulated temperature fluctuation at the exterior surface of the insulation layer of west facing wall

Experimental Validation

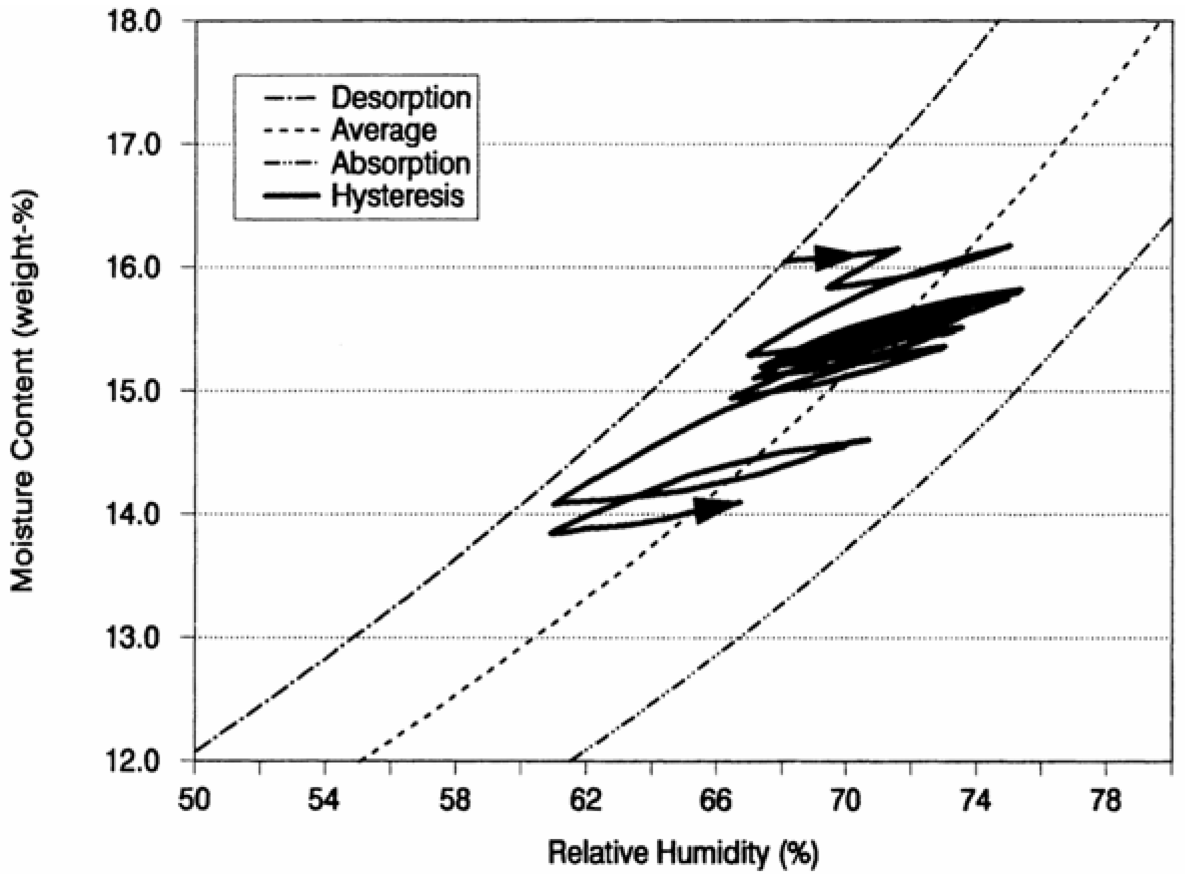


Measured and simulated RH fluctuation at exterior surface of the insulation layer of west facing wall

Experimental Validation

Local sorption equilibrium is not always achieved when fluctuations become very large:

- ► RH peaks dampened
- ► water content variations are still correct



Fraunhofer Institut Bauphysik

Limitations of the Model

Every model has its shares of limitations. The user must be aware of what the model can do and cannot do.

Limitations of the Model

Every model has its shares of limitations. The user must be aware of what the model can do and cannot do.

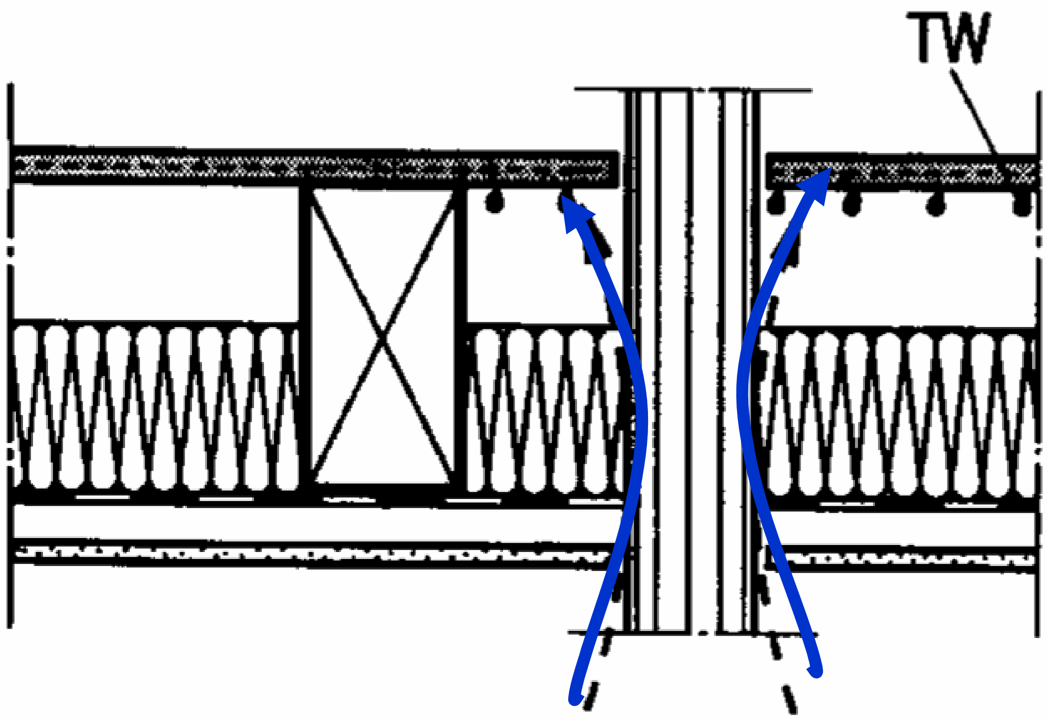
- More-dimensional structures

Limitations of the Model

Every model has its shares of limitations. The user must be aware of what the model can do and cannot do.

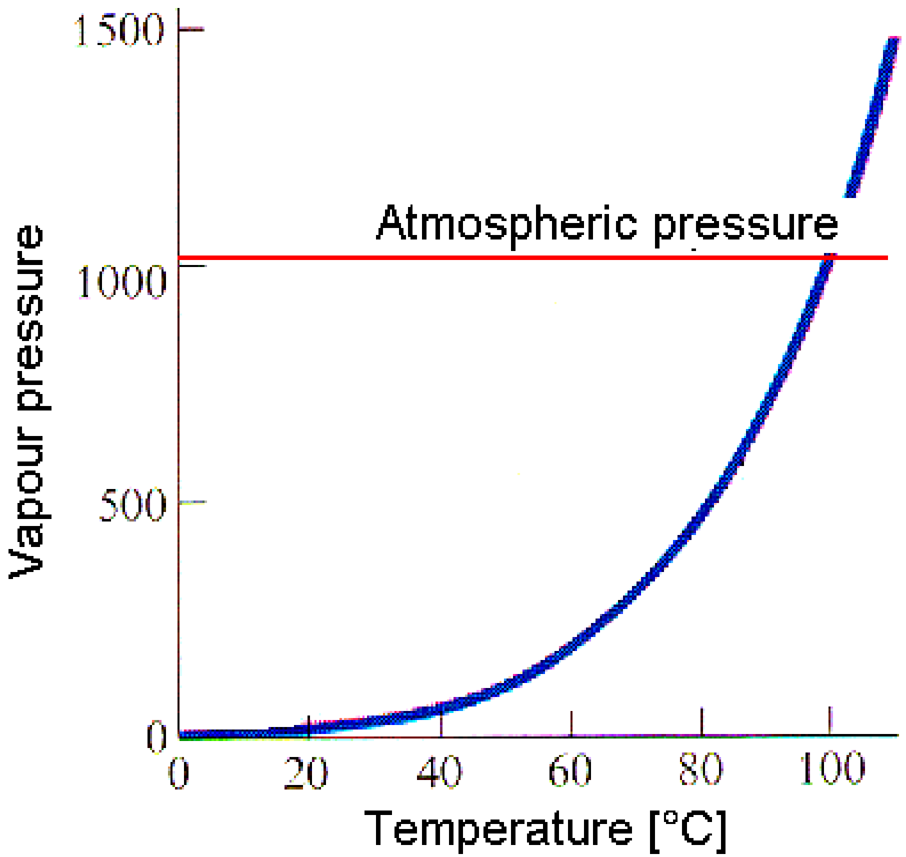
- More-dimensional structures

- Special transport phenomena (e.g. convection)



Boundary Conditions

- temperatures >> 70 °C (for example in case of fire)



Conclusions and Outlook

Benefits of hygrothermal envelope simulations:

- **visualization of dynamic heat and moisture transfer process**
  - **diurnal cycles (e.g. summer condensation)**
  - **seasonal cycles (e.g. winter condensation)**
  - **wetting/drying cycles (e.g. rain/sunshine)**
- **distinction of relevant parameters (sensitivity analysis)**
- **extrapolation in time, transfer to different indoor or outdoor climate**
- **product adaptation, optimization and development**

Hygrothermal simulations are fast and cost-effective, but:

- **simulation results depend on reliability of input data**
- **user’s expertise required !!!**

Conclusions and Outlook

WUFI®-courses

Germany, Holzkirchen, Stuttgart, Hannover > 25x

Switzerland, Zürich (EMPA) 2x

Austria, Vienna (TU Wien) 2x

Finland, Helsinki (VTT)

Japan, Tokyo (Ochanomizu University)

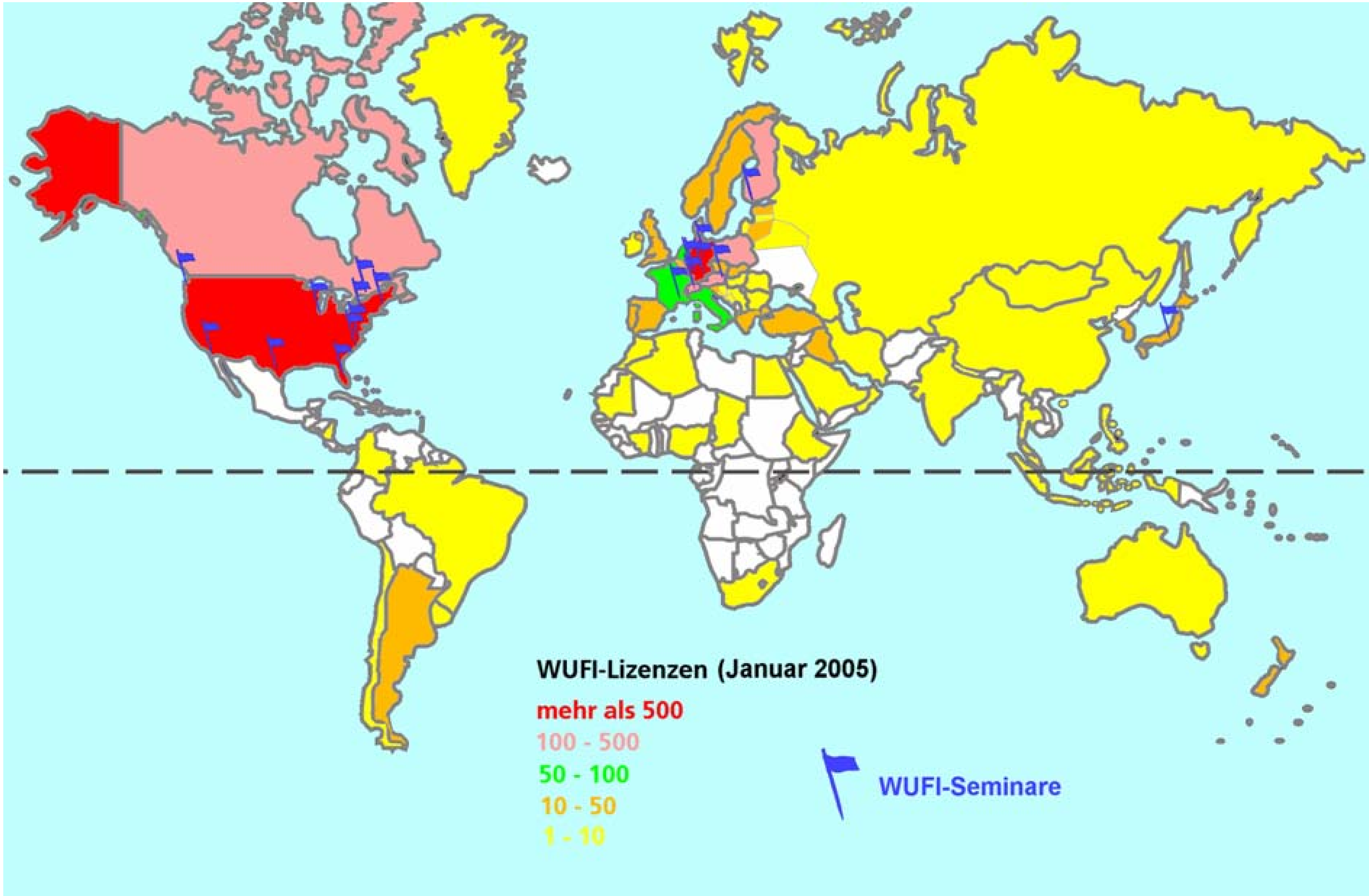
Canada, Montreal (Université Concordia)

USA (ORNL) 10x (**Pennstate** University (PA), **Charleston** (SC), ASTM-Conference, **Boston** (MA), Boston Society of Architects **Seattle** (WA), Wash. State Univ., **Clemson** (SC), Clemson Univ., **San Diego** (CA), DOE workshop, **Chicago** (IL), DOE workshop, **Philadelphia** (PA), CT course, **Clearwater Beach** (FL), Buildings IX-Conference, **San Antonio**, (Tx) DOE workshop)

Cooperations to develop country specific WUFI®-versions

USA (ORNL = Oak Ridge National Laboratory)
Finland (VTT Building Technology)
France (CSTB Grenoble)
Poland (TU-Lodz)
Norway (NBI/NTNU)
Japan (Ochanomizu University)
Brazil (University Santa Catarina) *in preparation*

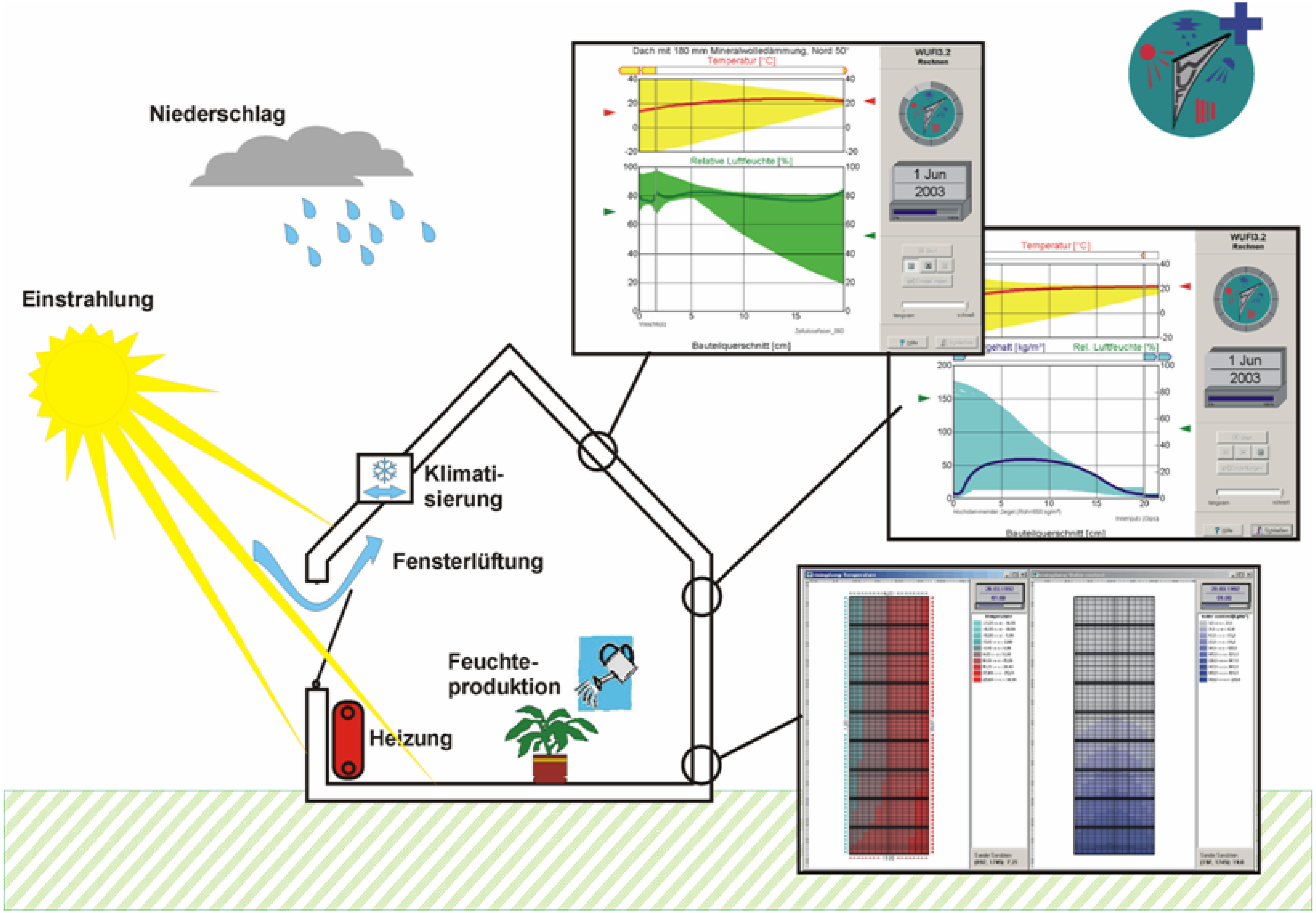
Building Envelope Design by Hygrothermal Simulations



Building Envelope Design by Hygrothermal Simulations

WUFI® R&D-team: Eitner, Pankratz, Kehrer, Zirkelbach, Künzel, Schmidt

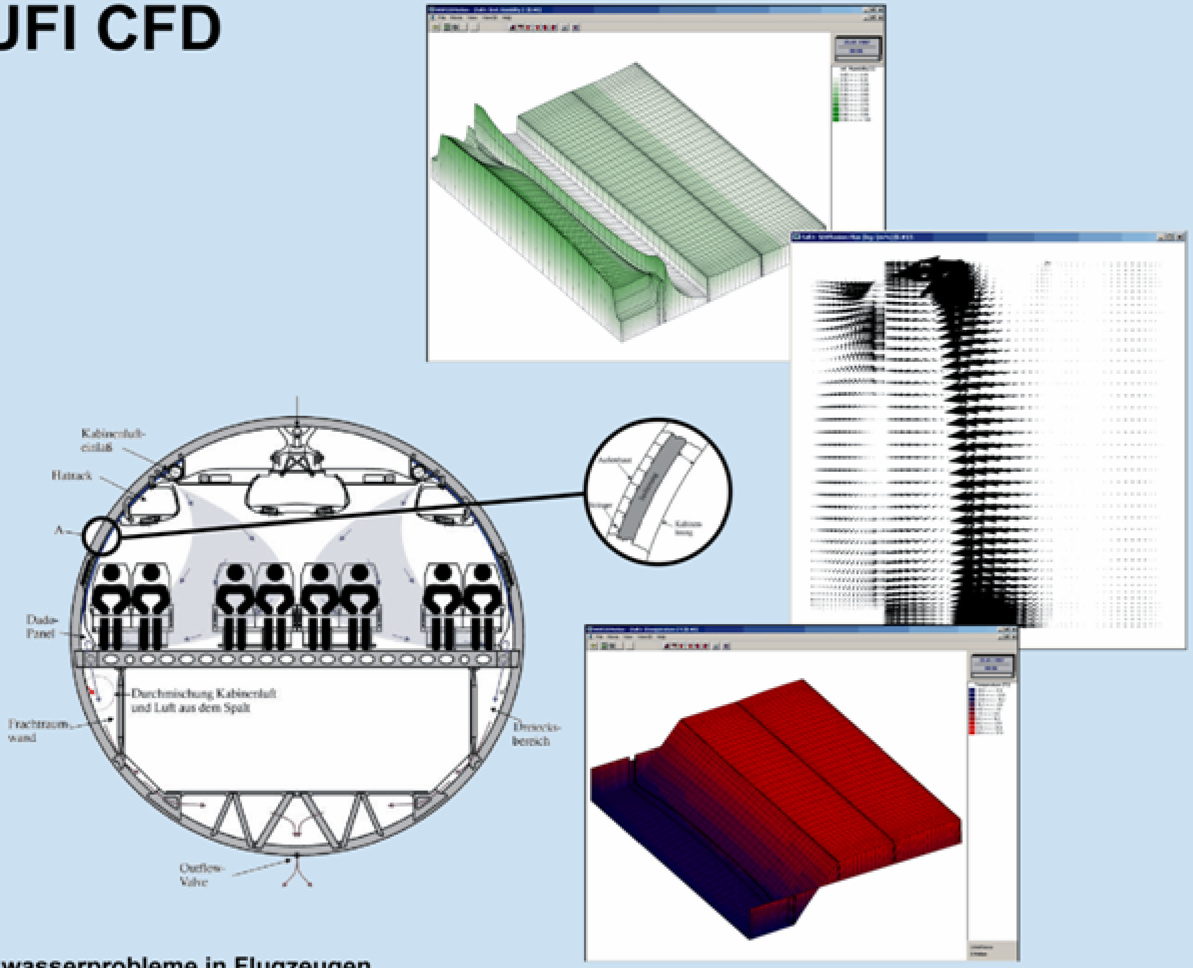
Outlook: hygrothermal building simulation (WUFI®-Plus)



Fraunhofer Institut Bauphysik

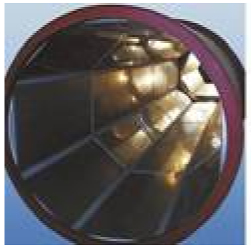
Outlook: CFD simulation with moisture transfer (WUFI®-CFD)

WUFI CFD

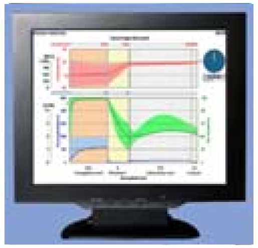
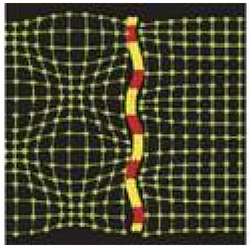


Tauwasserprobleme in Flugzeugen

Fraunhofer Institut Bauphysik






Hartwig M. Künzel
Andreas Holm
Daniel Zirkelbach

Building Envelope Design by Hygrothermal Simulations

IBP
Fraunhofer Institut Bauphysik