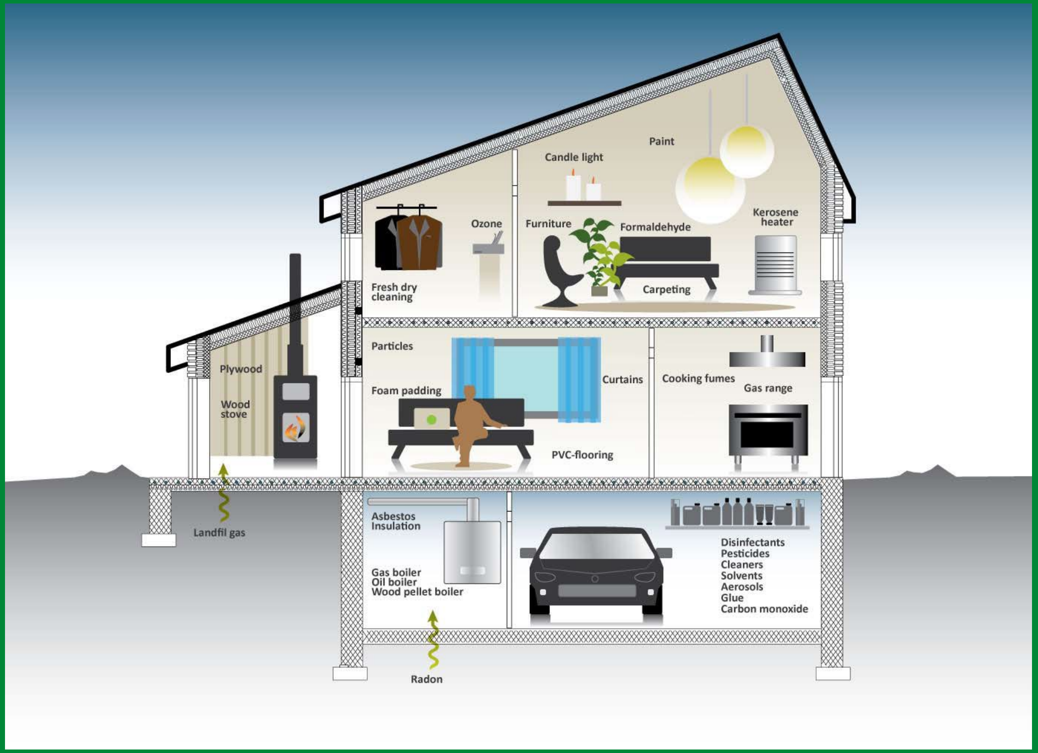
DTU-UMD Workshop on HVAC and Dehumidification Technologies

Ups and downs in moisture control – use of building physics knowledge to do it right

Prof. Carsten Rode

DTU Sustain, Technical University of Denmark



Source: International Center for Indoor Environment and Energy, DTU

Agenda

- IEA EBC Projects:
  - Annex 14, Condensation and Energy
  - Annex 24, Heat, Air and Moisture Transport
  - Annex 41, *Whole Building Heat, Air and Moisture Response*
  - Annex 68, *Design and Operational Strategies for High IAQ in Low Energy Buildings*
  - Annex 86, *Energy Efficient Indoor Air Quality Management in Residential Buildings*
- Materials in structures and in contact with indoor environments
  - Vapour retarders
  - Moisture buffering
  - Bio-based solutions
  - Innovative materials for IAQ management.
- Climate change, Quality, and Caring for sustainability

IEA EBC Projects

- Annex 14 - *Condensation and Energy* (1987 - 1990)
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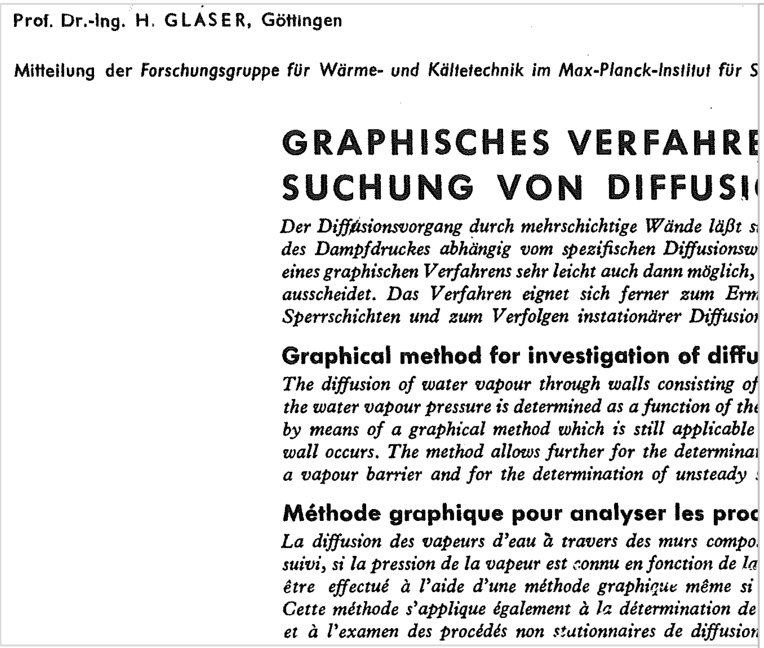
Glaser's method


Prof. Dr.-Ing. H. GLASER, Göttingen

Mitteilung der Forschungsgruppe für Wärme- und Kältetechnik im Max-Planck-Institut für S

GRAPHISCHES VERFAHRE
SUCHUNG VON DIFFUSI

Der Diffusionsvorgang durch mehrschichtige Wände läßt s
des Dampfdruckes abhängig vom spezifischen Diffusionsw
eines graphischen Verfahrens sehr leicht auch dann möglich,
ausscheidet. Das Verfahren eignet sich ferner zum Erm
Sperrschichten und zum Verfolgen instationärer Diffusio

Graphical method for investigation of diffu

The diffusion of water vapour through walls consisting of
the water vapour pressure is determined as a function of the
by means of a graphical method which is still applicable
wall occurs. The method allows further for the determina
a vapour barrier and for the determination of unsteady

Méthode graphique pour analyser les proc

La diffusion des vapeurs d'eau à travers des murs compo
suivi, si la pression de la vapeur est connu en fonction de la
être effectué à l'aide d'une méthode graphique même si
Cette méthode s'applique également à la détermination de
et à l'examen des procédés non stationnaires de diffusion

- Steady state
- Water vapour diffusion (only)
- Simplified boundary conditions

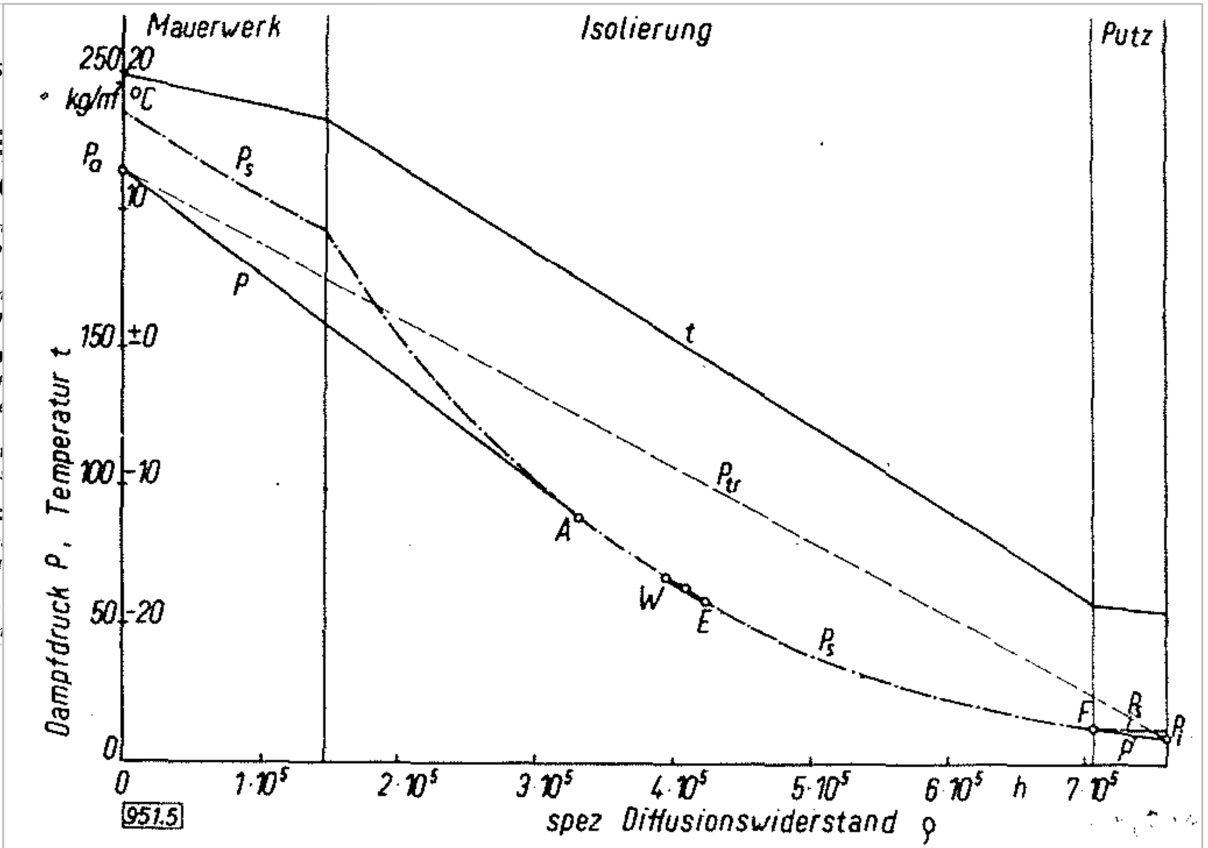
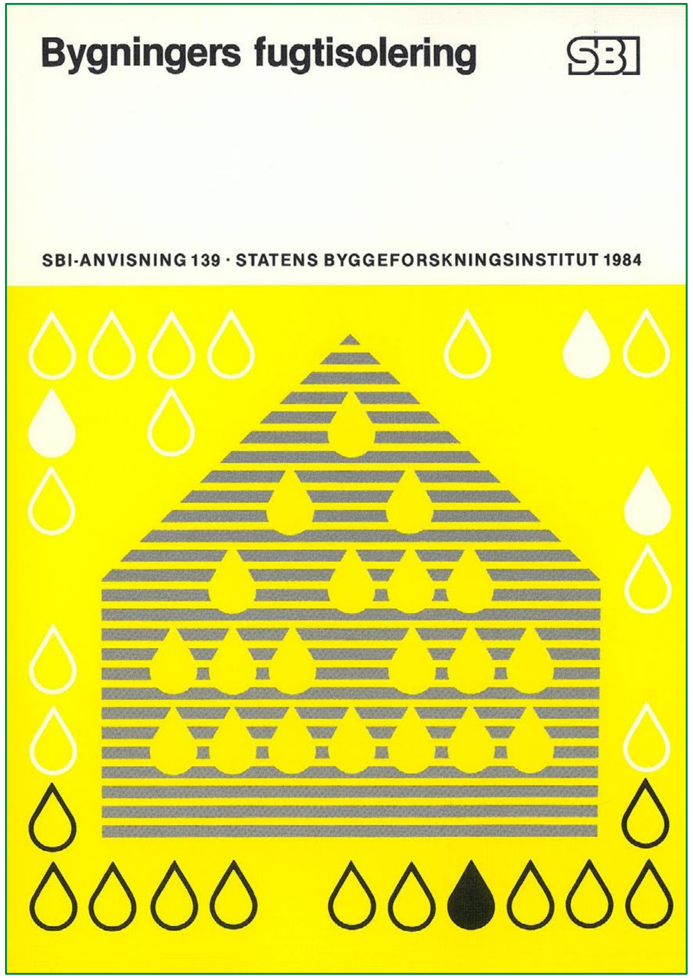
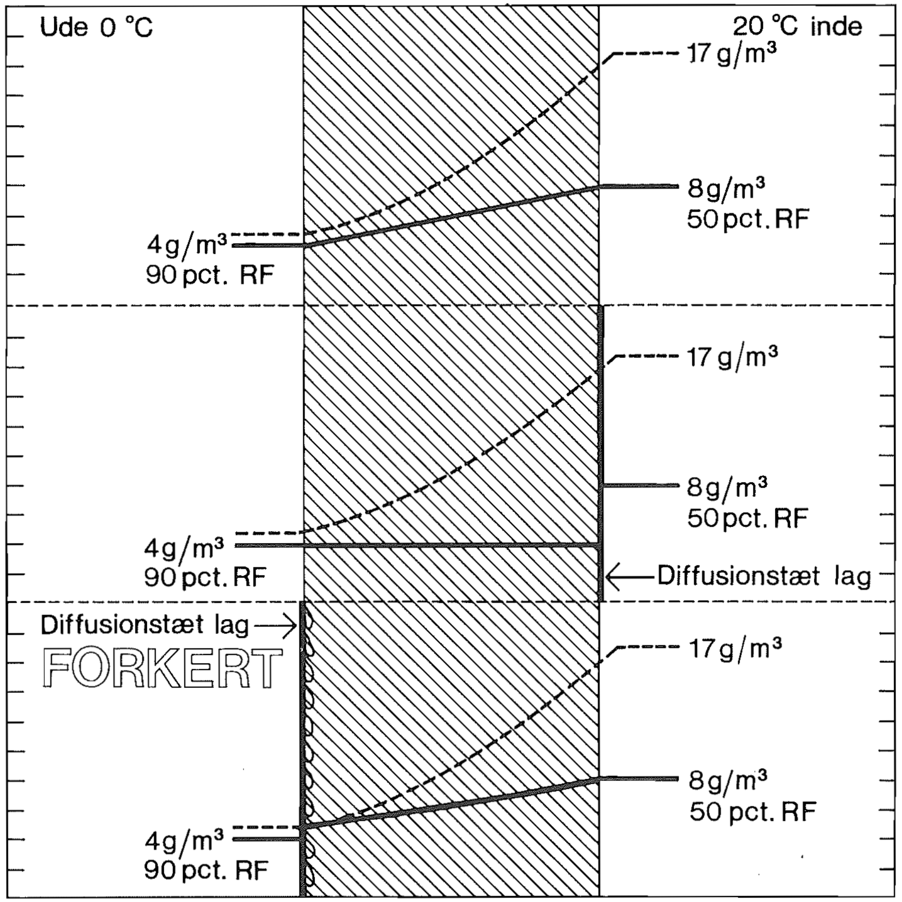


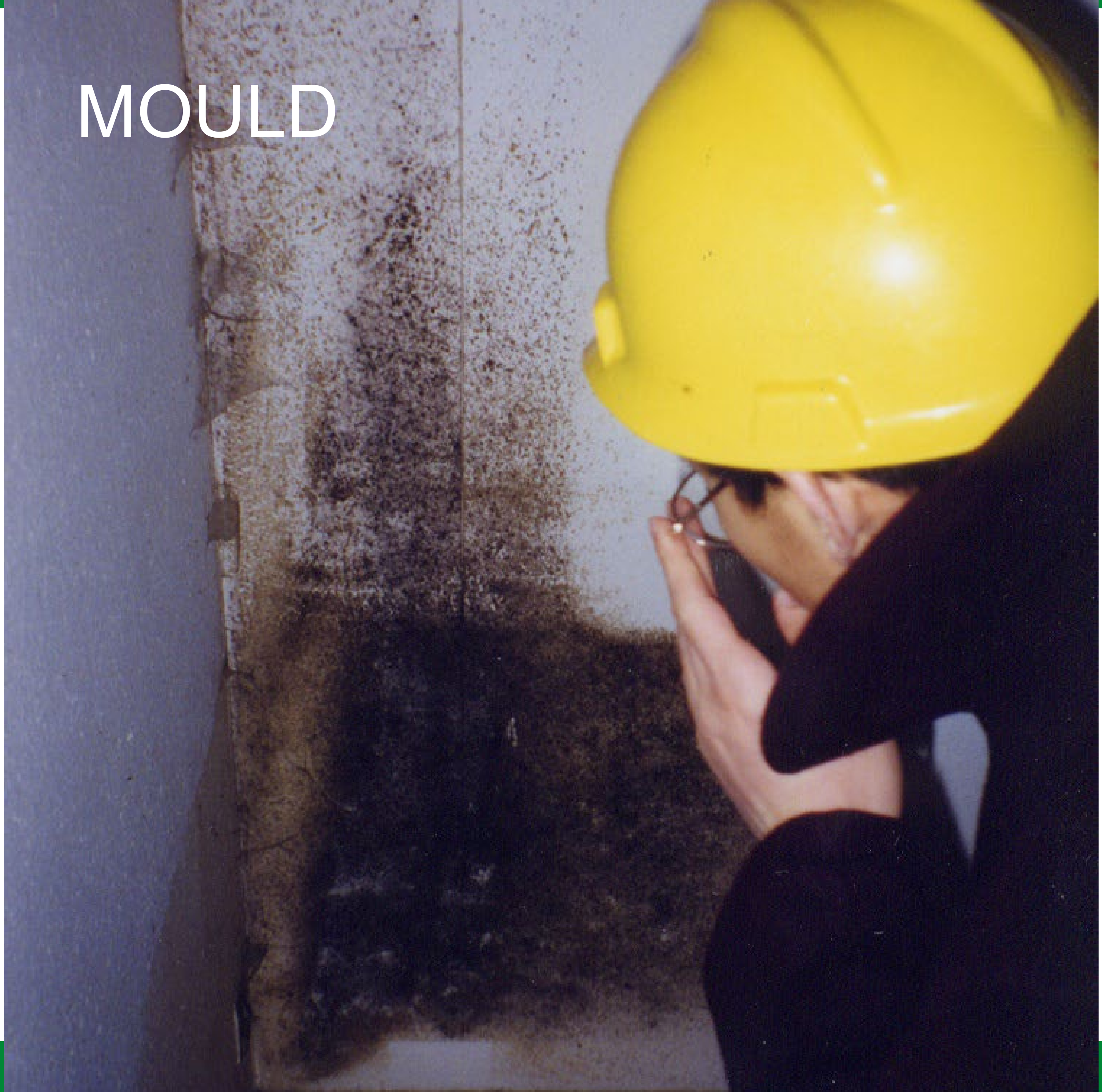
Bild 3. Temperatur- und Dampfdruckverlauf in einer Kühlraumwand

Danish Building Research Institute
SBI Guidelines (SBI Anvisninger)





MOULD



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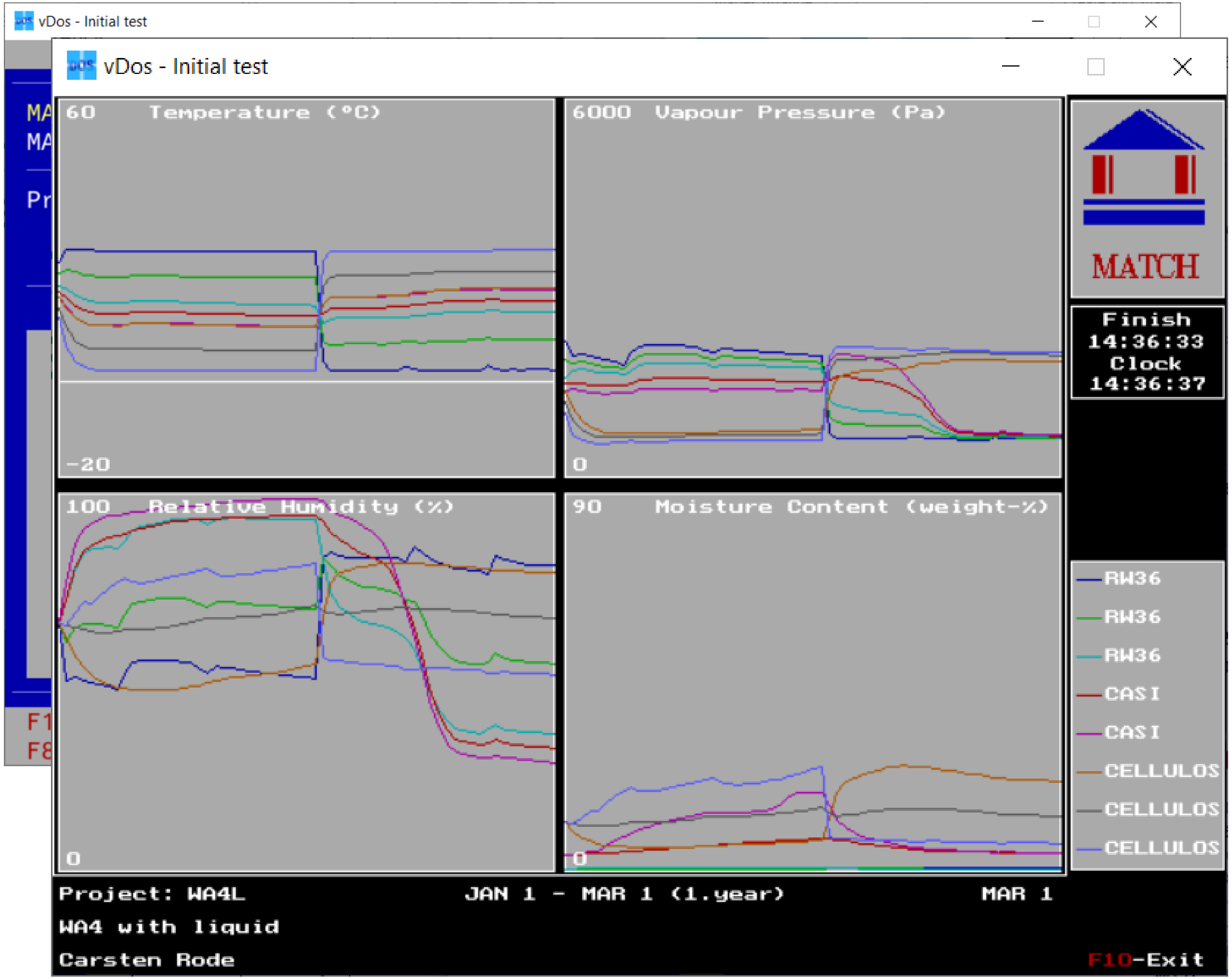
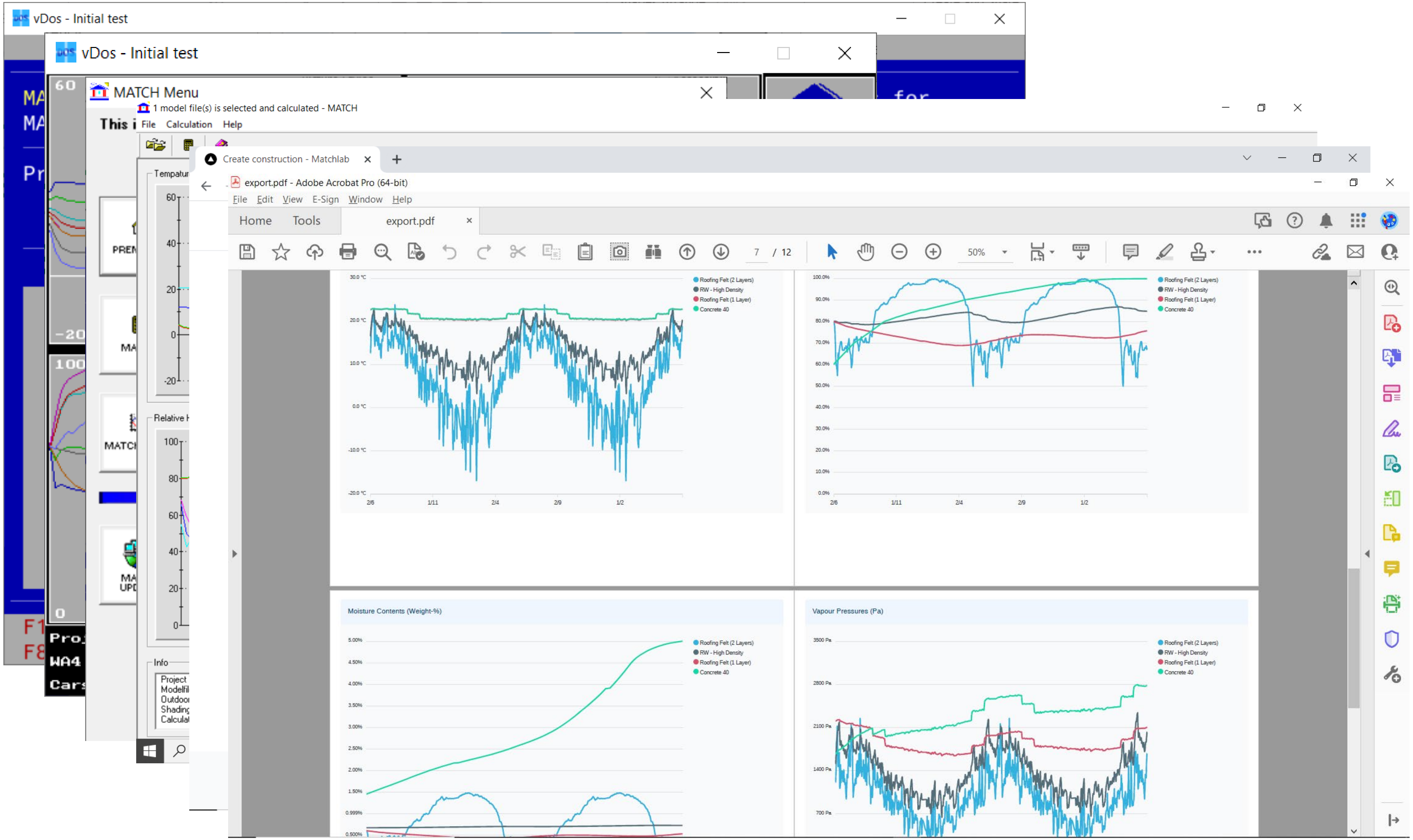

vDos - Initial test
vDos - Initial test
60 Temperature (°C)
-20
6000 Vapour Pressure (Pa)
0
100 Relative Humidity (%)
0
90 Moisture Content (weight-%)
0
MATCH
Finish
14:36:33
Clock
14:36:37
RW36
RW36
RW36
CASI
CASI
CELLULOS
CELLULOS
CELLULOS
Project: WA4L
JAN 1 - MAR 1 (1.year)
MAR 1
WA4 with liquid
Carsten Rode
F10-Exit

DTU


vDos - Initial test
vDos - Initial test
MATCH Menu
1 model file(s) is selected and calculated - MATCH
File Calculation Help
Create construction - Matchlab
export.pdf - Adobe Acrobat Pro (64-bit)
File Edit View E-Sign Window Help
Home Tools export.pdf
7 / 12
50%
Roofing Felt (2 Layers)
RW - High Density
Roofing Felt (1 Layer)
Concrete 40
Moisture Contents (Weight-%)
Vapour Pressures (Pa)
Info
Project

IEA EBC Projects

Energy in Buildings and Communities Programme

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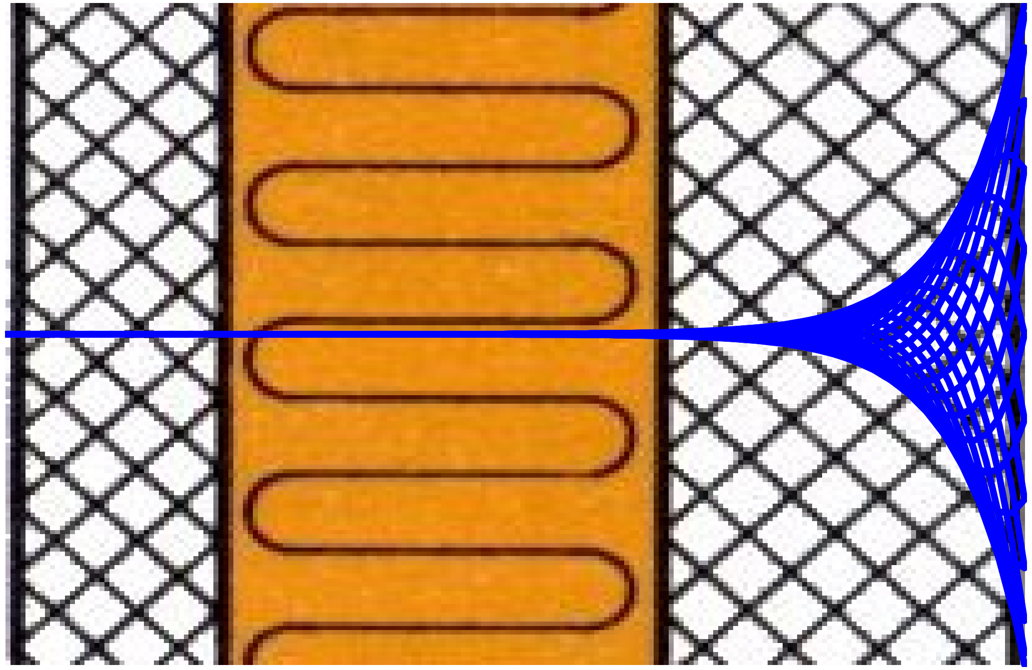
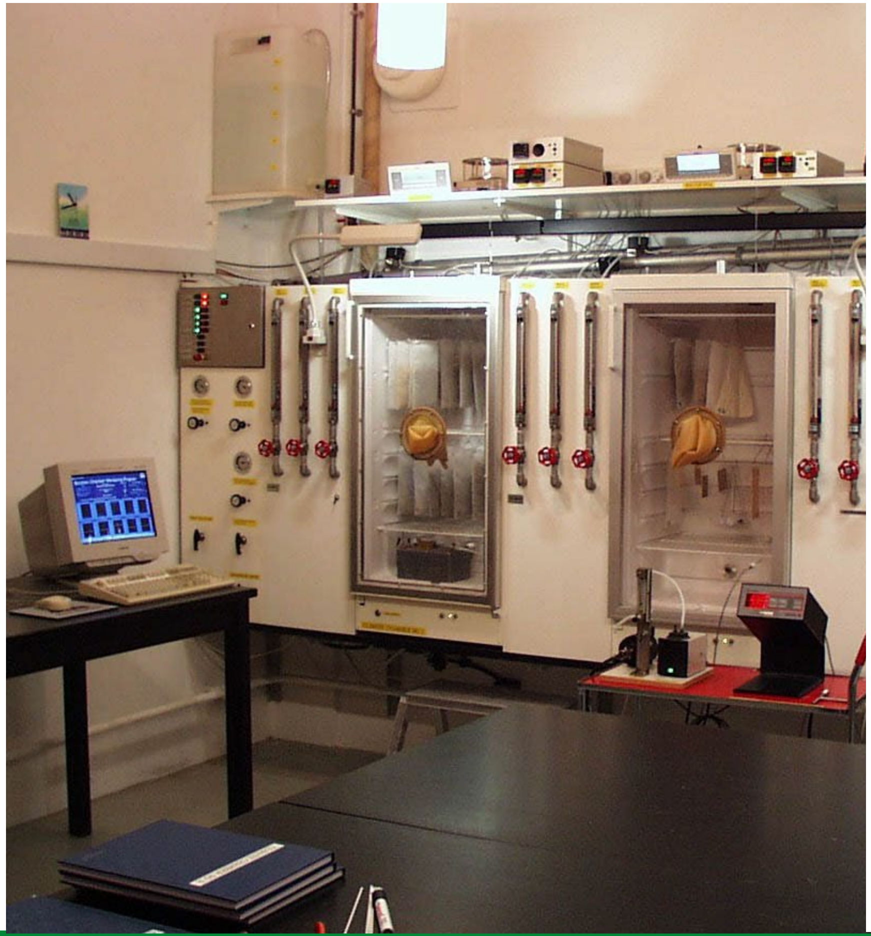
Moisture Buffering

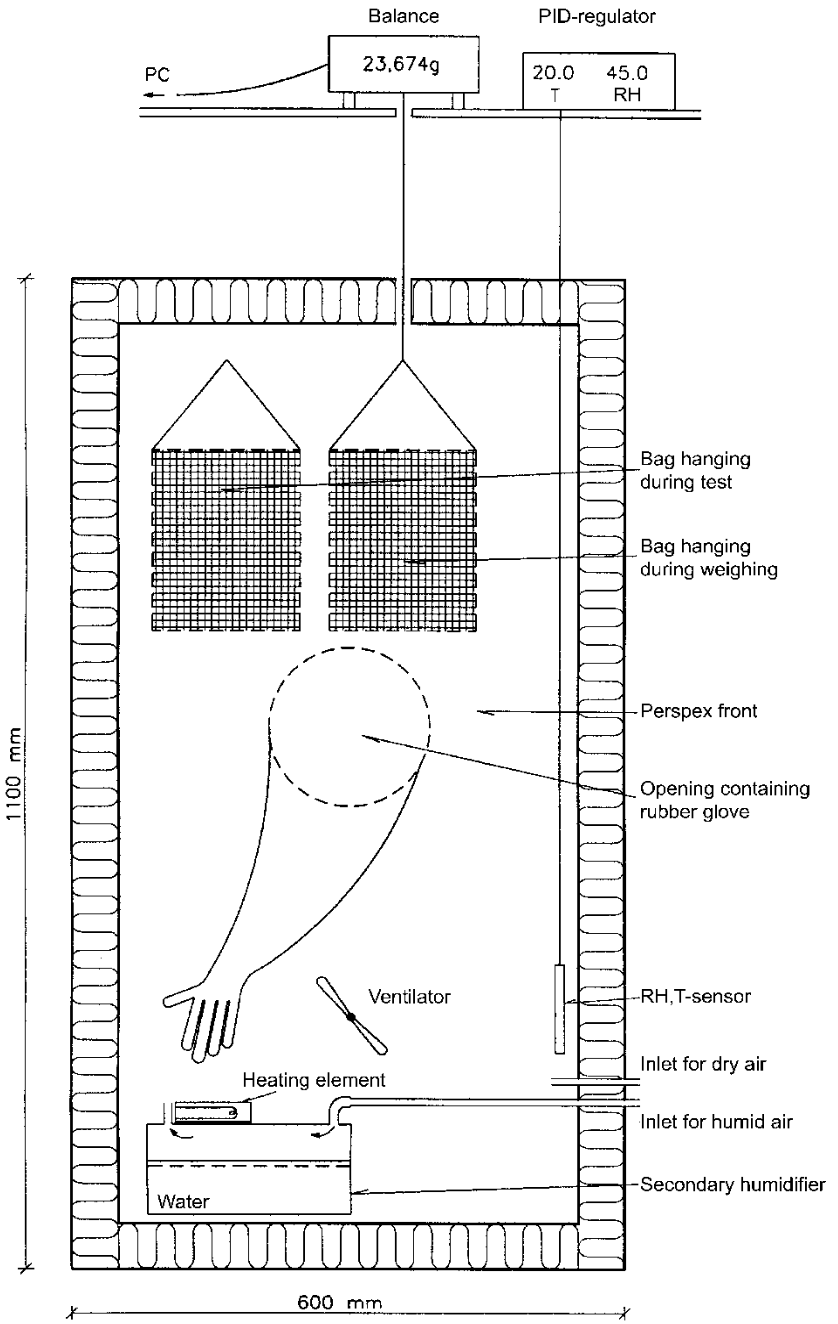


Determination of Practical Moisture Bu

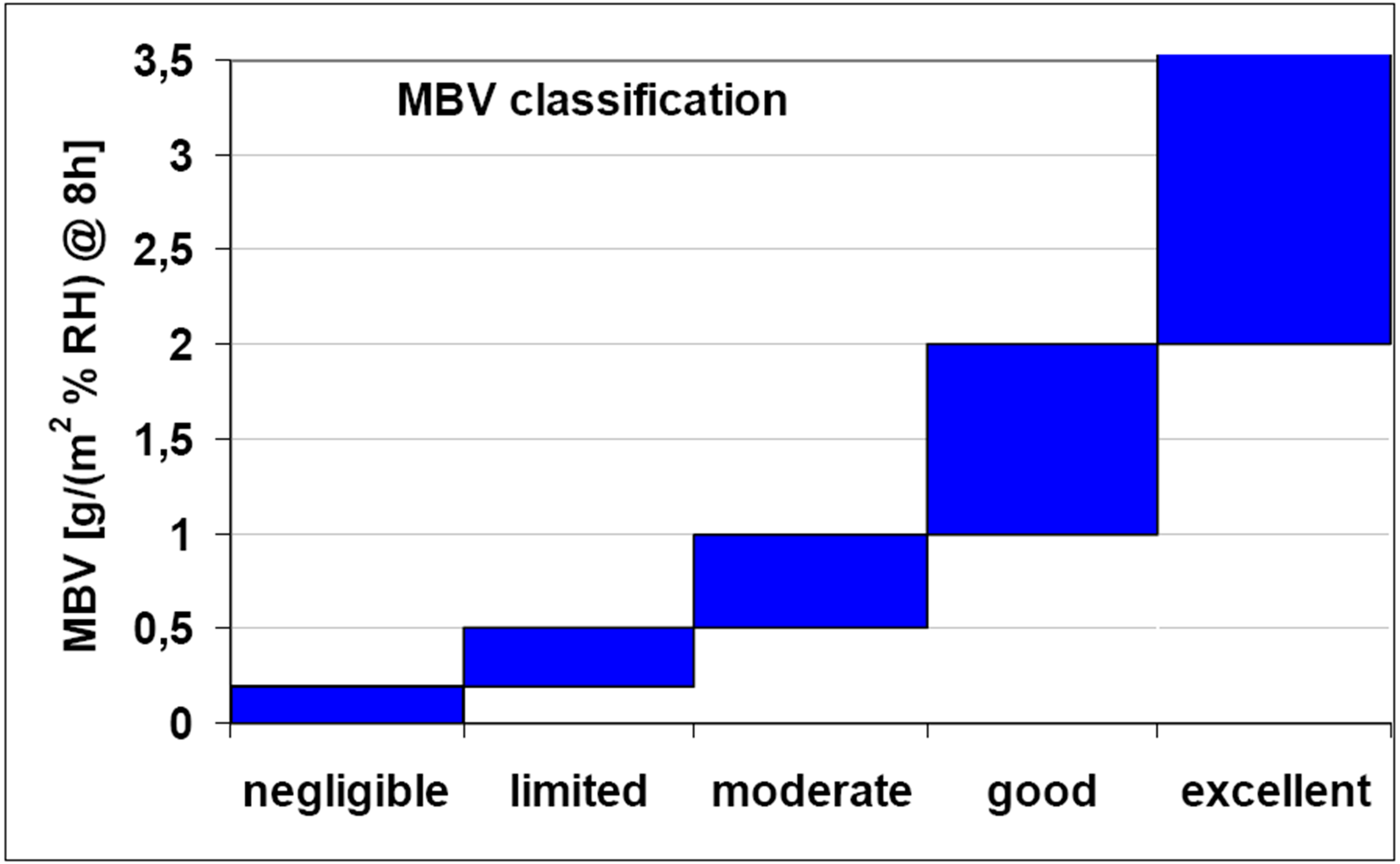
MBV

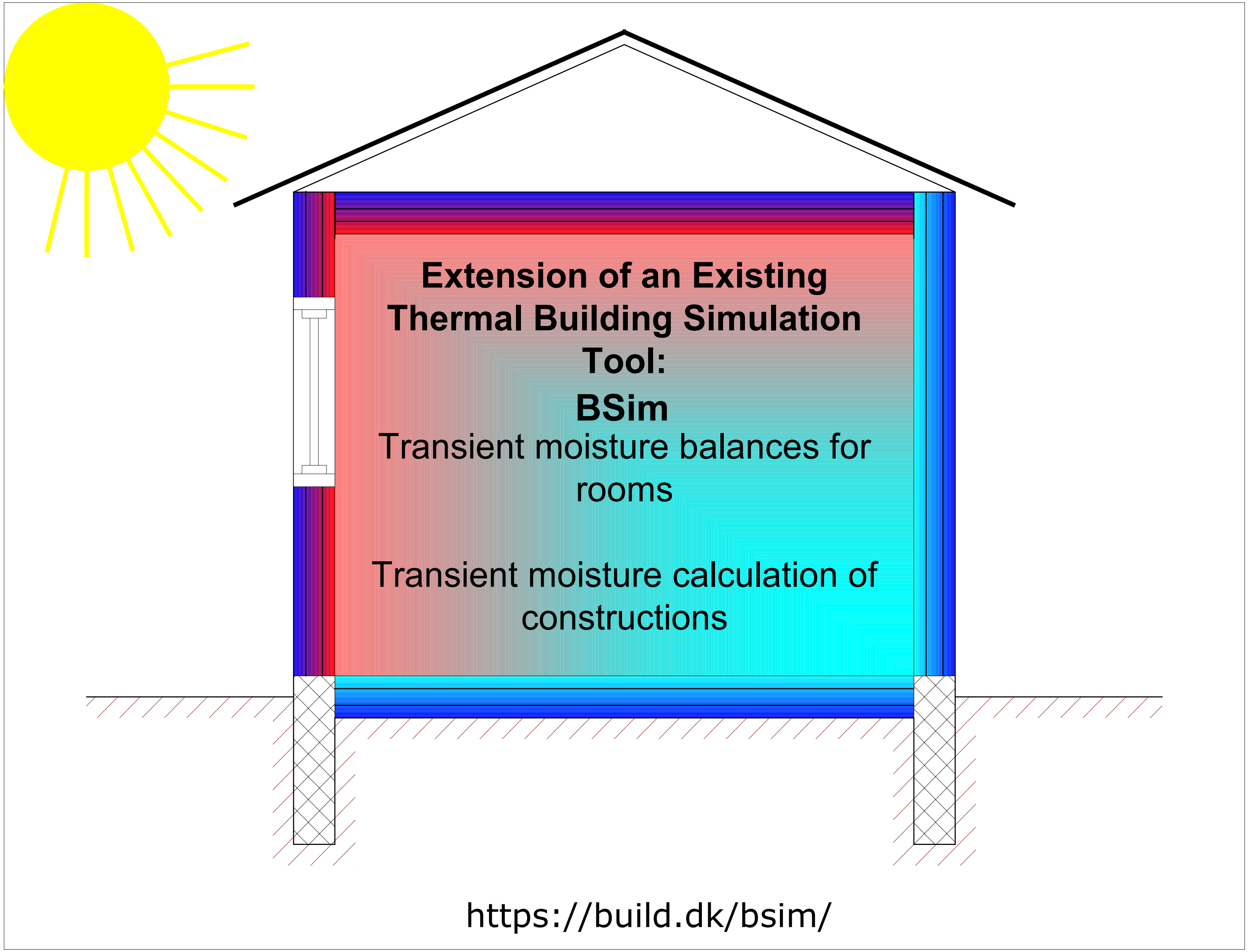
(Climatic Chambers)





MBV Classification




Extension of an Existing Thermal Building Simulation Tool:
BSim
Transient moisture balances for rooms
Transient moisture calculation of constructions
https://build.dk/bsim/

The Thermal Simulation Tool

- Calculation of the thermal condition of buildings
- Energy balance
- Multi-zone model

Heat gains from solar radiation, people, light & equipment

Heating and cooling systems

Heat and air exchange between zones

Infiltration and venting

Various ventilation systems

Heat recovery

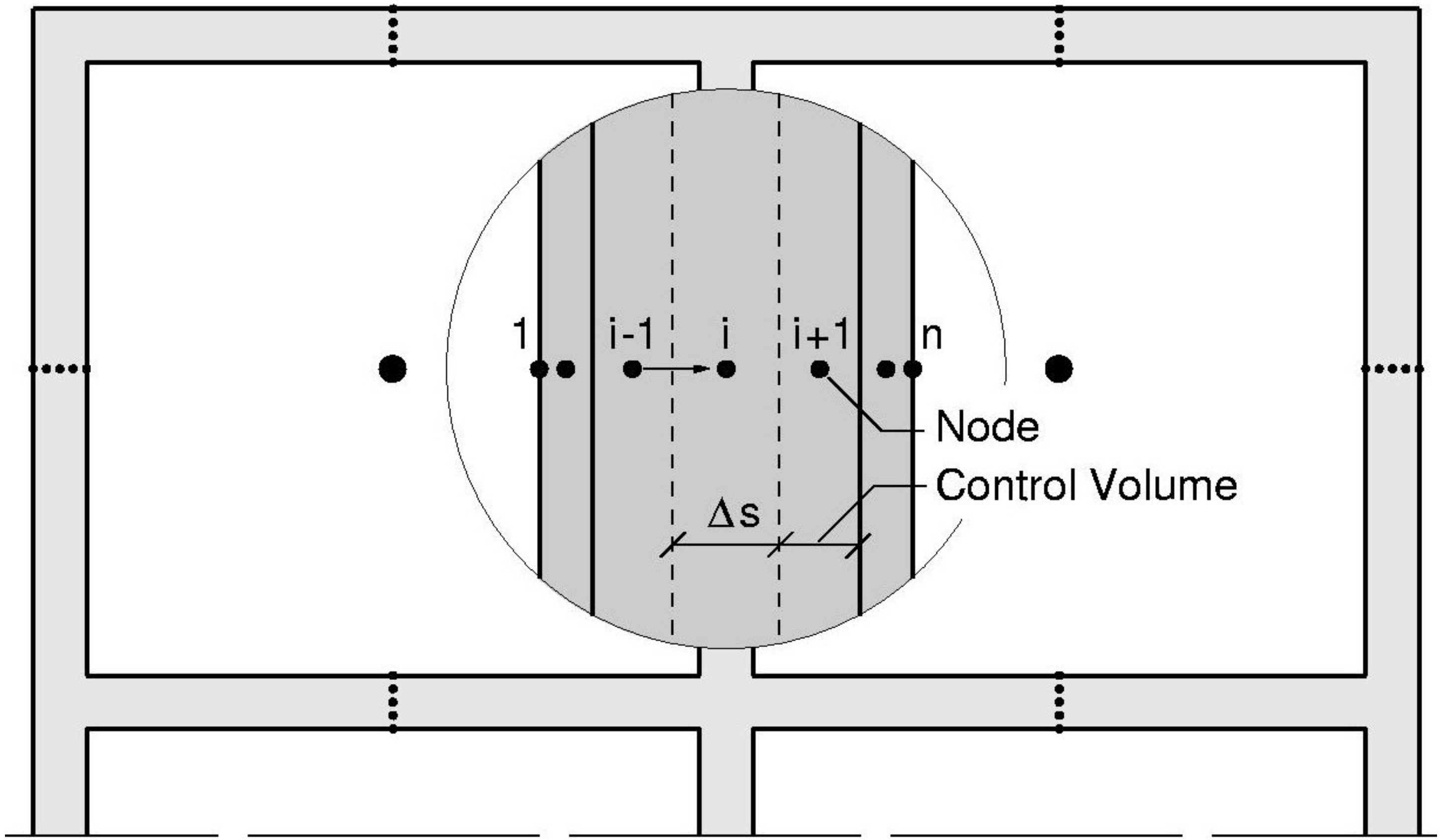
Surface temperatures

Shading conditions

Whole Building Moisture Model

- Finite Control Volume model for moisture
- Moisture transport by vapour diffusion
- Transient equations mainly like in existing moisture transport model for building envelopes
- Material properties needed:
  - Sorption curves
  - Moisture dependent vapor permeability
- Lewis relation determines moisture transfer coefficient at surfaces

Node Points in Indoor Air and Constructions



Humidity Balance for Zone Air

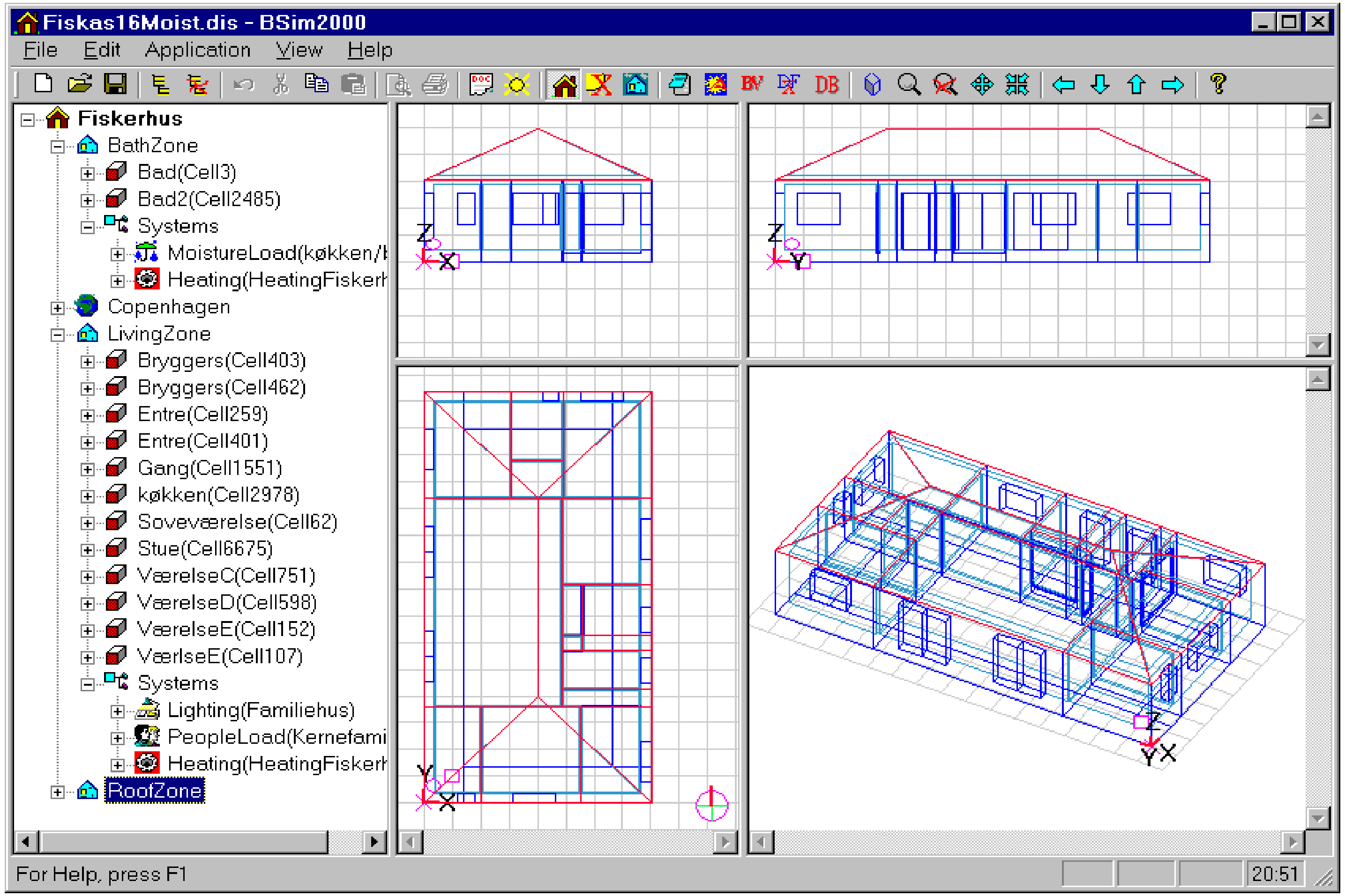
The following influences are considered:

- Humidity transfer from adjoining constructions
- Contribution of humidity from various sources and activities, e.g.:

  Person load, laundry and drying, bathing, cooking, industrial processes, humidification/drying

- Supply of humidity from outdoor air
- Supply of humid air from ventilation systems
- Humid air transferred from other zones (mixing)

Example: Indoor Humidity Conditions in a Dwelling

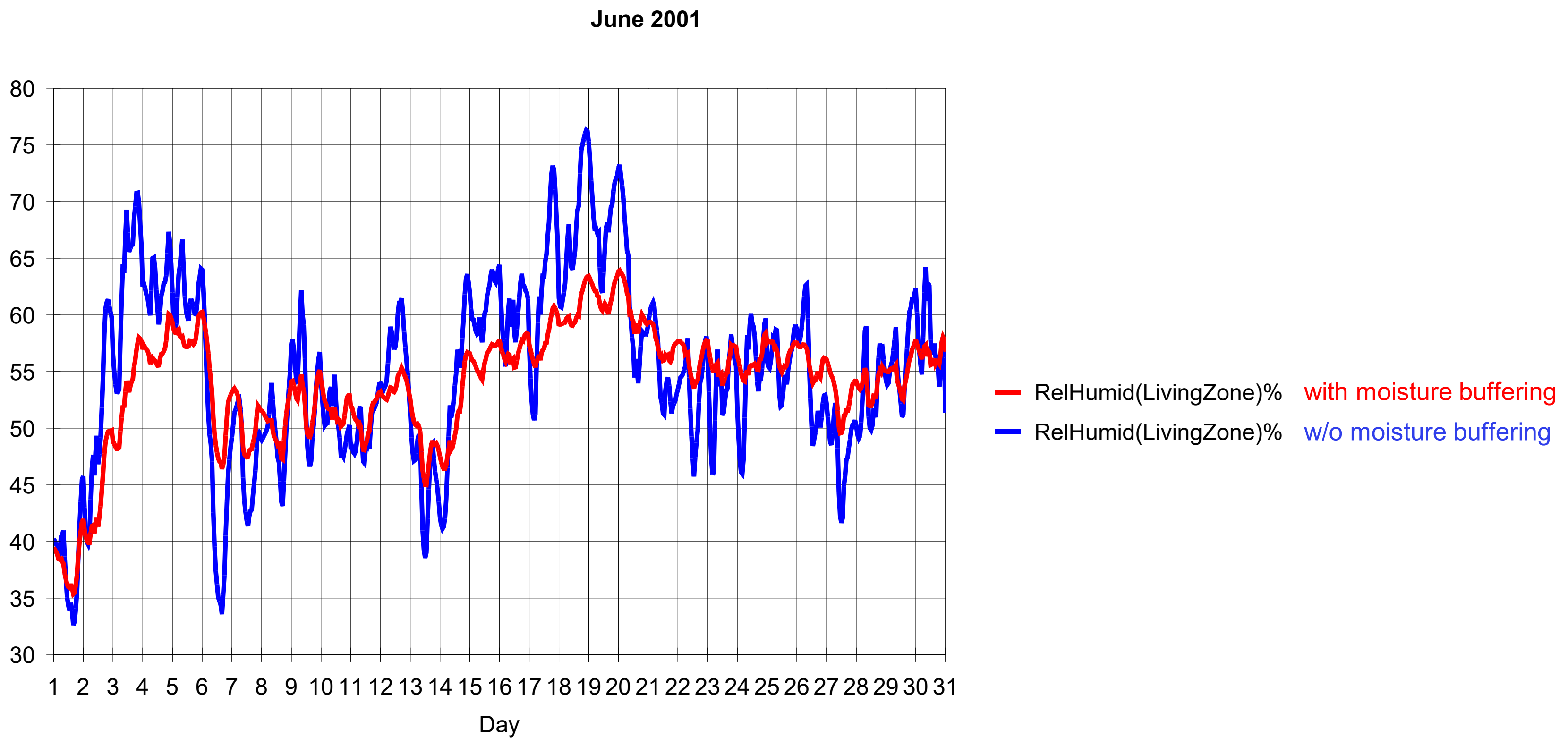


The building is made of concrete, with:

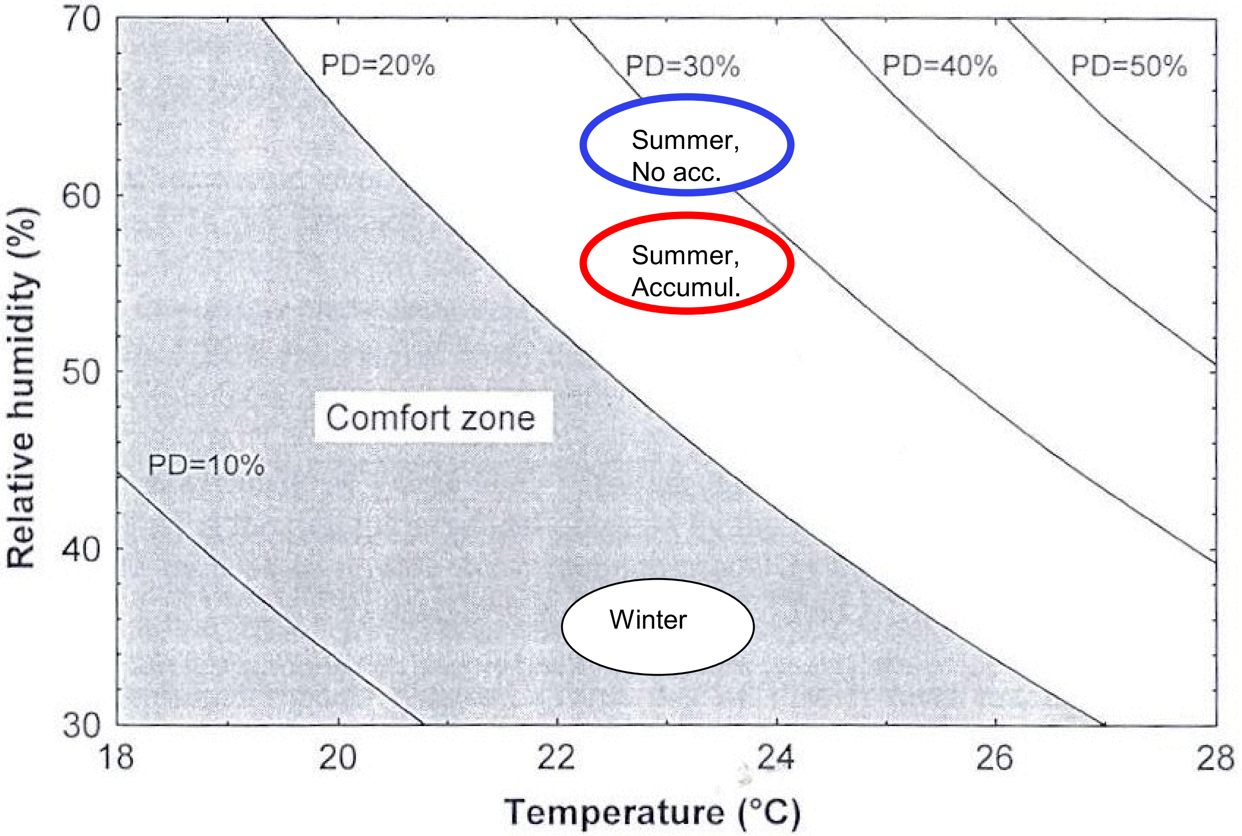
- 10 mm wool carpet on floors
- 20 mm mineral fiber boards in ceiling
- 13 mm painted plasterboard as cladding of inner walls

Example:

Humidity in Living-room, June

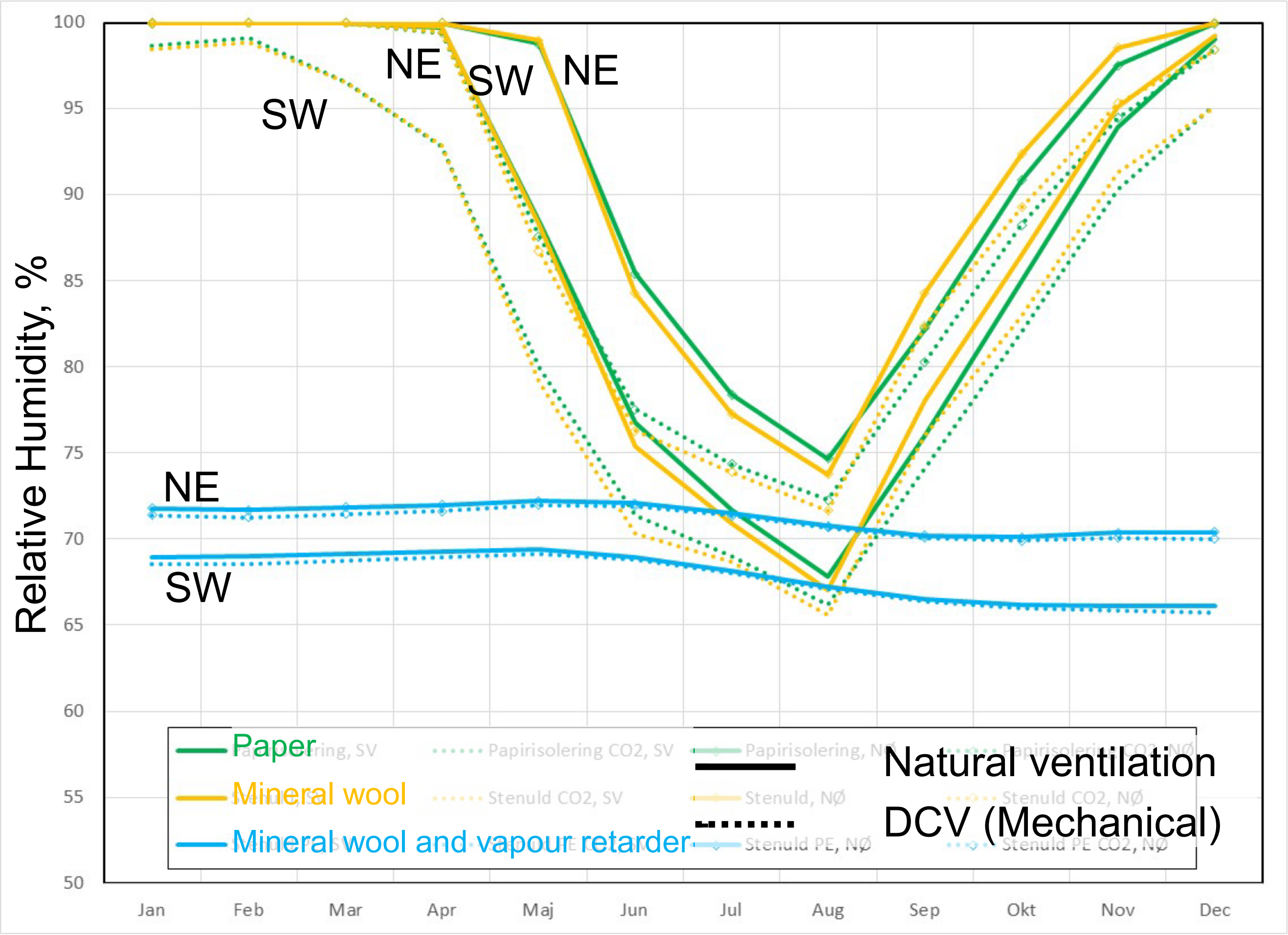


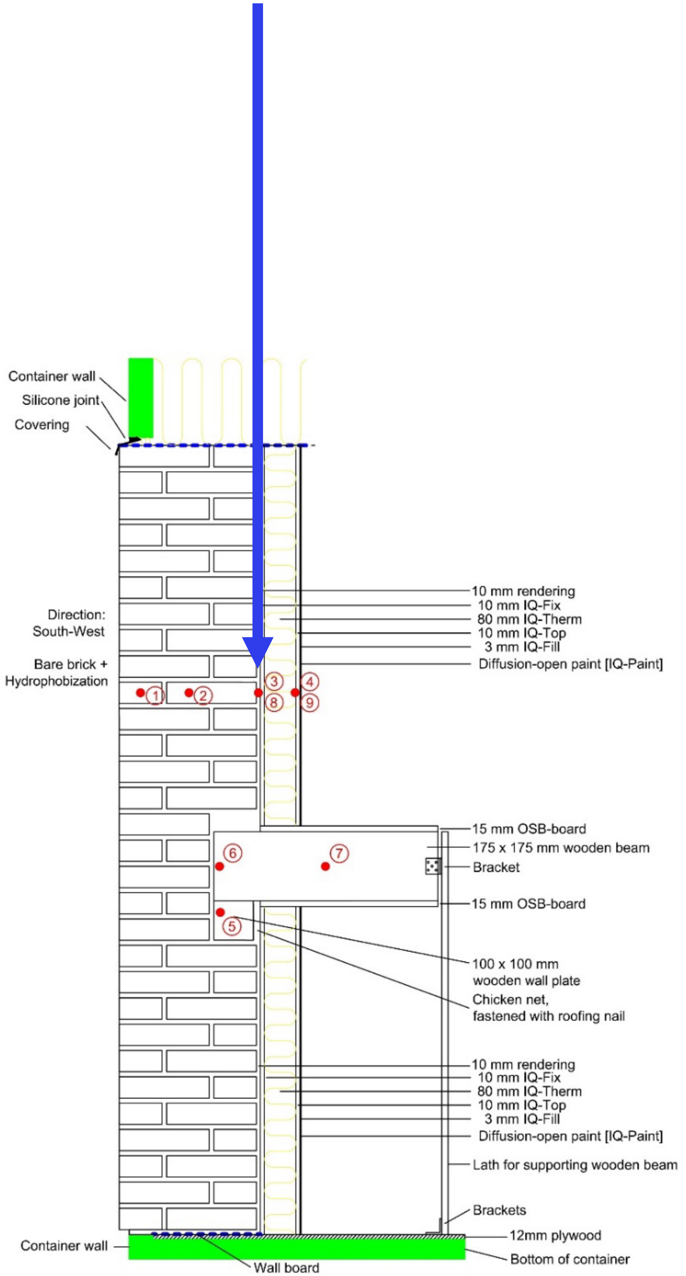
Consequences on Comfort



Bio-based solutions

Moisture in Insulation





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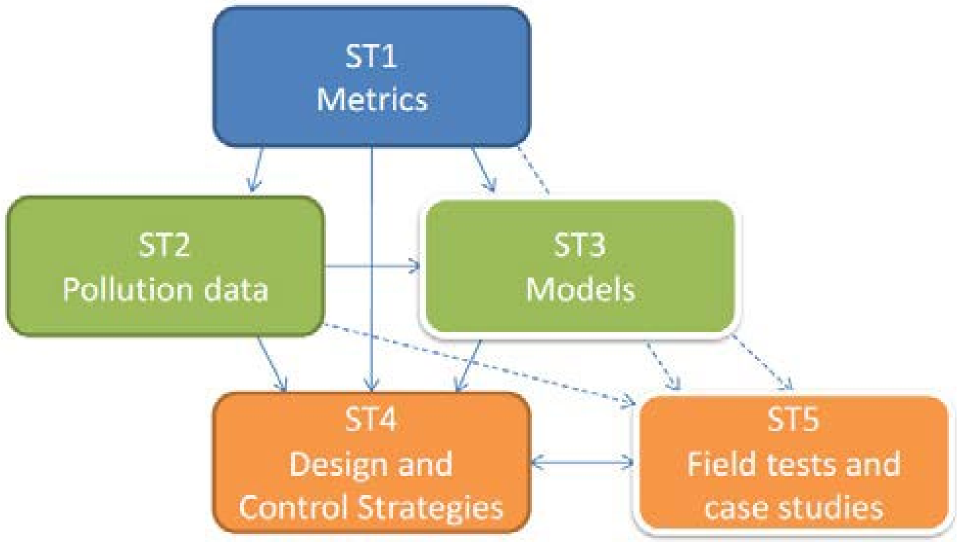
IEA EBC Annex 68

Design and Operational Strategies for High IAQ in Low Energy Buildings

Operating Agent: Carsten Rode

- **Subtask 1: Defining the metrics.** Provide indices: IAQ and energy consumption.
- **Subtask 2: Pollutant loads in residential buildings.** Collect data on transport, retention and emission properties of VOC’s under temperature, humidity and airflow conditions.
- **Subtask 3: Modelling – review, gap analysis and categorization.** Review, gap analysis and classification of models. Gather reference cases for entire buildings.
- **Subtask 4: Strategies for design and control of buildings.** State-of-the-art for and from: building designers, facility managers, manufacturers, housing developers and authorities.
- **Subtask 5: Field measurements and case studies.** Collect case studies among participants. Review of measuring technology.



Similarity Approach - Aspiration

Modelling of heat, air and moisture flows is well established for:

- Materials,
- Assemblies,
- Whole buildings.

Similarities in physics and mathematical treatment also with gaseous diffusion and retention of volatile organic compounds (VOCs).

Evolution of IEA EBC Annex projects: Annex 24 -> Annex 41 -> Annex 68

CHAMPS: Combined Heat, Air, Moisture and Pollutants Simulation

Provision of models, tools and data.

Similarity in Diffusion Models

General Fick's law for diffusion of a gas x:

$$j_{diff}^{x} = -K_x \cdot \nabla p_x$$

where:

j_{diff}^{x} Diffusive flux of the constituent x, kg/m^{2}s
K_x Vapour conductivity of the constituent x, kg/(m·s·Pa)
p_x Partial pressure of constituent x, Pa

For water vapour diffusion (v), with:

$$K_v(\theta_l) = \frac{D_{v,air}(T)}{\mu_v R_v T} \cdot f(\theta_l)$$

the flux is calculated as:

$$j_{diff}^{v} = -\frac{D_{v,air}(T)}{\mu_v R_v T} \cdot f(\theta_l) \cdot \nabla p_v$$

where:

$D_{v,air}$ Diffusion coefficient of water in still air, m²/s
μ_v Vapour diffusion resistance factor, -
R_v Gas constant for water vapour, J/(kg·K)
T Absolute temperature, K
θ_l Volumetric liquid moisture content, K

For VOC diffusion:

$$j_{diff}^{voc} = -D_m \nabla C_m = -D_e \nabla C_a$$

where:

j_{diff}^{voc} Diffusive flux of the VOC, kg/m^{2}s
D_m Diffusivity of VOC in material, m^2/s
C_m Total mass of VOC per volume of material, kg/m^3
D_e Effective Diffusivity of VOC in pore air, m^2/s
C_a Mass of VOC per volume of pore air, kg/m^3

Using:

$$\nabla p_{voc} = R_{voc} T \cdot \nabla C_a \qquad \text{(isothermal conditions)}$$

the flux as function of ∇p_{voc} becomes:

$$j_{diff}^{voc} = -K_{voc} \nabla p_{voc} = -\frac{D_{voc,air}(T)}{\mu_{voc} R_{voc} T} \nabla p_{voc}$$

where:

j_{diff}^{voc} Diffusive flux of the VOC, kg/m^{2}s
p_{VOC} Partial pressure of the VOC, Pa
$D_{voc,air}$ Diffusion coefficient in still air, m^2/s
T Absolute Temperature, K
R_{voc} Specific gas constant of VOC, J/kgK

Similarity in Retention Models

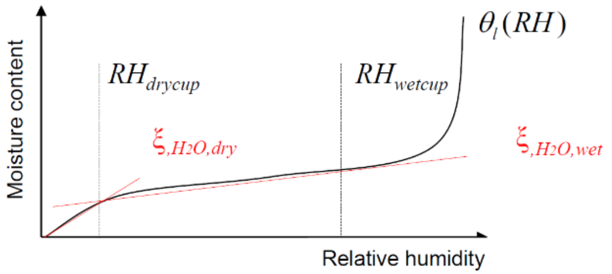
Water vapour (sorption curve)

Relative humidity

$$\varphi = \frac{p_v}{p_{v,sat}(T)}$$

Moisture capacity

$$\xi = \frac{\partial \theta_l}{\partial \varphi}$$



"Partition coefficient" for water vapour

$$K_{ma,H_2O} = \frac{\partial w}{\partial v} = \frac{\rho_l \partial \theta_l}{\frac{1}{R_v T}\partial p_v} = \frac{\rho_l R_v T}{p_{v,sat}(T)}\xi$$

where:

- w Absorbed moisture content, kg/m^3
- v Humidity of air, kg/m^3
- ρ_l Density of water, kg/m^3
- R_v Gas constant for water vapour =461.5 J/(kg·K)

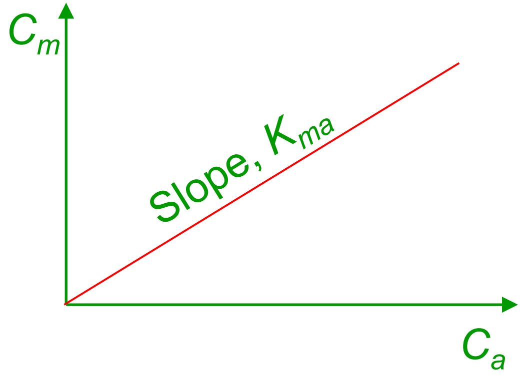
VOCs

Partition coefficient

$$C_m = K_{ma}\, C_a$$

It also means:

$$D_e = K_{ma}\, D_m$$



VOC	K_{ma}	D_m m²/s
Acetaldehyde	17,300	$1.67\cdot10^{-11}$
Acrolein	627	$5.16\cdot10^{-08}$
Alpha-pinene	1,740	$1.74\cdot10^{-10}$
Benzene	266	$7.33\cdot10^{-10}$
Formaldehyde	2,940	$4.84\cdot10^{-10}$
Naphthalene	263,000	$2.39\cdot10^{-11}$
Styrene	1,210	$1.00\cdot10^{-10}$
Toluene	968	$2.68\cdot10^{-10}$

Results – Deliverables

The **project has been completed**, results can be found on the homepage http://www.iea-ebc-annex68.org/

D1: **Subtask 1** Report on Metrics for high IAQ and energy efficiency in residential buildings

D2: **Subtask 2** Report on Pollutant loads in energy efficient residential buildings under in-use conditions

D3: **Subtask 3** Report on Modelling of IAQ and energy efficiency - review, gap analysis & categorization

D4: **Subtask 4** Report on Current challenges, selected case studies and innovative solutions covering indoor air quality, ventilation design and control in residences

D5: **Subtask 5** Report on Field tests and case studies – documentation of residential buildings, with regards to performance on achieving optimal combination of good IAQ and low energy use

D6: A **database of VOC emissions** for IAQ simulations

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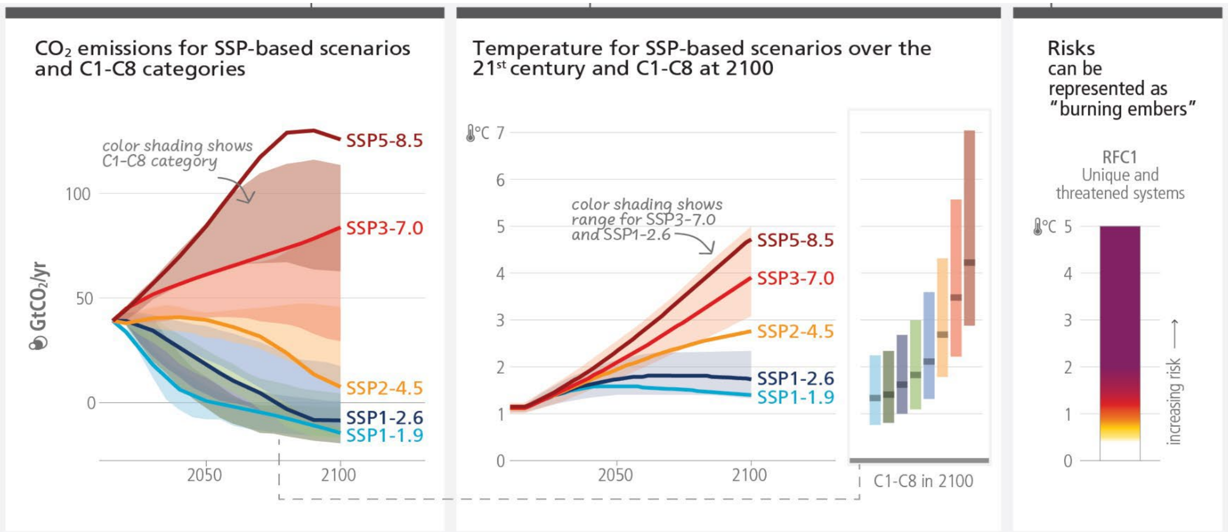
CHANGING CLIMATE



b) **Scenarios and pathways across AR6 Working Group reports**

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

c) **Determinants of risk**

IPCC SIXTH ASSESSMENT REPORT

NEW OUTDOOR CLIMATIC LOADS


COPENHAGEN 2011

Pictures from Ingeniøren and Danmarks Radio

Fonden BYG-ERFA

The purpose of the foundation is to disseminate experiences on technical matters in construction to thereby increase the technical quality.
The dissemination takes place primarily through the publication of experience sheets based on established technical issues.
But also other forms of experience gathering and dissemination can be used to promote the purpose.
The foundation's purpose is non-profit/charitable.
Dissemination is to subscribers in the building industry.

Experience sheets

- 18–20 new or revised experience sheets (2–4 pages) are issued per year.
  Each sheet describes a known building physics or engineering problem in construction.
- Suggestions for topics come from BYG-ERFA's technical expert group, the board, the secretariat, the author group, subscribers, organisations, and other parties of the industry.
- In special cases, a warning sheet may be issued notifying of a known technical issue that has arisen in construction.
- The sheets are accepted as *General shared technical knowledge*, which may be used in disputes in court.

Front page

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Back

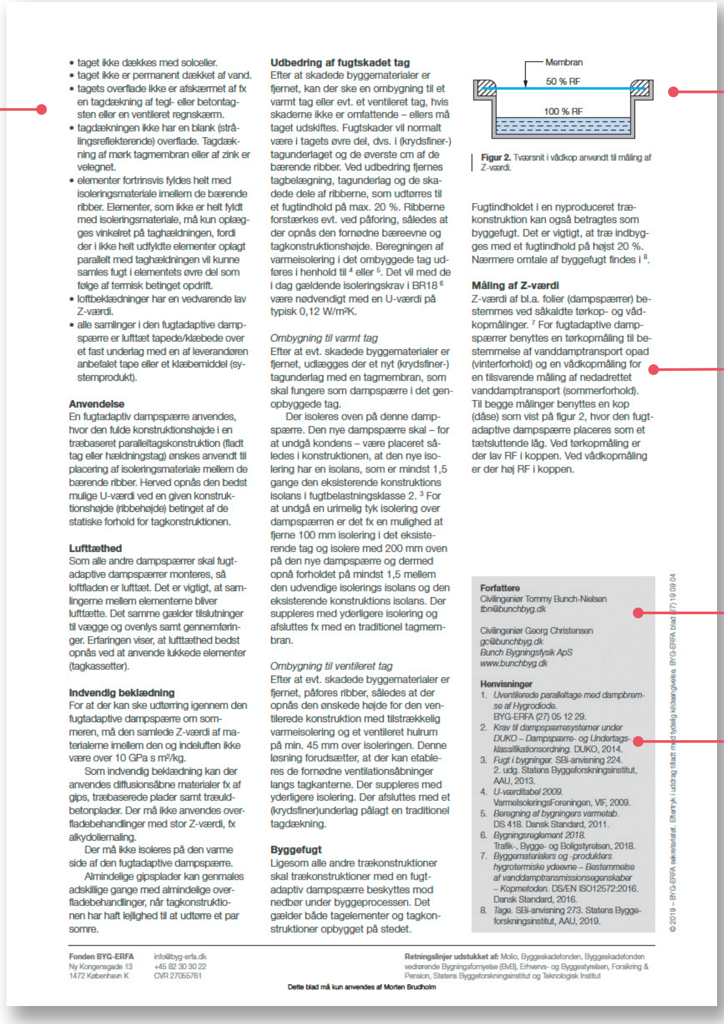
Prevention

Illustration

Operation and maintenance

Author

References



- taget ikke dækkes med solceller.
- taget ikke er permanent dækket af vand.
- tagets overflade ikke er afskærmet af fx en tagdækning af tegl- eller betontagsten eller en ventileret regnskærm.
- tagdækningen ikke har en blank (strålingsreflekterende) overflade. Tagdækning af mørk tagmembran eller af zink er velegnet.
- elementer fortrinsvis fyldes helt med isoleringsmateriale imellem de bærende ribber. Elementer, som ikke er helt fyldt med isoleringsmateriale, må kun oplægges vinkelret på taghældningen, fordi der i ikke helt udfyldte elementer oplagt parallelt med taghældningen vil kunne samles fugt i elementets øvre del som følge af termisk betinget opdrift.
- loftbeklædninger har en vedvarende lav Z-værdi.
- alle samlinger i den fugtadaptive dampspærre er lufttæt tapede/klæbede over et fast underlag med en af leverandøren anbefalet tape eller et klæbemiddel (systemprodukt).

Anvendelse
En fugtadaptiv dampspærre anvendes, hvor den fulde konstruktionshøjde i en træbaseret paralleltagskonstruktion (fladt tag eller hældningstag) ønskes anvendt til placering af isoleringsmateriale mellem de bærende ribber. Herved opnås den bedst mulige U-værdi ved en given konstruktionshøjde (ribbehøjde) betinget af de statiske forhold for tagkonstruktionen.

Lufttæthed
Som alle andre dampspærrer skal fugtadaptive dampspærrer monteres, så loftfladen er lufttæt. Det er vigtigt, at samlingerne mellem elementerne bliver lufttætte. Det samme gælder tilslutninger til vægge og ovenlys samt gennemføringer. Erfaringen viser, at lufttæthed bedst opnås ved at anvende lukkede elementer (tagkassetter).

Indvendig beklædning
For at der kan ske udtørring igennem den fugtadaptive dampspærre om sommeren, må den samlede Z-værdi af materialerne imellem den og indeluften ikke være over 10 GPa s m²/kg.

Som indvendig beklædning kan der anvendes diffusionsåbne materialer fx af gips, træbaserede plader samt træuldbetonplader. Der må ikke anvendes overfladebehandlinger med stor Z-værdi, fx alkydoliemaling.

Der må ikke isoleres på den varme side af den fugtadaptive dampspærre.

Almindelige gipsplader kan gennemles adskillige gange med almindelige overfladebehandlinger, når tagkonstruktionen har haft lejlighed til at udtørre et par somre.

Udbedring af fugtskadet tag
Efter at skadede byggematerialer er fjernet, kan der ske en ombygning til et varmt tag eller evt. et ventileret tag, hvis skaderne ikke er omfattende – ellers må taget udskiftes. Fugtskader vil normalt være i tagets øvre del, dvs. i (krydsfiner-) tagunderlaget og de øverste cm af de bærende ribber. Ved udbedring fjernes tagbelægning, tagunderlag og de skadede dele af ribberne, som udtørres til et fugtindhold på max. 20 %. Ribberne forstærkes evt. ved påforing, således at der opnås den fornødne bæreevne og tagkonstruktionshøjde. Beregningen af varmeisolering i det ombyggede tag udføres i henhold til [4] eller [5]. Det vil med de i dag gældende isoleringskrav i BR18 [6] være nødvendigt med en U-værdi på typisk 0,12 W/m²K.

Ombygning til varmt tag
Efter at evt. skadede byggematerialer er fjernet, udlægges der et nyt (krydsfiner-) tagunderlag med en tagmembran, som skal fungere som dampspærre i det genopbyggede tag.

Der isoleres oven på denne dampspærre. Den nye dampspærre skal – for at undgå kondens – være placeret således i konstruktionen, at den nye isolering har en isolans, som er mindst 1,5 gange den eksisterende konstruktions isolans i fugtbelastningsklasse 2. [3] For at undgå en urimelig tyk isolering over dampspærren er det fx en mulighed at fjerne 100 mm isolering i det eksisterende tag og isolere med 200 mm oven på den nye dampspærre og dermed opnå forholdet på mindst 1,5 mellem den udvendige isolerings isolans og den eksisterende konstruktions isolans. Der suppleres med yderligere isolering og afsluttes fx med en traditionel tagmembran.

Ombygning til ventileret tag
Efter at evt. skadede byggematerialer er fjernet, påfores ribber, således at der opnås den ønskede højde for den ventilerede konstruktion med tilstrækkelig varmeisolering og et ventileret hulrum på min. 45 mm over isoleringen. Denne løsning forudsætter, at der kan etableres de fornødne ventilationsåbninger langs tagkanterne. Der suppleres med yderligere isolering. Der afsluttes med et (krydsfiner)underlag pålagt en traditionel tagdækning.

Byggefugt
Ligesom alle andre trækonstruktioner skal trækonstruktioner med en fugtadaptiv dampspærre beskyttes mod nedbør under byggeprocessen. Det gælder både tagelementer og tagkonstruktioner opbygget på stedet.

Membran
50 % RF
100 % RF

Figur 2. Tværsnit i vådkop anvendt til måling af Z-værdi.

Fugtindholdet i en nyproduceret trækonstruktion kan også betragtes som byggefugt. Det er vigtigt, at træ indbygges med et fugtindhold på højst 20 %. Nærmere omtale af byggefugt findes i [8].

Måling af Z-værdi
Z-værdi af bl.a. folier (dampspærrer) bestemmes ved såkaldte tørkop- og vådkopmålinger. [7] For fugtadaptive dampspærrer benyttes en tørkopmåling til bestemmelse af vanddamptransport opad (vinterforhold) og en vådkopmåling for en tilsvarende måling af nedadrettet vanddamptransport (sommerforhold). Til begge målinger benyttes en kop (dåse) som vist på figur 2, hvor den fugtadaptive dampspærre placeres som et tætsluttende låg. Ved tørkopmåling er der lav RF i koppen. Ved vådkopmåling er der høj RF i koppen.

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About the Danish Building Defect Fund

- Is a privately owned institution established by law in 1986 (The Law on Public Housing).
- Established due to poor quality and an extensive number of building defects in public housing in the 1960s and 1970s.
- Comprices new public housing since 1986. Since 2011 The Fund comprises publicly subsidised renovations and since 2021 renewals in publicly subsidised private housing.
- Covers up to 95 % of the costs for repairing building defects for 20 years after finishing the building, renovation or building renewal.

BYGGESKADEFONDEN

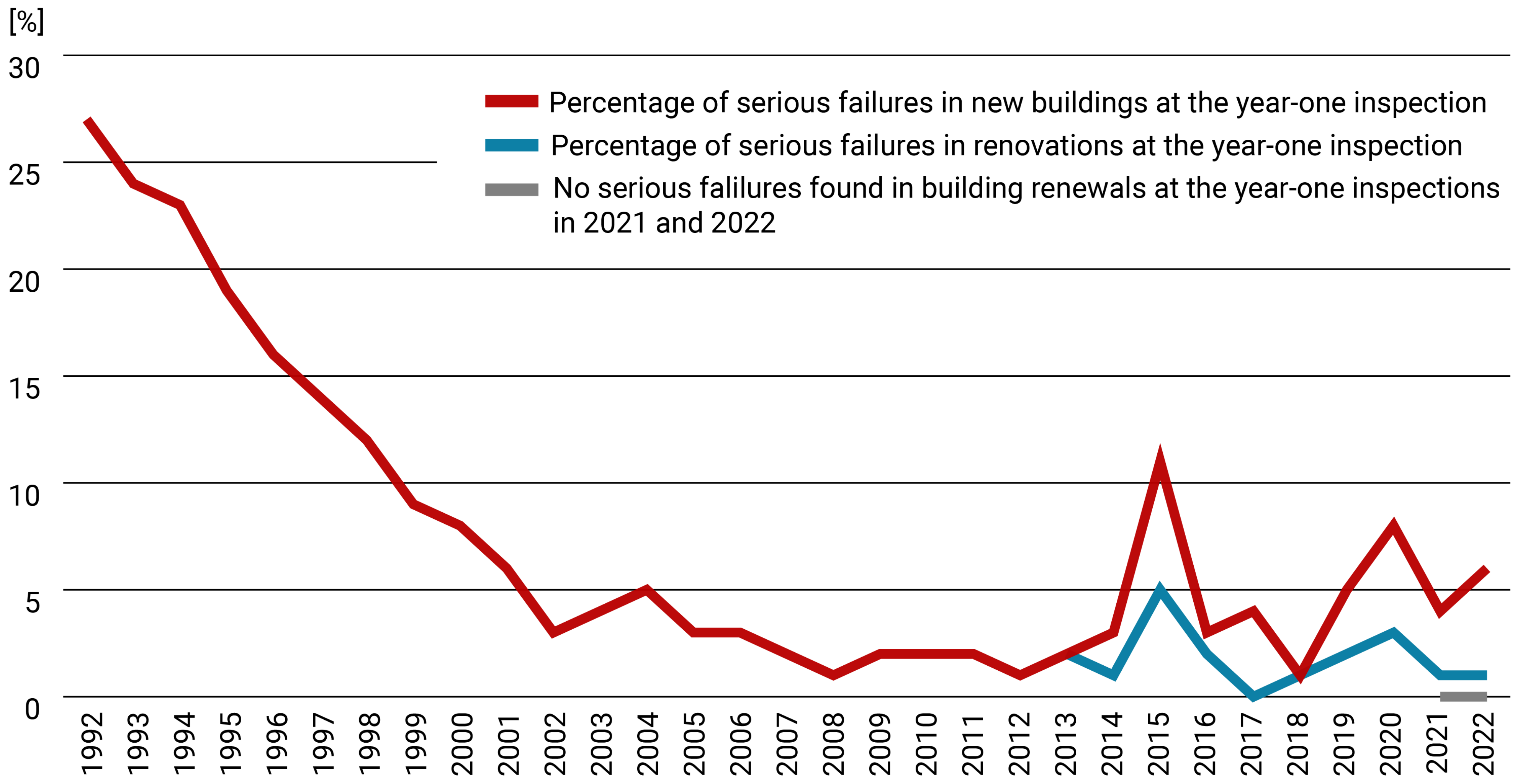
The purpose of The Danish Building Defect Fund

Carry out year-one and year-five building inspections

Give financial support to the repair of building defects

Communicate findings to the building sector to prevent building defects

Percentage of serious failures at year-one inspections



THANK YOU!

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Photo: Egil Borchersen

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AIR TIGHTNESS

AND POTENTIAL

MOISTURE PROBLEMS

SOLUTION

AS **AIR-TIGHT** AS POSSIBLE

AUTOMATIC **DEMAND CONTROLLED** MECHANICAL VENTILATION SYSTEM WITH **HEAT RECOVERY**

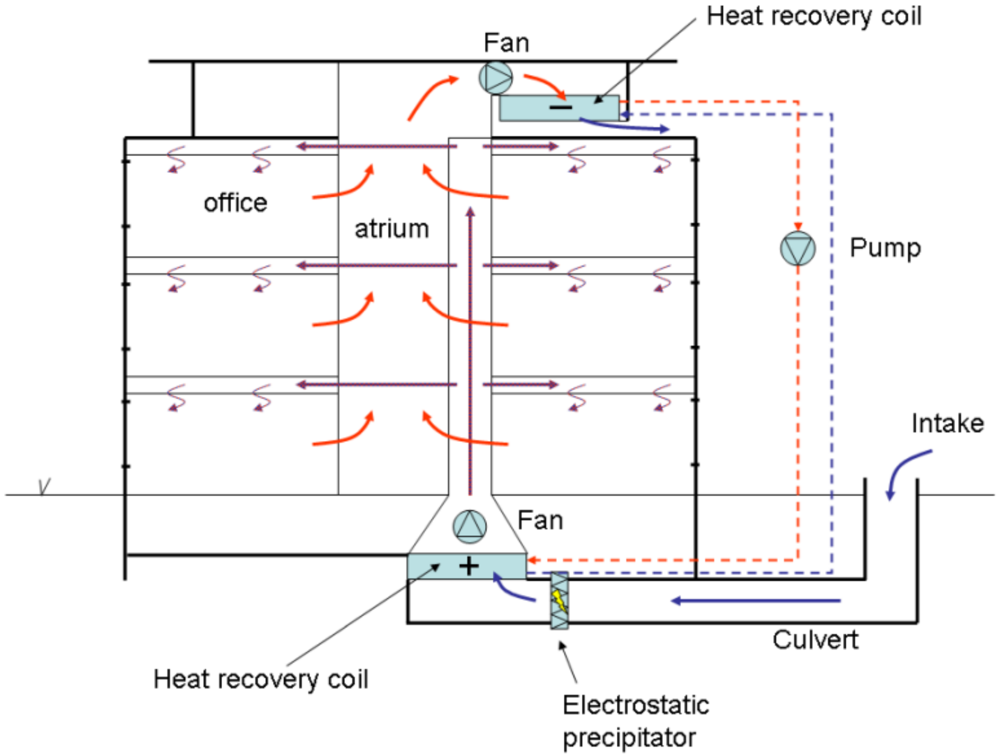

GRACE VYCOR PLUS
LIMITED 30 WARRANTY

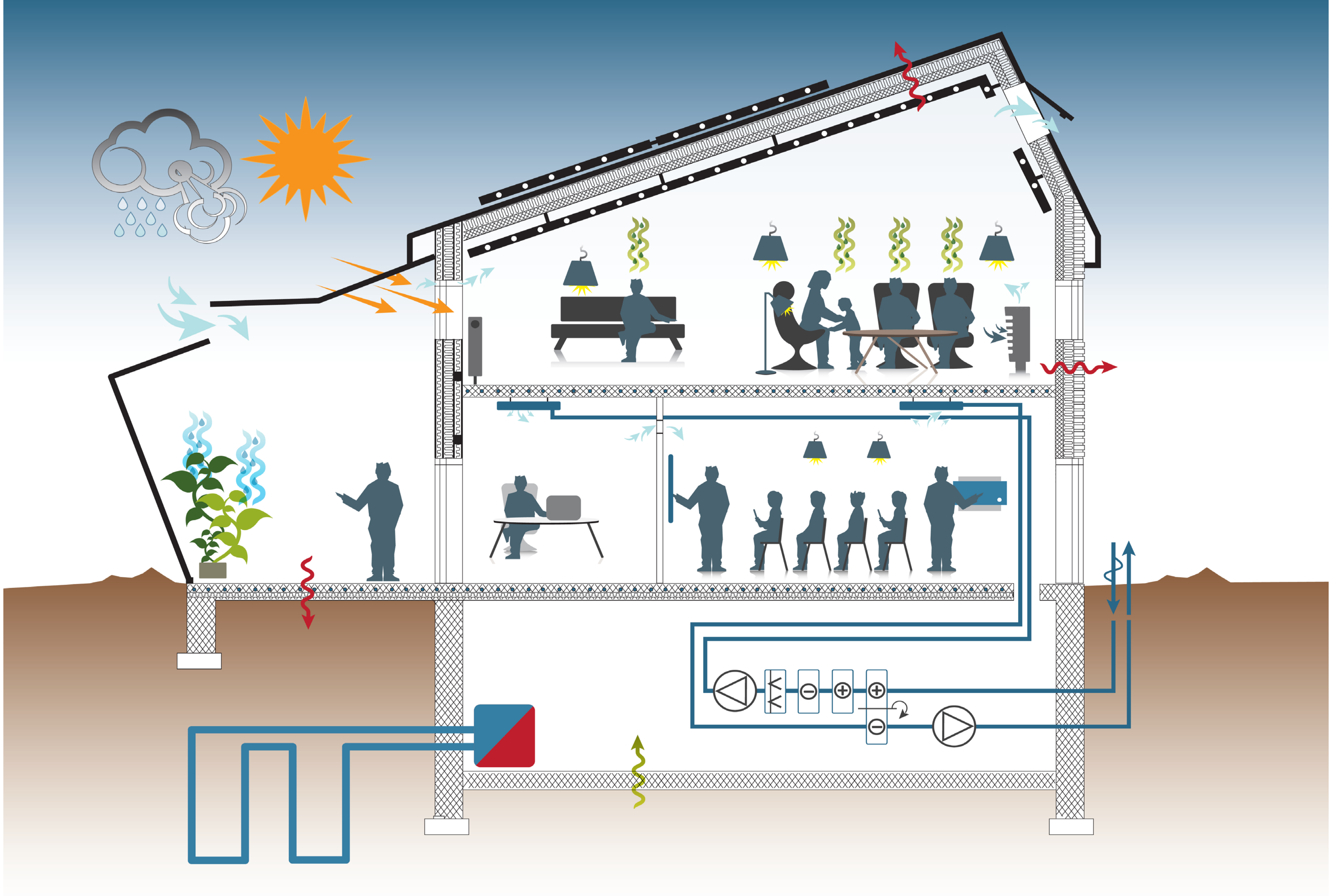
VENTILATION

- Should be sufficient
- But not more (demand control, personal ventilation)

- Natural
- Mechanical
- Balanced
- Hybrid

- Heat Recovery





Source: International Center for Indoor Environment and Energy, DTU

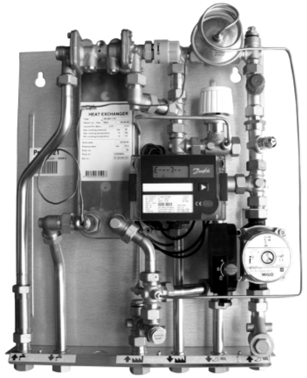
BUILDING ENVELOPE

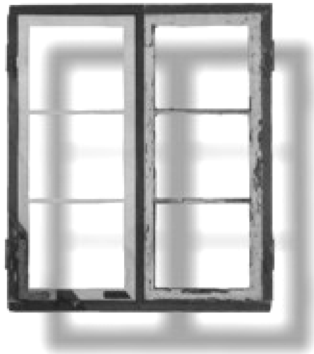
- Thermal insulation
- Windows
- Thermal bridges
- Thermal mass and Phase Change Materials (PCM)
- Roofs and attics
- Basements, crawl spaces, and floor on ground structures
- Shading systems
- Durability
- Moisture and mould

BUILDING SERVICES

- Ventilation
- Energy supply systems, incl. heat pumps
- Domestic hot water
- Controls
- Shading / passive cooling techniques
- Lighting and daylight
- Integrated solutions
- Low temperature heating / High temperature c

BUILDING PRODUCTS





HEATING AND COOLING CLIMATES

Photo from Sisimiut, Grenland, by Martin Kotol