Climate, the Building Envelope & Environmental Management

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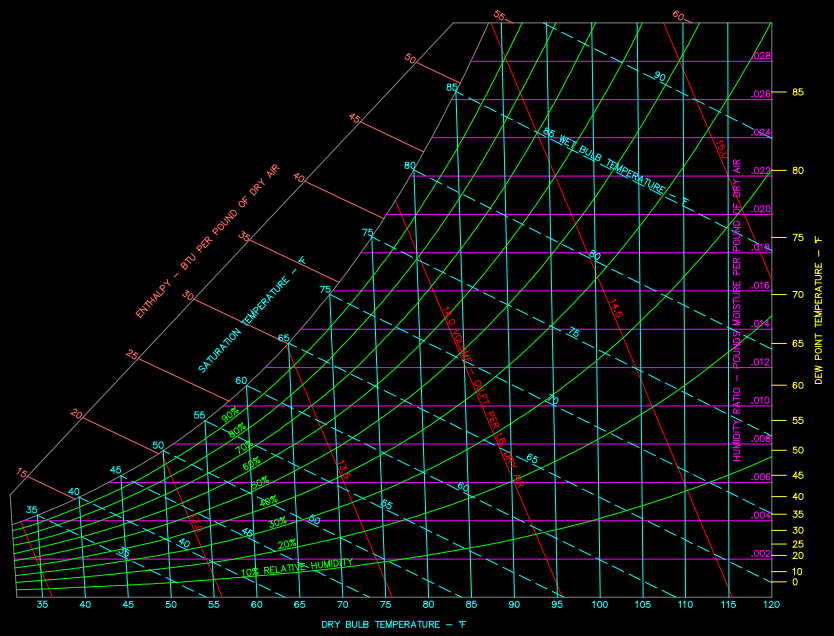
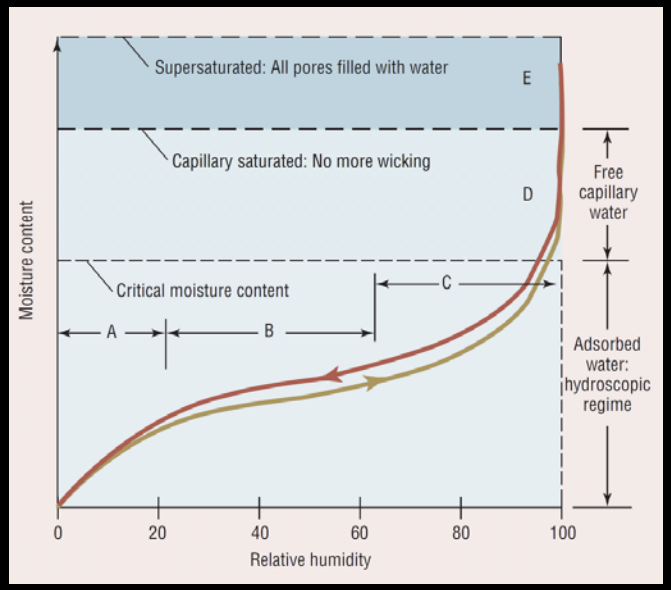
Necessary Basics: The Physics of Air and Moisture

An understanding of psychrometrics & material response to moisture is essential to informed decisions about collections environments





J. F. Straube

"Scotty," Chief Engineer of the Starship Enterprise protested: *"I cannot ignore the laws of physics! "*

We cannot afford to ignore them either.

Necessary Basics: the Climate

The external thermal energy & moisture that drive the interior environment

Cloud Cleaner, 2000 Robert & Shanna ParkeHarrison

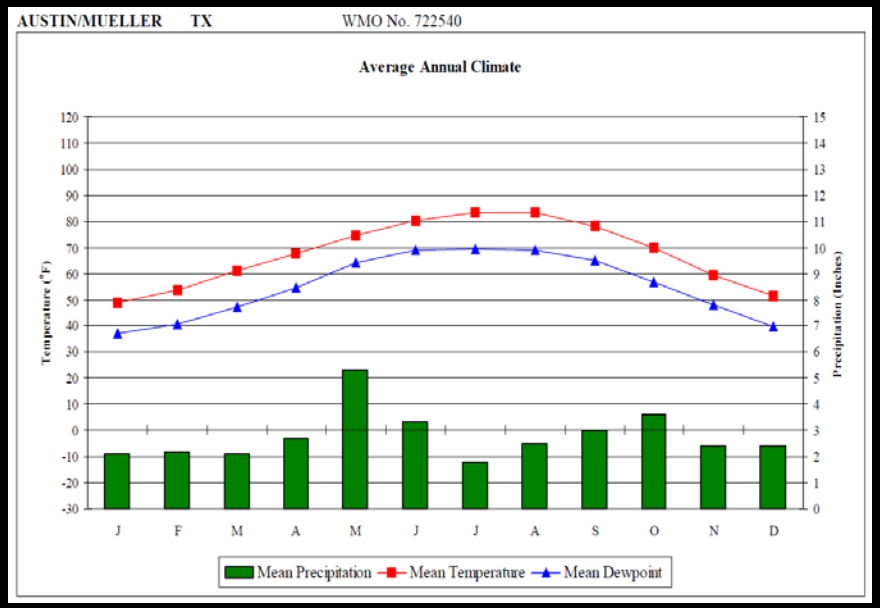
Bob Dylan sang: *"You don't have to be a weatherman to know which way the wind is blowin'…"*

The way the wind is blowing today, we need to find better solutions.

Climate & Weather

Climate is defined by the statistics of air temperature, atmospheric moisture vapor, atmospheric pressure, wind, precipitation, solar radiation and other meteorological elements recorded for a given region over long periods of time.

In the short term, climate is experienced as weather, the present and often highly variable condition of these same elements

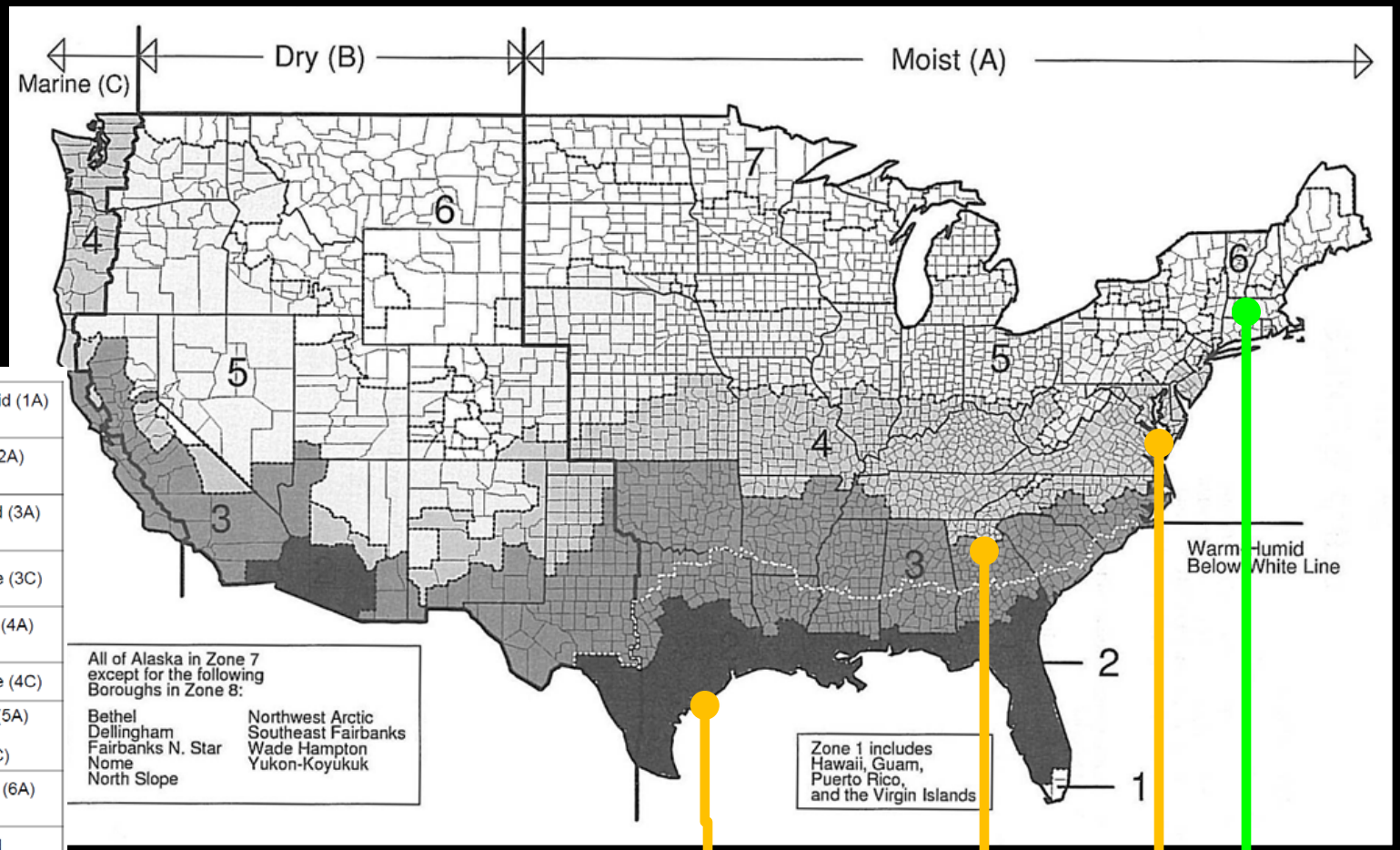


Climate Data

John Constable, A day in Hampstead Heath, 1821
http://www.artandarchitecture.org.uk/stories/

17 Climate Zones in the US

1A and 1B	Very Hot –Humid (1A) Dry (1B)
2A and 2B	Hot-Humid (2A) Dry (2B)
3A and 3B	Warm – Humid (3A) Dry (3B)
3C	Warm – Marine (3C)
4A and 4B	Mixed-Humid (4A) Dry (4B)
4C	Mixed – Marine (4C)
5A, 5B, and 5C	Cool-Humid (5A) Dry (5B) Marine (5C)
6A and 6B	Cold – Humid (6A) Dry (6B)
7	Very Cold
8	Subarctic



2A Hot-Humid: Corpus Christi, TX

3A Warm-Humid: Atlanta, GA

4A Mixed-Humid: Washington, DC

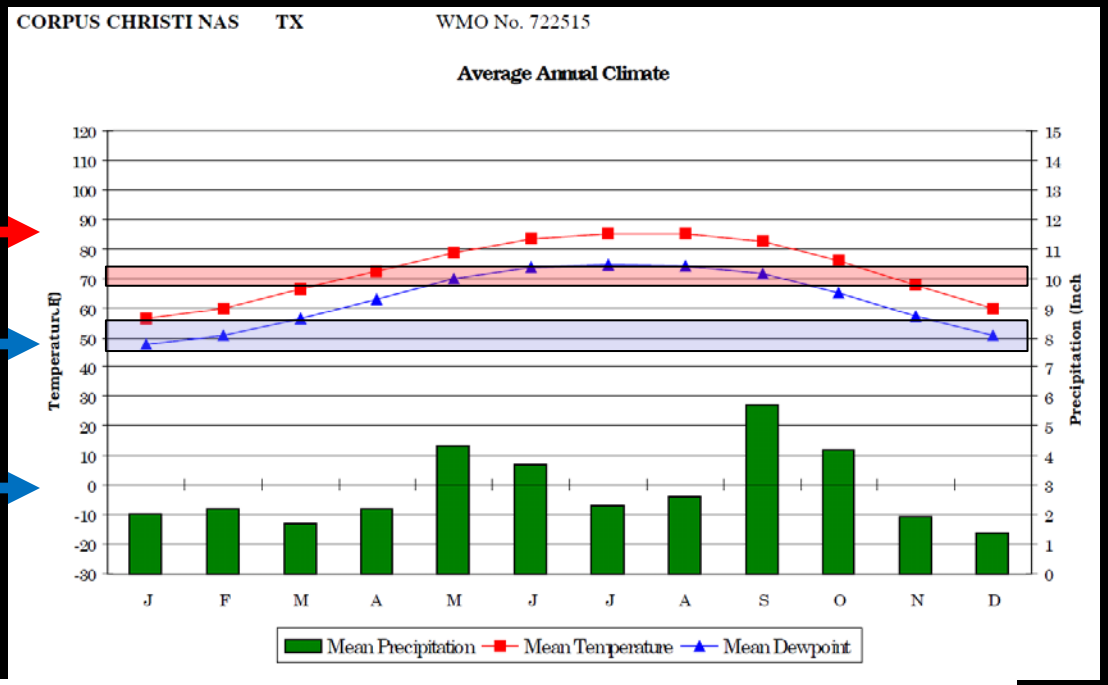
5A Cool-Humid: Chicopee, MA

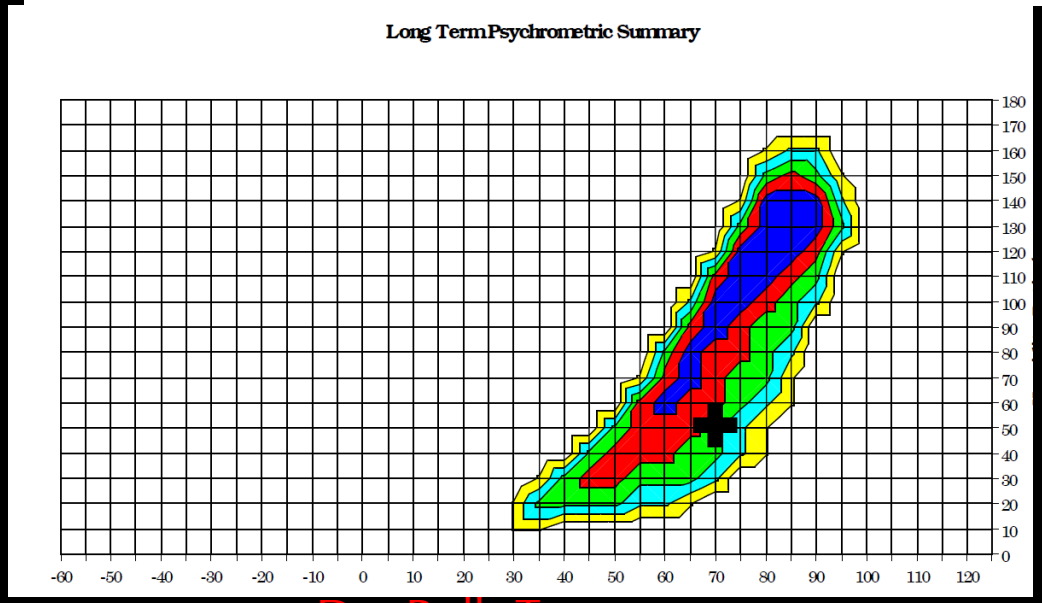
Zone 2A Hot-Humid
Corpus Christi, TX

Dry Bulb Temperature

Dewpoint Temperature
(Moisture Vapor)

Rainfall





Moisture vapor →

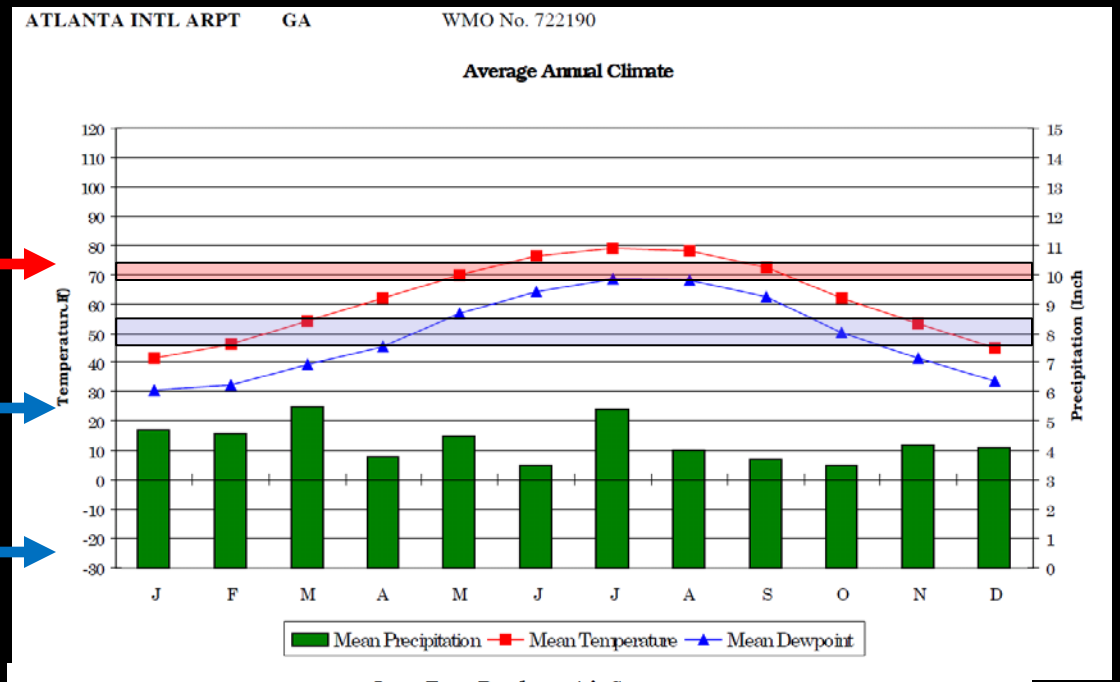
Dry Bulb Temperature →

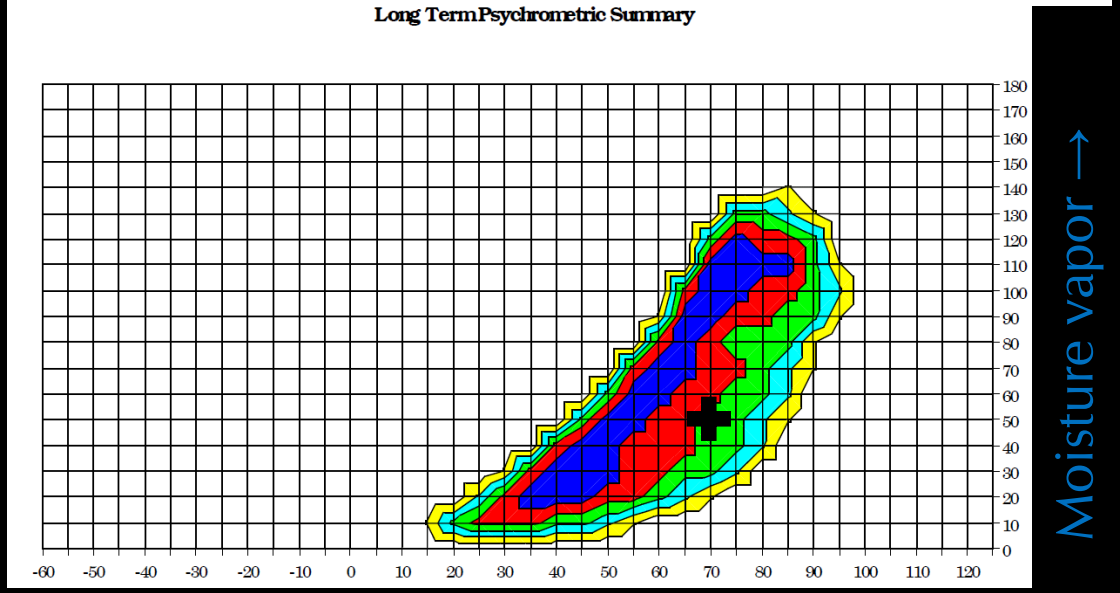
Zone 3A Warm-Humid
Atlanta, GA

Dry Bulb Temperature

Dewpoint Temperature
(Moisture Vapor)

Rainfall



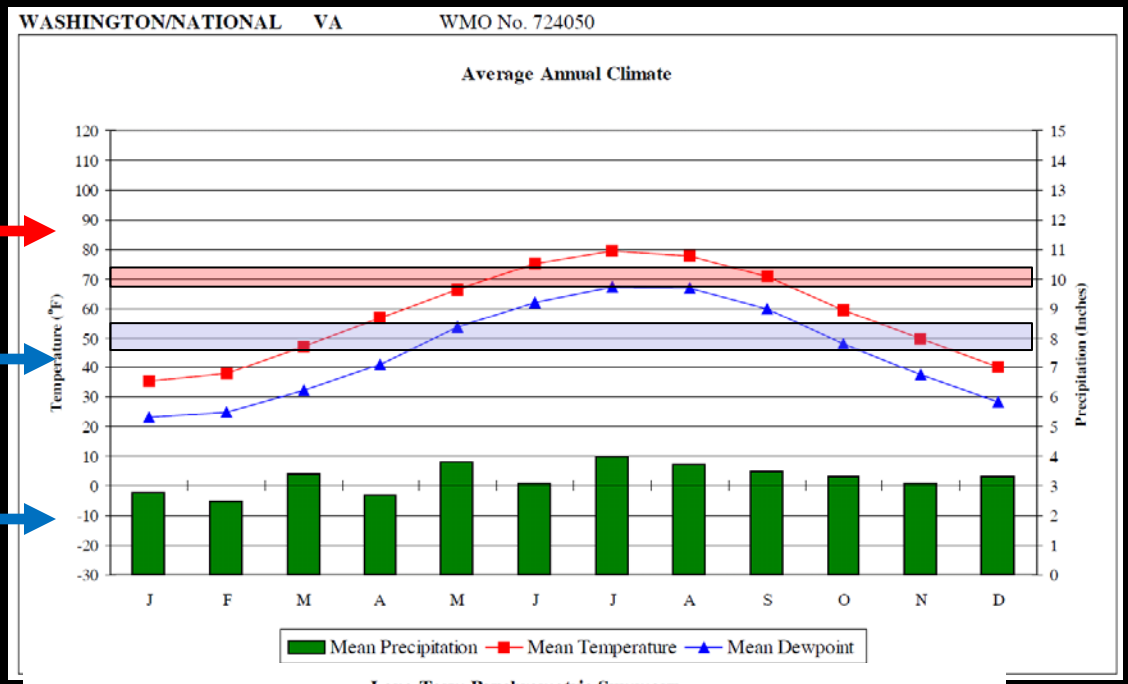


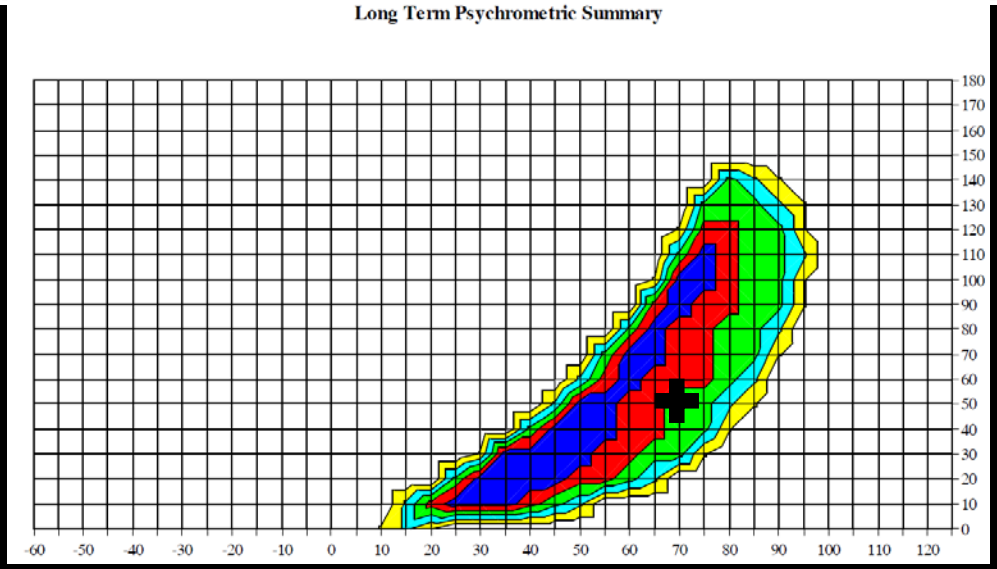
Zone 4A Mixed - Humid
Washington, DC

Dry Bulb Temperature

Dewpoint Temperature
(Moisture Vapor)

Rainfall





Moisture vapor →

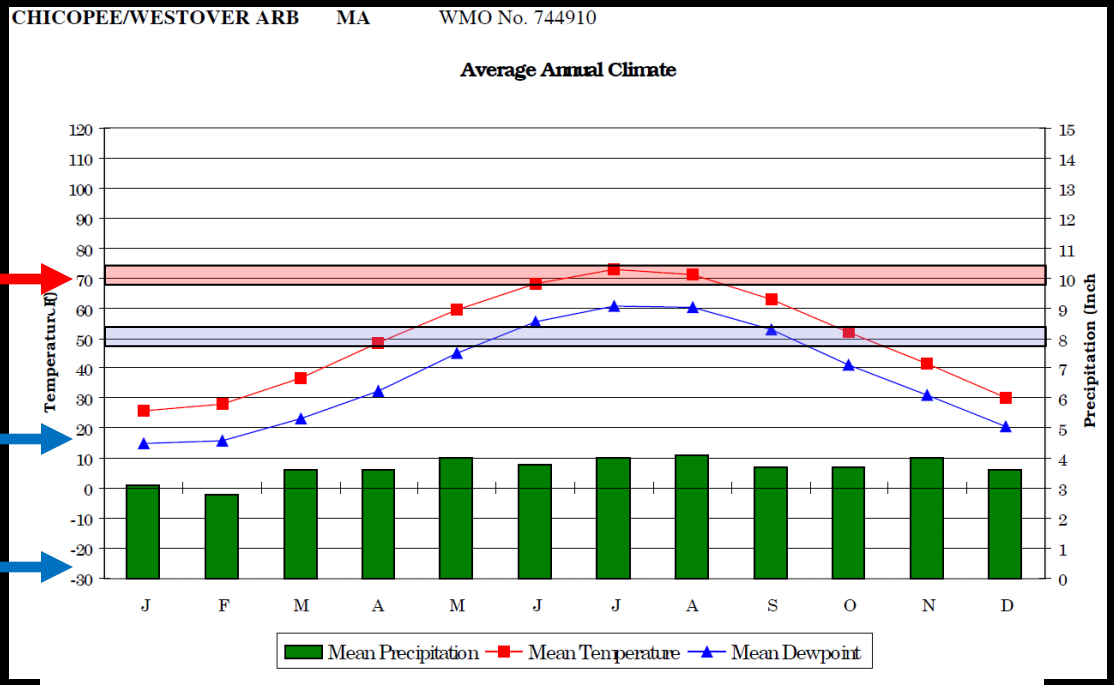
Dry Bulb Temperature →

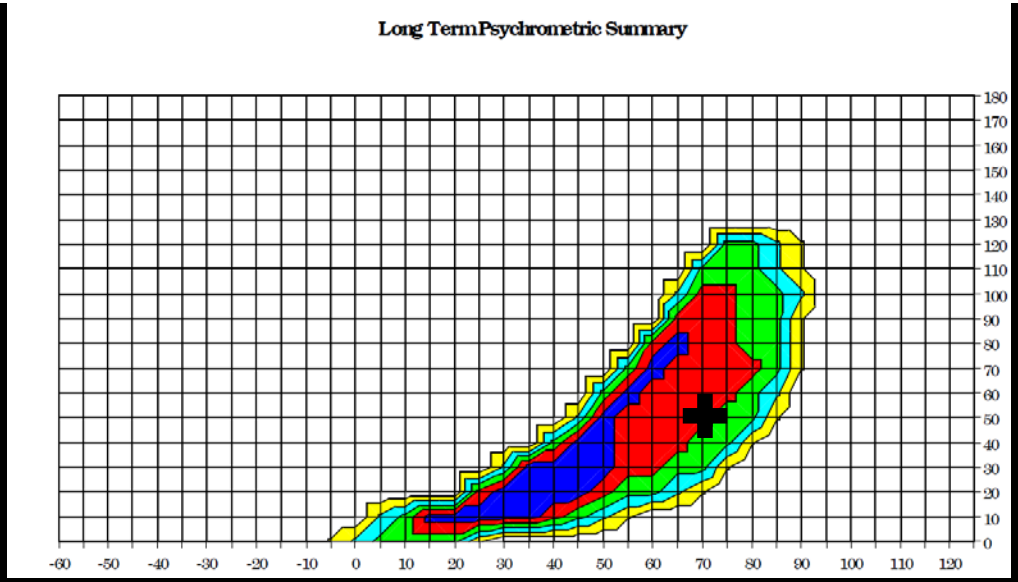
Zone 5A Cool-Humid
Chicopee, MA

Dry Bulb Temperature

Dewpoint Temperature
(Moisture Vapor)

Rainfall





Moisture vapor →

Dry Bulb Temperature →

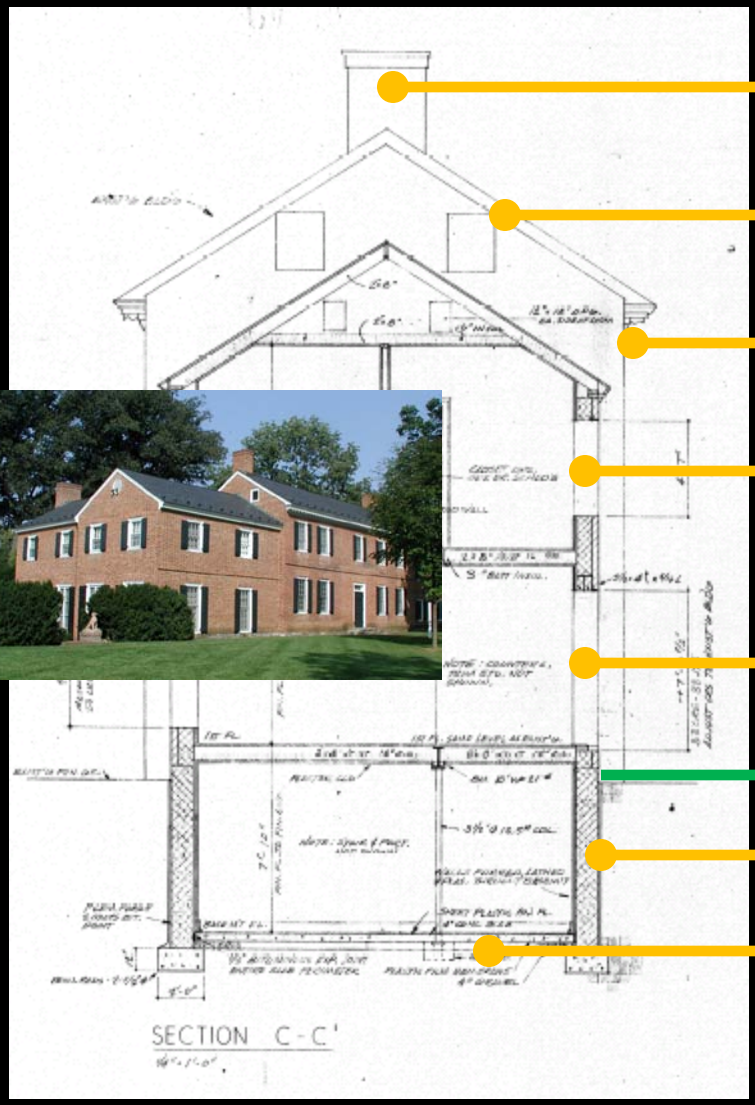
Why think about the building envelope?

- The building envelope protects collections from extremes & fluctuations in exterior T & moisture
- An effective building envelope reduces size & operating cost of the HVAC system needed for a interior conservation environment
- An effective building envelope can protect collections from rapid change in interior T & RH when the HVAC system fails.
- An historic building envelope is part of the historic fabric & must be protected from unintended consequences of interior climate control

The importance of the building envelope should come as no surprise…

We learned about it in our nursery rhymes!

What is included in the building envelope?



Projections, chimneys, flues, parapets

Roofs, eaves, gables

Walls above grade

Windows

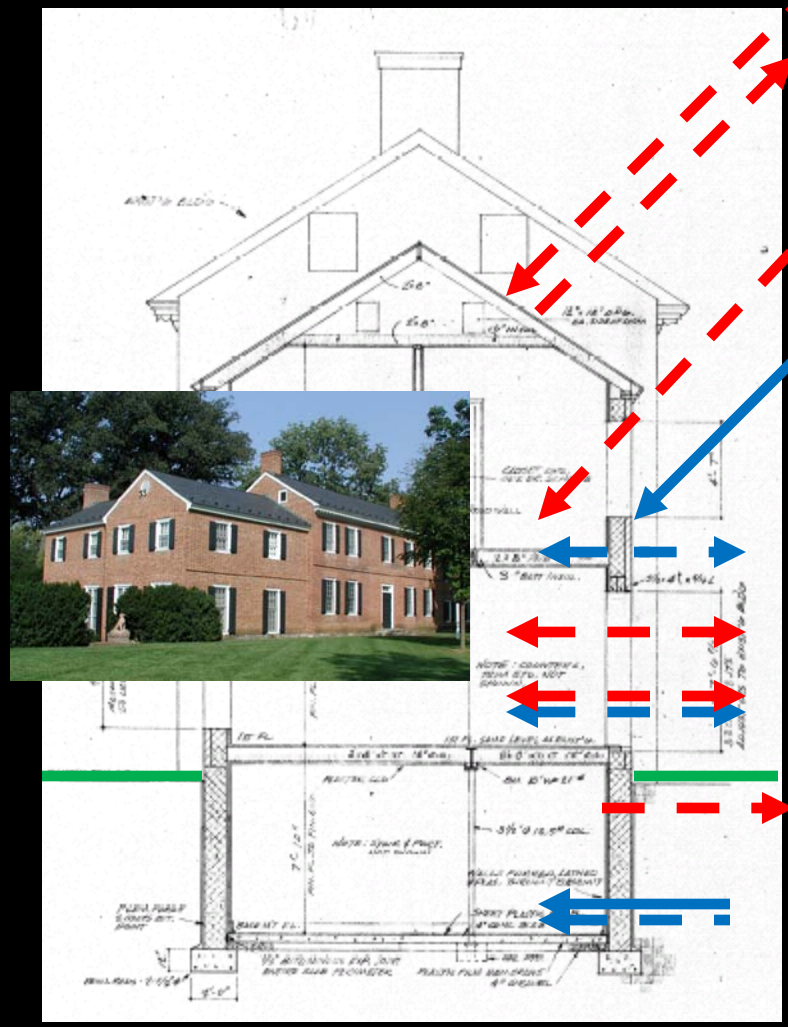
Doors

Above grade
<u>and</u>
Below grade

Walls below grade

Floor slabs, earth floors,
elevated floors above open spaces

Climate results in external moisture & thermal energy loads



Thermal gains from solar radiation &
Thermal losses from night re-radiation

Thermal gains from solar radiation thru windows

Water (liquid) from rain, absorbed

Water (vapor) drying to inside or outside

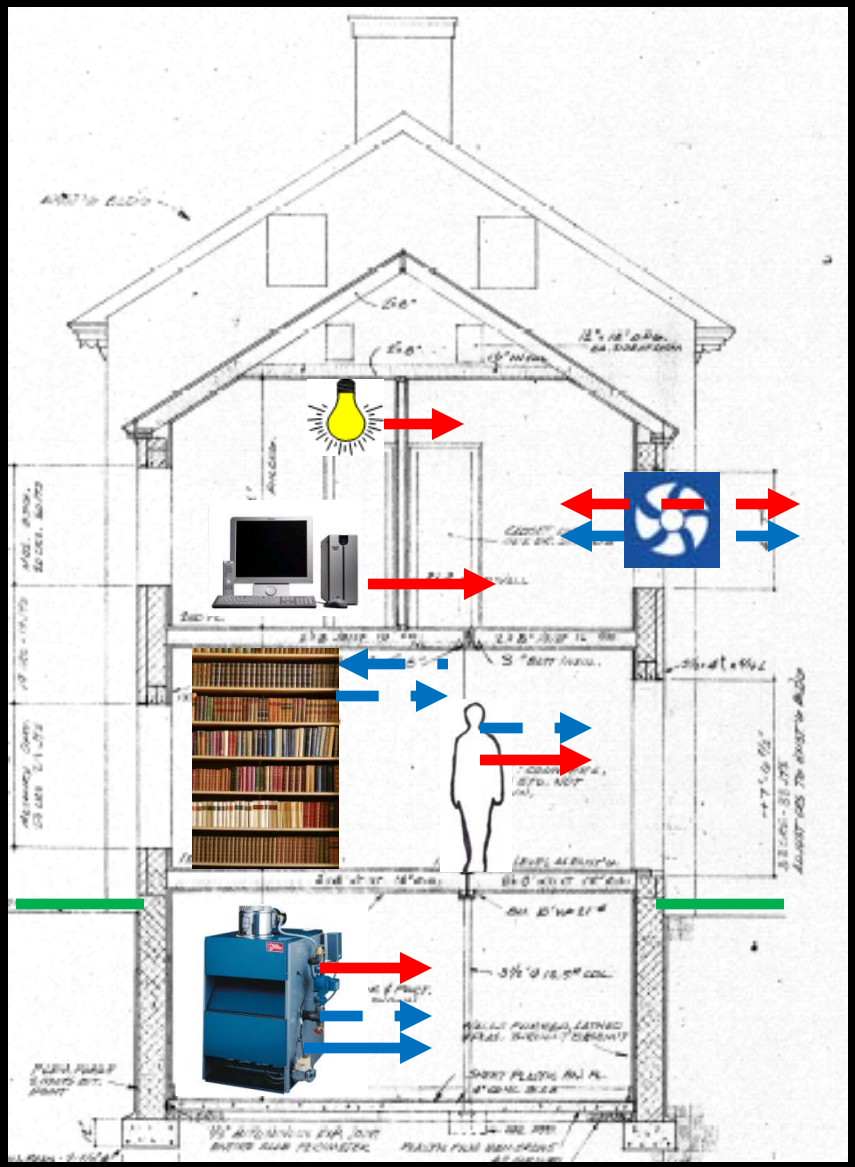
Thermal losses/gains due to convection
Thermal/Water vapor losses/gains w. air exchange

Thermal losses to soil at frost line, neutral below

Water (liquid + vapor) gains from soil moisture

These are dynamic, synergistic processes that we try to manage with the envelope

Building occupancy results in internal moisture & thermal energy loads



Thermal gains from lights & office equipment

Water (vapor) adsorption/desorption
of porous materials & contents

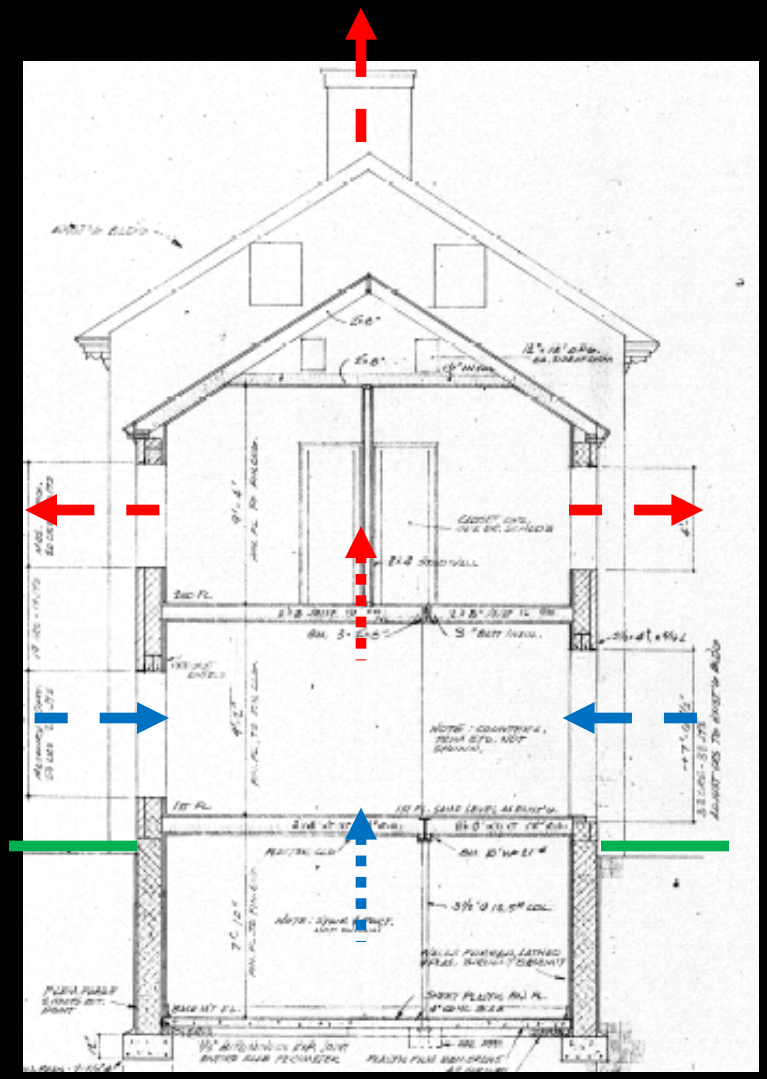
Thermal/Water vapor losses/gains
from ventilation air for occupant health

Thermal/Water vapor gains from occupants

Thermal/ Water (liquid + vapor)
gains from building systems

We can manage these loads
in how we use & occupy the building

Stack effect & the building envelope:
warm buoyant air drives air & moisture exchange



Warm air, being less dense,
rises in the building, up stairways or thru floor penetrations

Warm air exfiltrates at the upper story
Warm air exfiltrates thru open flues also

The exfiltrated air is replaced by
cooler exterior air at the lower stories, or from the crawl space/basement

Moisture vapor exchange results also

Applicable guidance

- NPS: *S of I Standards for the Treatment of Historic Properties - 1995*
- AIC: *Code of Ethics and Guidelines for Practice*
- APT/AIC: *New Orleans Charter for Joint Preservation of Historic Structures & Artifacts*
- ASHRAE: *Applications Chapter 21, Museums, Galleries Archives & Libraries*
- NFPA 909: *Code for the Protection of Cultural Resources Properties - Museums, Libraries, and Places of Worship - 2005*
- NFPA 914: *Code for Fire Protection of Historic Structures - 2007*
- Jurisdictional Codes: Building, Fire, Systems & Energy Conservation

New Orleans Charter

1. Institutions' statements of mission should recognize the need to preserve the unique character of both the historic structure and artifacts.
2. The preservation needs of the historic structure and of the artifacts should be defined only after study adequate to serve as the foundation for the preservation of both.
3. Requisite levels of care should be established through the interdisciplinary collaboration of all qualified professionals with potential to contribute.
4. Appropriate preservation must reflect application of recognized preservation practices, including assessment of risk before and after intervention, and the expectation of future intervention.
5. Measures which promote the preservation of either historic structure or the artifacts, at the expense of the other, should not be considered.
6. Regarding public use, the right of future generations to access and enjoyment must outweigh immediate needs.
7. Appropriate preservation strategies should be guided by the specific needs and characteristics of the historic structure and artifacts.
8. Appropriate documentation of all stages of a projects is essential, and should be readily accessible and preserved for the future.
9. The most appropriate action in a particular case is one which attains the desired goal with the least intervention to the historic structure and the artifacts.
10. Proposed preservation strategies should be appropriate to the ability of the institution to implement and maintain them.

ASHRAE Applications Chapter 21
Museums, Galleries, Archives & Libraries

- Issued in 1999, revised in 2003 & 2007, next revision in development
- Developed by conservation scientists & mechanical engineers
- Provides a "standard of care" for a design engineer
- Provides basis for realistic and achievable environmental criteria
- Envelope portion addresses northern four-season climate zones (Zones 4, 5, 6, & upper portion of 3),
- Envelope portion requires care in hot/humid climate zones (Zones 1,2 & lower part of 3)
- Provides information & guidance, *but not an implementation methodology*

Principles of ASHRAE Chapter 21

- No two collections are identical
- T & RH targets based on climate, envelope & collections needs
- Acknowledges limitations of historic & non-historic building envelopes
- Results in environmental criteria that can maximize collections life within the limitations of the building envelope
- Best undertaken by a collaborative team
  Collections conservator, engineer, architect, curators – collections, interpretation & education, facilities/maintenance staff/contractor, director & chief financial officer, key board members

ASHRAE links the potential "class of control" to building typology & climate

Table 4 Classification of Climate Control Potential in Buildings

Category of Control	Building Class	Typical Building Construction	Typical Type of Building	Typical Building Use	System Used	Practical Limi of Climate Control	Class of Control Possible
Uncontrolled	I	Open structure	Privy, stocks, bridge, sawmill, well	No occupancy, open to viewers all year.	No system.	None	D (if benign climate)
	II	Sheathed post and beam	Cabins, barns, sheds, silos, icehouse	No occupancy. Special event access.	Exhaust fans, open windows, supply fans, attic venting. No heat.	Ventilation	C (if benign climate) D (unless damp climate)
Partial control	III	Uninsulated masonry, framed and sided walls, single-glazed windows	Boat, train, lighthouse, rough frame house, forge	Summer tour use. Closed to public in winter. No occupancy.	Low-level heat, summer exhaust ventilation, humidistatic heating for winter control.	Heating, ventilating	C (if benign climate) D (unless hot, damp climate)
	IV	Heavy masonry or composite walls with plaster. Tight construction; storm windows	Finished house, church, meeting house, store, inn, some office buildings	Staff in isolated rooms, gift shop. Walk-through visitors only. Limited occupancy. No winter use.	Ducted low-level heat. Summer cooling, on/off control, DX cooling, some humidification. Reheat capability.	Basic HVAC	B (if benign climate) C (if mild winter) D
Climate controlled	V	Insulated structures, double glazing, vapor retardant, double doors	Purpose-built museums, research libraries, galleries, exhibits, storage rooms	Education groups. Good open public facility. Unlimited occupancy.	Ducted heat, cooling, reheat, and humidification with control dead band.	Climate control, often with seasonal drift	AA (if mild winters) A B
	VI	Metal wall construction, interior rooms with sealed walls and controlled occupancy	Vaults, storage rooms, cases	No occupancy. Access by appointment.	Special heating, cooling, and humidity control with precision constant stability control.	Special constant environments	AA A Cool Cold Dry

American Society of Heating Refrigeration & Air Conditioning Engineers, Applications Handbook Chapter 21, Museums, Libraries & Archives

Building envelope typologies:
Sheathed post & beam (ASHRAE Class II)

Original purposes:
Barns, sheds, mills, agricultural buildings or seasonal cabins.

Typical construction:
Wood-framed & wood-clad or metal-clad, no insulation, no vapor retarder, large loose-fitting doors, few windows, earth floors or wood floor w. shallow crawl space.

Performance characteristics:
High air and moisture exchange rate, low solar heat radiant gain thru windows, small thermal mass, small mass for moisture buffering.

Building envelope typologies
Uninsulated masonry, framed & sided walls (ASHRAE Class III)

Original purposes:
Early industrial buildings, modest houses & commercial buildings.

Typical construction:
Simple masonry walls or wood-framed & wood-clad walls, plaster interior finish, no insulation, no vapor retarder, single-glazed windows, wood floors over shallow crawl space or basement or concrete slab-on-grade.

Performance characteristics:
Moderate air and moisture exchange rate, solar heat radiant gain at windows, moderate mass to volume ratio for thermal & moisture buffering.

Building envelope typologies
Heavy masonry, composite walls, storm windows (ASHRAE Class IV)

Original purposes:
Substantial houses, educational, civic & religious buildings.

Typical construction:
Thick masonry walls or insulated/brick-filled wood-framed walls, interior finishes/plaster, single-glazed windows w. storm sash, dense foundation walls, concrete floor in crawl space or basement. No vapor retarder. Insulation unlikely, except in attic.

Performance characteristics:
Low to moderate air & moisture exchange rate, high thermal mass, moderate moisture buffering mass, solar radiant gain at windows.

Building envelope typologies
Insulated, vapor retardant, double glazed, w. vestibules (ASHRAE Building V)

Original purposes:
Recent museum buildings, recent offices, storage & industrial building.

Typical construction:
Metal-framed or concrete-framed, insulated walls (block or metal panels), insulated membrane or metal roofing. Vapor retarders in all planes. Few windows, double-glazed. Vestibule entries. Tight construction.

Performance characteristics:
Low air & moisture exchange rate, low to moderate thermal mass, low moisture buffering mass, solar radiant gain on dark surfaces, especially roofs.

Building envelope typologies
Tight construction, perimeter buffer, limited occupancy (ASHRAE Class VI)

Original purposes:
Purpose-built collections storage, robust storage structures & special mfrg building.

Typical construction:
Metal- or concrete-framed, insulated walls (block or metal panels), insulated membrane or metal roofing. Vapor retarders in all planes. No windows. Vestibule entries. Tight construction.

Performance characteristics:
Low air & moisture exchange rate, low to moderate thermal mass, low moisture buffering mass, interior spaces buffered from exterior surfaces by cavities or corridors.

Building envelopes - Special considerations
(No ASHRAE Building Class)

Structures on piers
open crawl spaces

Subgrade structures
& vaults

Mixed envelopes, i.e.,
wood above masonry

Glass structures
greenhouse to modern

ASHRAE 21 defines possible "classes of control"…

Table 3 Temperature and Relative Humidity Specifications for Collections

Type	Set Point or Annual Average	Maximum Fluctuations and Gradients in Controlled Spaces: Class of Control	Short Fluctuations plus Space Gradients	Seasonal Adjustments in System Set Point	Collection Risks and Benefits
General Museums, Art Galleries, Libraries, and Archives All reading and retrieval rooms, rooms for storing chemically stable collections, especially if mechanically medium to high vulnerability.	50% rh (or historic annual average for permanent collections) Temperature set between 59 and 77°F *Note*: Rooms intended for loan exhibitions must handle set point specified in loan agreement, typically 50% rh, 70°F, but sometimes 55% or 60% rh.	**AA** Precision control, no seasonal changes	±5% rh, ±4°F	Relative humidity no change Up 9°F; down 9°F	No risk of mechanical damage to most artifacts and paintings. Some metals and minerals may degrade if 50% rh exceeds a critical relative humidity. Chemically unstable objects unusable within decades.
		A Precision control, some gradients or seasonal changes, not both	±5% rh, ±4°F	Up 10% rh, down 10% rh Up 9°F; down 18°F	Small risk of mechanical damage to high-vulnerability artifacts; no mechanical risk to most artifacts, paintings, photographs, and books. Chemically unstable objects unusable within decades.
			±10% rh, ±4°F	RH no change Up 9°F; down 18°F	
		B Precision control, some gradients plus winter temperature setback	±10% rh, ±9°F	Up 10%, down 10% rh Up 18°F, but not above 86°F	Moderate risk of mechanical damage to high-vulnerability artifacts; tiny risk to most paintings, most photographs, some artifacts, some books; no risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		C Prevent all high-risk extremes	Within 25 to 75% rh year-round Temperature rarely over 86°F, usually below 77°F		High risk of mechanical damage to high-vulnerability artifacts; moderate risk to most paintings, most photographs, some artifacts, some books; tiny risk to many artifacts and most books. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.
		D Prevent dampness	Reliably below 75% rh		High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs. Mold growth and rapid corrosion avoided. Chemically unstable objects unusable within decades, less if routinely at 86°F, but cold winter periods double life.

American Society of Heating Refrigeration & Air Conditioning Engineers, Applications Handbook Chapter 21

Improving envelope performance
the case for non-mechanical (passive) strategies

- Utilize fixed & operable elements of the building & site
- Reduce peak external loads on the interior environment
- Moderate fluctuations from changing external or internal loads
- Thereby reduce the size/capacity of mechanical systems
- The systems can operate more efficiently, due to smaller range
- Require commissioning & maintenance, just like mechanical systems

Any non-mechanical strategy must be developed for the specifics of each collection, climate, building, site & institutional capacity.

Essential non-mechanical strategies

- Eliminate moisture at the source
  roof drainage, surface water & subsurface water, irrigation systems management
- Minimize uncontrolled air & moisture vapor infiltration/exfiltration
  entries, windows & doors, open flues, any envelope perforations
- Minimize or control direct & indirect solar gain
  landscape for shade, shades/blinds/filters at windows & skylights, cool roofs

"Excellent!" cried Watson
"Elementary," replied Holmes

These strategies are obvious, but are often overlooked or ignored

Essential Non-Mechanical Strategies

- Zone the building according to environmental needs
  more stable needs at interior, less stable needs along perimeter & under roof
- Separate collections zones from people "comfort" zones
  this is especially true for office areas where comfort affects productivity
- Manage the peak visitor count, especially on peak cooling days
- Separate collections from events/variable occupant loads

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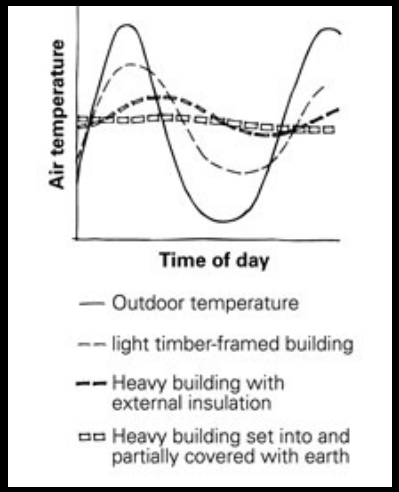
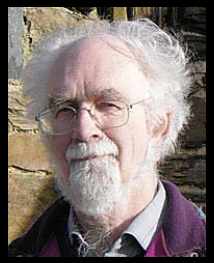
The Envelope & Thermal Mass

It depends on climate, use & materials…

Michael C. Henry, 2006





Tim Padfield: *"The climate in unventilated stores & archives can be entirely passively controlled in <u>temperate</u> regions."*

In other climates, it can help.

Thermal Mass in Buildings

- Slows transport of thermal energy from outside to inside and reverse (+)
  but interior thermal loads may still dominate
- Stabilizes T & stable T yields stable RH (+)
  provided that there is no moisture vapor gain or loss in the space
- In Dry climates, can raise interior T (night) & lower interior T (day) (+)
  but this requires a substantial diurnal temperature range
- In Zone 2 Hot-Humid, thermal mass yields high interior T, lower RH (+/-)
- Provides thermal inertia when systems are off (+)

- In all climates, location of insulation (inside/outside) is critical (!)
- Less effective cool/cold zones if interior T is not maintained (!)
- In Zone 4A, Mixed-Humid, interior RH may be high in spring if interior T is low over winter (!)
- Must also address the roof (!)
  These tend to be low-mass due to cost and weight.

The Envelope & Simple Geothermal

Geothermal is the rage, but why buy all the pipes & pumps?

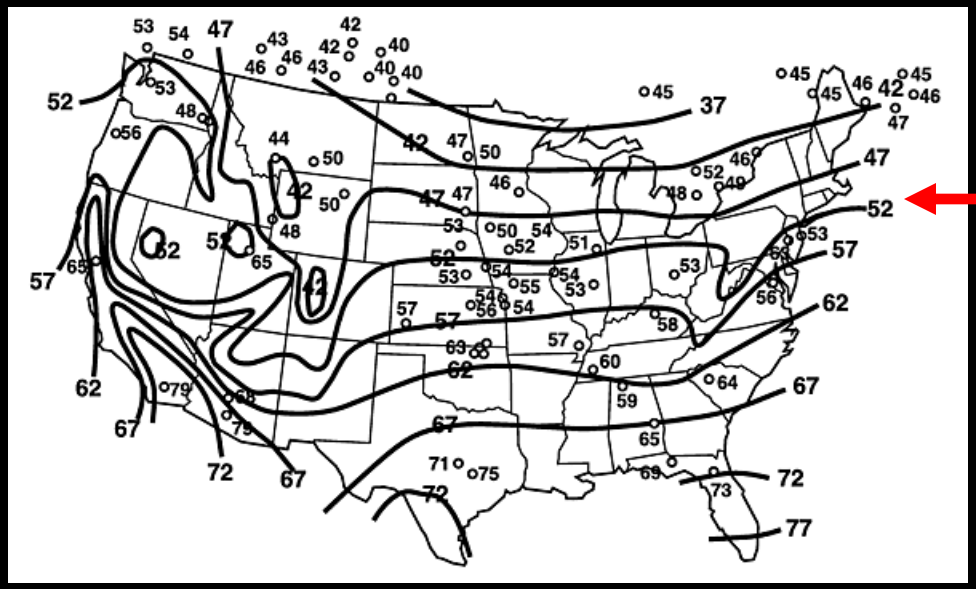
Janet Sheridan, W&HA, 2011

"My potatoes don't like light, mold or heat,
and I don't need air conditioning!
I put my money in that (earthen) bank!"

Problem solved?

Simple Geothermal: Earth-Banked & Below-Grade Structures

- A semi-infinite variant of high thermal mass design (+), (!)
- Soil T below frost line is more stable than ambient air T (+)
- Soil T below frost line is near the range of conservation T (+)
- Soil is a free heating or cooling source, when used passively (+)
- Soil type & groundwater are considerations for heat transfer (!)
- Exterior waterproofing is critical (!)
- Interior dew point temperature must be below wall temperature (!)



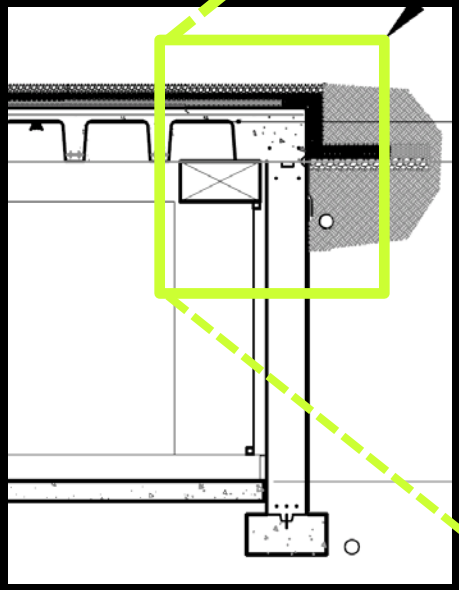
http://www.geo4va.vt.edu/A1/A1.htm

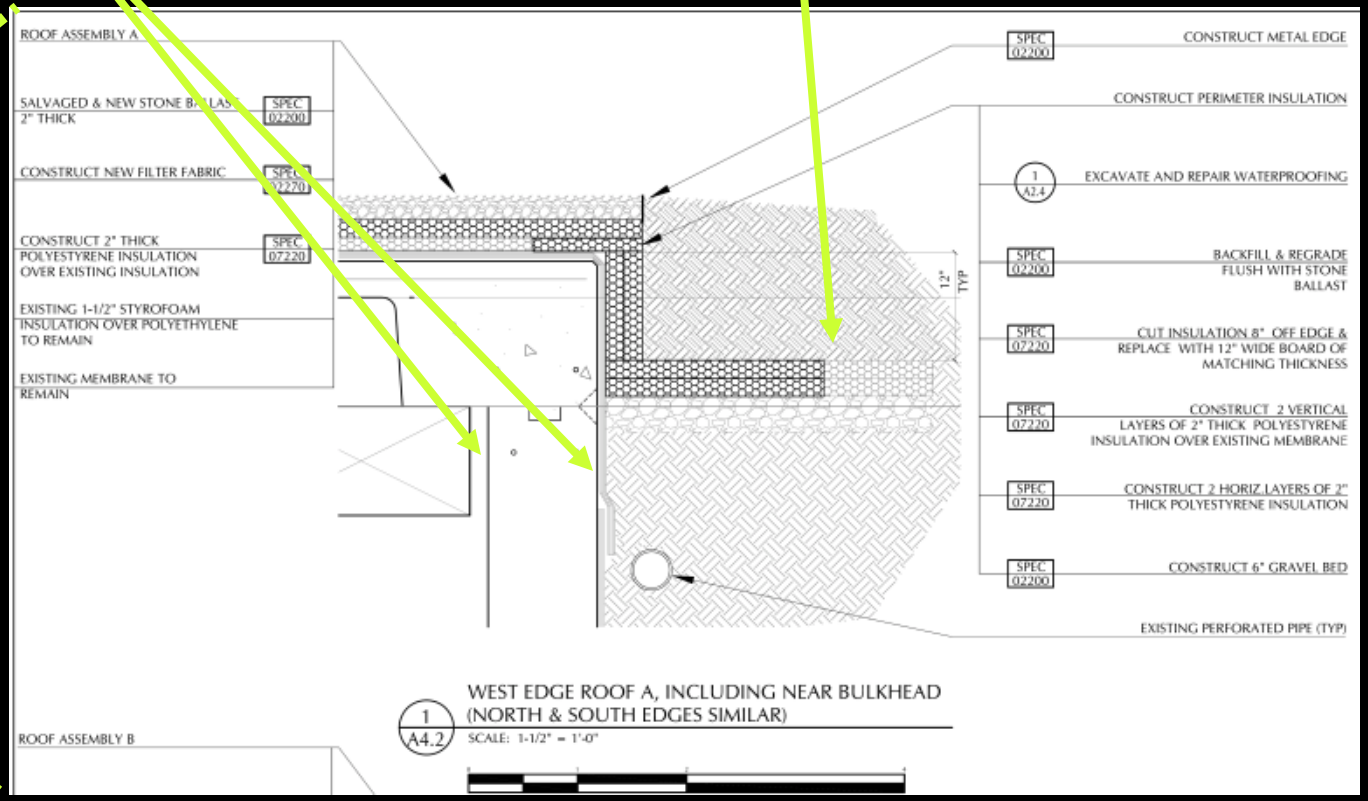
Average soil temperature below frost line

Earth-Banked & Sub-Grade Structures: Rethinking Insulation

frost-protected foundation design

- Insulation "apron" around structure, just below grade
- No insulation inside/outside the wall below frost line



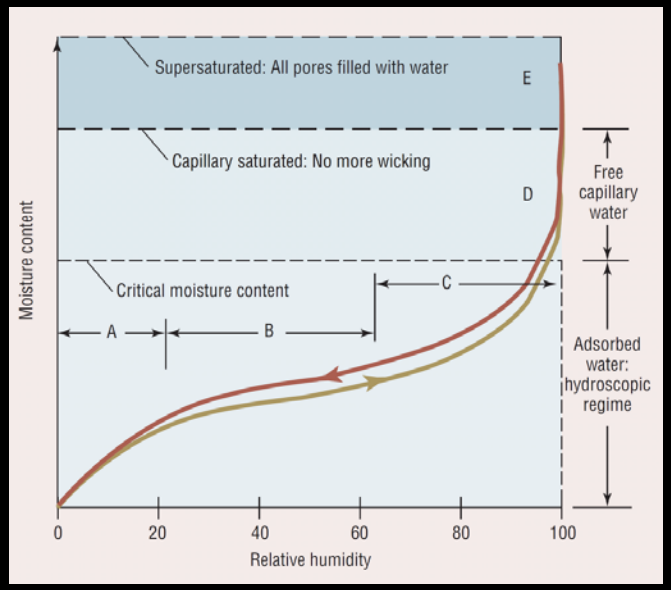


Watson & Henry Associates

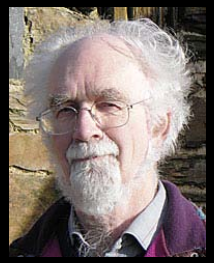
The Envelope & Moisture Buffering

It depends on climate, building use & materials…

Michael C. Henry, 2003



J. F. Straube



Tim Padfield: *"Passive climate control of museum exhibition rooms is limited by the large air exchange required by people."*

Passive strategies cannot overcome large air exchange or internal loads

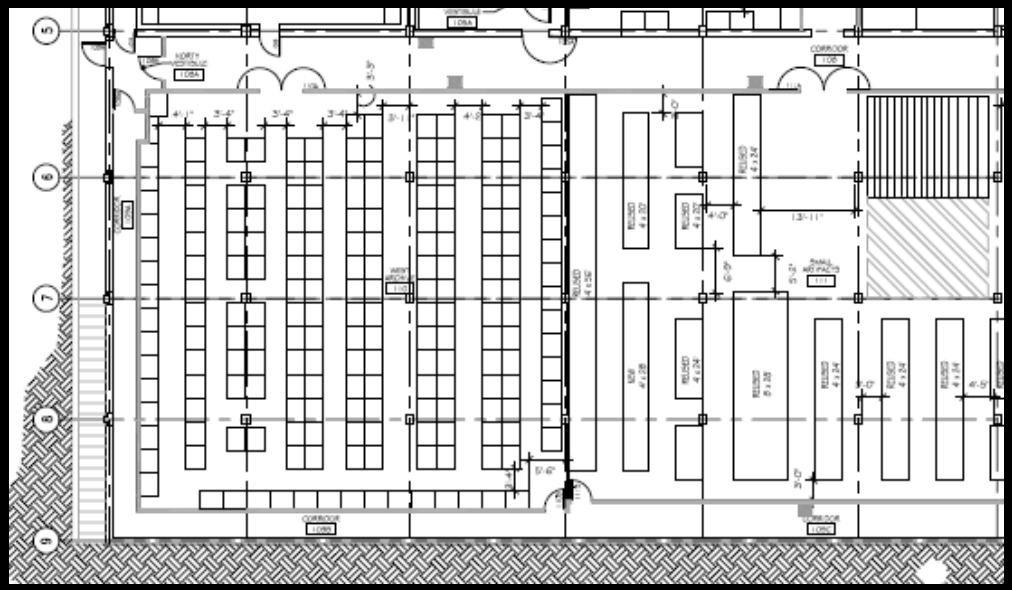
Moisture Buffering with Building Materials

- Can moderate daily variations in interior RH (+)
  But response (adsorption/desorption) time is slow
- Can moderate seasonal variations in interior RH (+)
  But this applies to buildings with low occupancy, small infiltration & very small ventilation loads
- Provides buffering when systems are shut down (+)

- Does not remove excess moisture from interior or exterior sources (!)
  Dehumidification is required for these loads
- Buffering must be substantial relative to moisture capacity of room air (!)
- Response time depends on surface area of the buffer material (!)
  Paints and coatings may diminish performance
- Porous construction materials may require long drying time.

Multiple Envelopes: Cascaded Thermal & Moisture Gradients

Box in box enclosures



Michael C. Henry, 2008

L. L. Bean (the company): *"The "layering" method is the most effective way to dress for a wide range of winter conditions."*

It can work for buildings, too.

Box in Box, Layered Enclosures

- Distributes functions of the exterior wall between two walls (+)
  vapor control is in warm interior wall, resolves condensation issue
  exterior wetting and drying remains with the exterior wall
  leaks are in the corridor
- Reduces steep moisture vapor gradients across the wall assembly (+)
- Enhances thermal stability (+)
  isolates space from exterior T swings and radiant gains/losses
- Allows adaptation of existing conventional exterior wall assemblies (+)
  An excellent rehabilitation/adaptive reuse strategy

- Requires additional space for perimeter corridors (!)
- Extra cost of wall construction (!)
- Roof must be dealt with also (!)

Mini-Envelopes: Collection Housing

We focus on space T & RH,
but what does the stored material experience?

Foekje Boersma, 2007

Mini-Envelopes: Buffering by Collections Housings

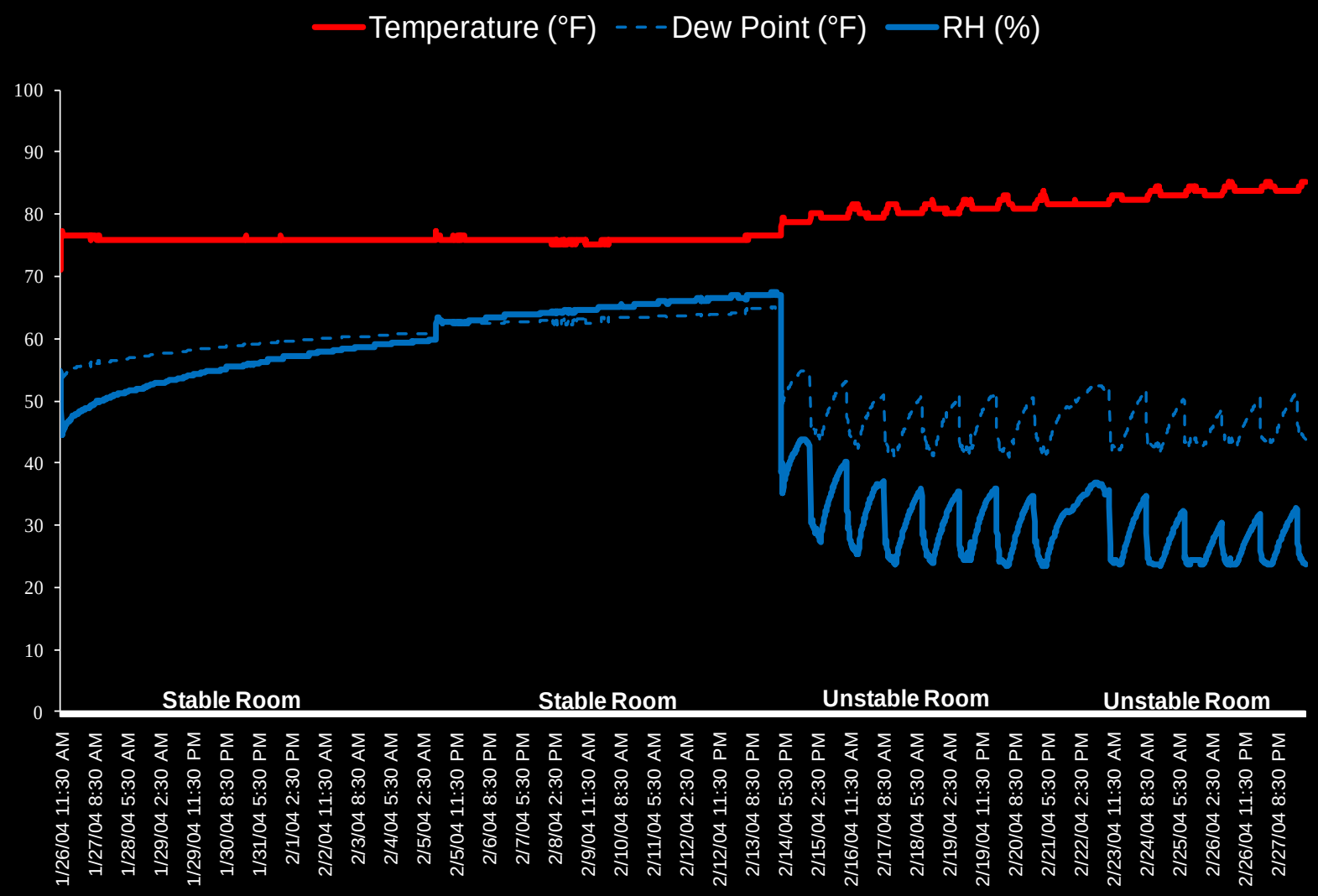
A simple field trial for buffering of textiles & paper in housings & cabinets in a passive, thermally massive, moisture-buffered, double-wall collections storage & archives building near Ahmednaggar India

Michael C. Henry, 2003

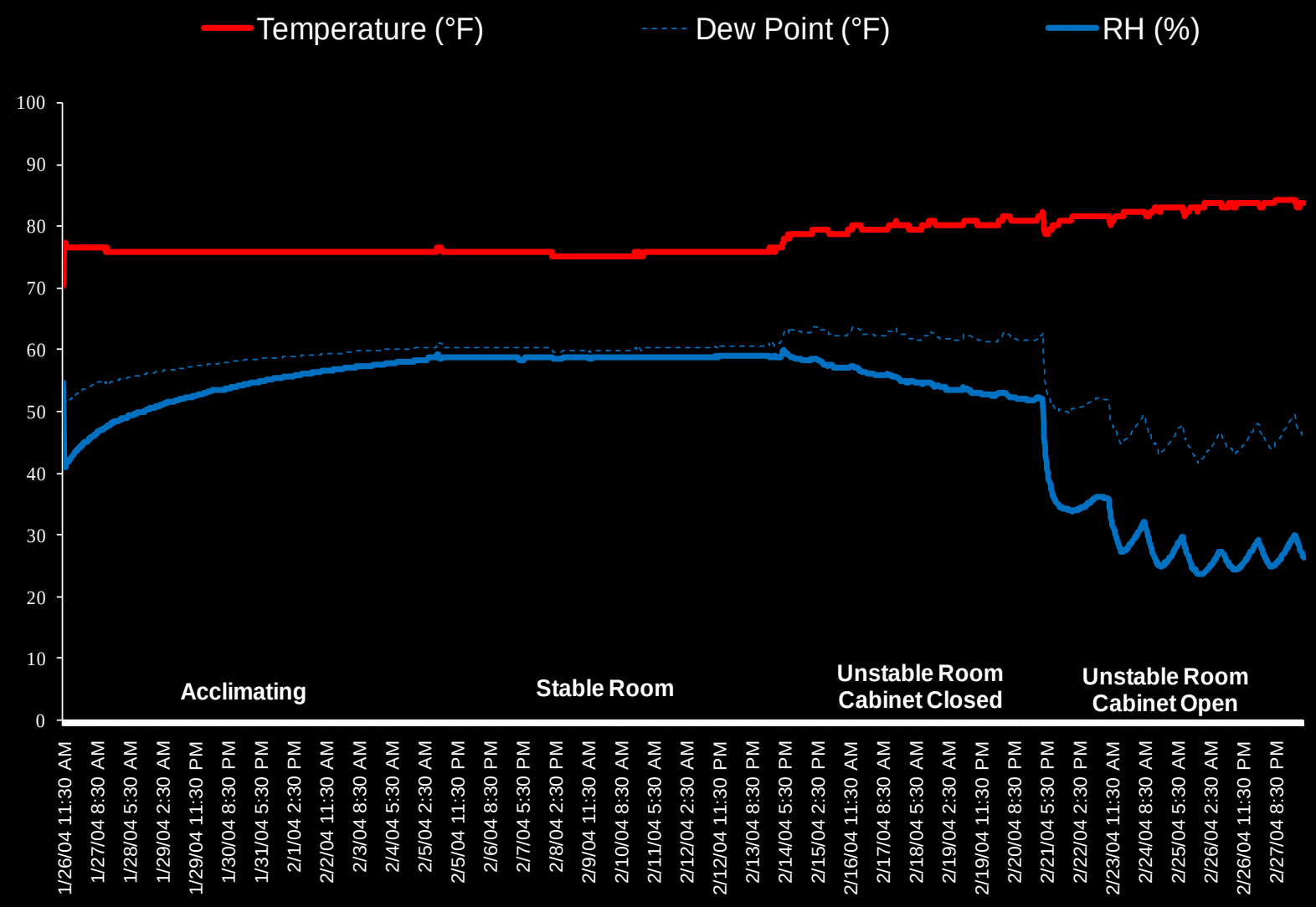
Michael C. Henry, 2003

- Interval 1: proxy materials acclimated in stable unconditioned room
- Interval 2: in *Coroplast*® boxes, set in metal cabinets with gasketed doors closed in stable room
- Interval 3: moved to unstable room, cabinet doors remain closed
- Interval 4: cabinet doors opened in unstable room

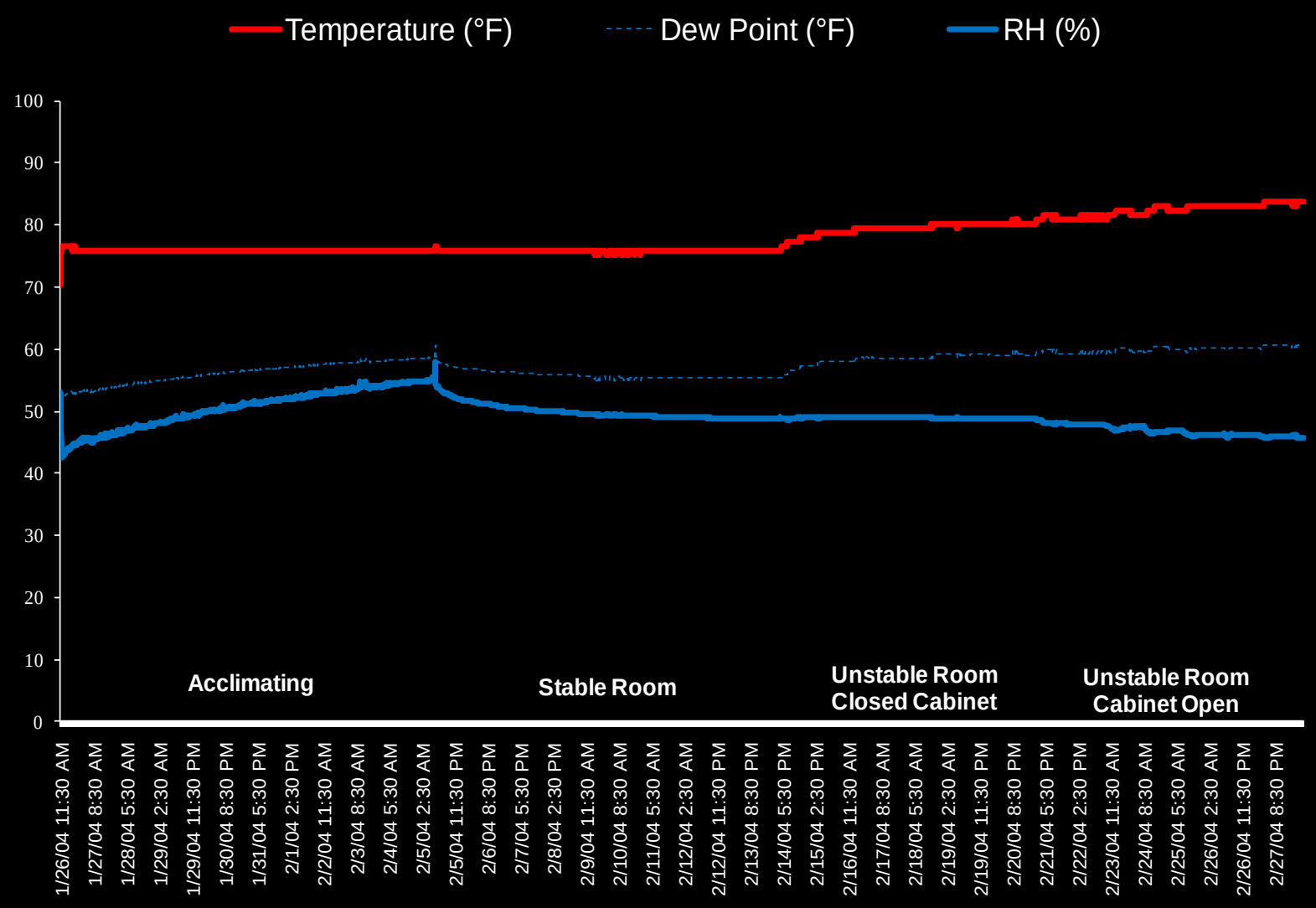
Housing Trial: Room Conditions



Housing Trial
Textile Bundle in Box



Housing Trial
Paper in Box



Envelope Damage from Interior Environments

Problems occur when:

- $T_{surface}$ of low permeability materials is below $T_{dewpoint}$ in the assembly
- Porous materials experience high RH within the envelope assembly due to moisture or due to low T
- Rate of moisture intake (liquid & vapor) exceeds rate of drying (vapor)
- In dry climates/seasons, moisture vapor flow tends to be outward
- In humid climates/seasons, moisture vapor flow tends to be inward

Using analysis to avoid moisture related problems in envelope assemblies

Thermal & moisture gradients in envelopes
can be estimated by static equilibrium analysis,
…but the reality is dynamic & this requires dynamic simulation.

A computer simulation of heat and moisture,
such as WUFI, can provide the dynamic simulation.

Wärme- und Feuchtetransport instationär
("Transient Heat and Moisture Transport")

http://www.wufi-pro.com/

Dynamic analysis & WUFI

For heat transport, WUFI takes into account:

- thermal conduction
- enthalpy flows through moisture movement with phase change
- short-wave solar radiation
- nighttime long-wave radiation cooling.

Convective heat transport by air flows has been disregarded.

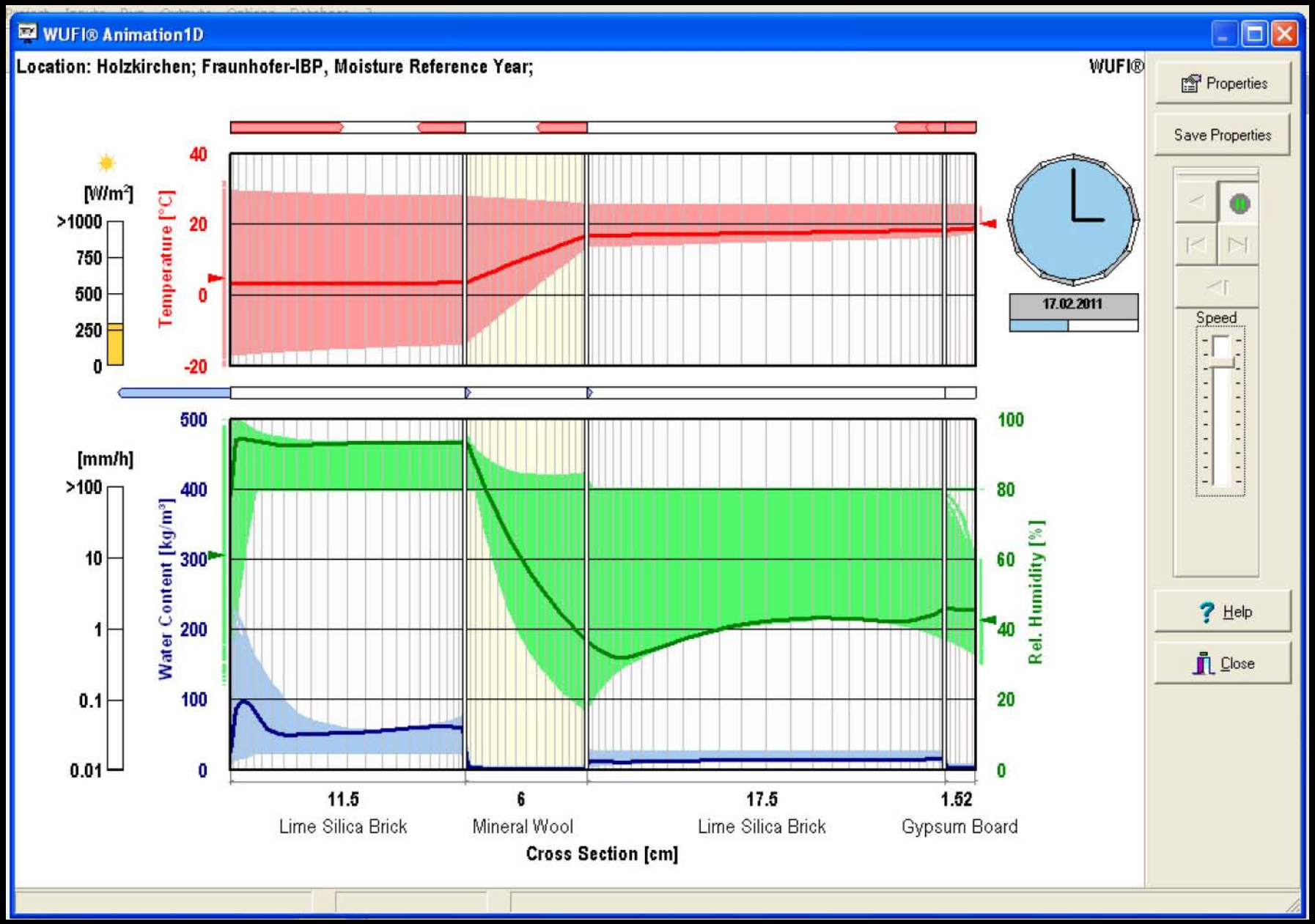
The vapor transport mechanisms included in WUFI are:

- vapor diffusion
- solution diffusion.

The liquid transport mechanisms taken into account are:

- capillary conduction
- surface diffusion.

Seepage flow through gravitation is not included.


WUFI® Animation1D
Location: Holzkirchen; Fraunhofer-IBP, Moisture Reference Year;
WUFI®
Properties
Save Properties
Speed
Help
Close
[W/m²]
>1000
750
500
250
0
Temperature [°C]
40
20
0
-20
17.02.2011
[mm/h]
>100
10
1
0.1
0.01
Water Content [kg/m³]
500
400
300
200
100
0
Rel. Humidity [%]
100
80
60
40
20
0
11.5
Lime Silica Brick
6
Mineral Wool
17.5
Lime Silica Brick
1.52
Gypsum Board
Cross Section [cm]

In real buildings conditions will vary,
so simulations & analysis must be applied with care…
the actual construction may differ from assumptions in the model!

Thank you for listening

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