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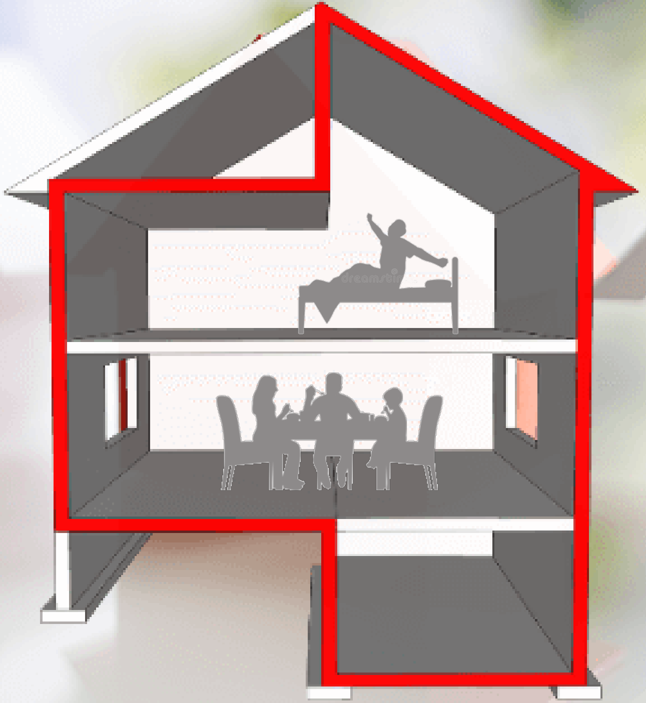


ENG-445
Building Energetics

Cooling in Buildings – Emission Systems and Thermal Comfort

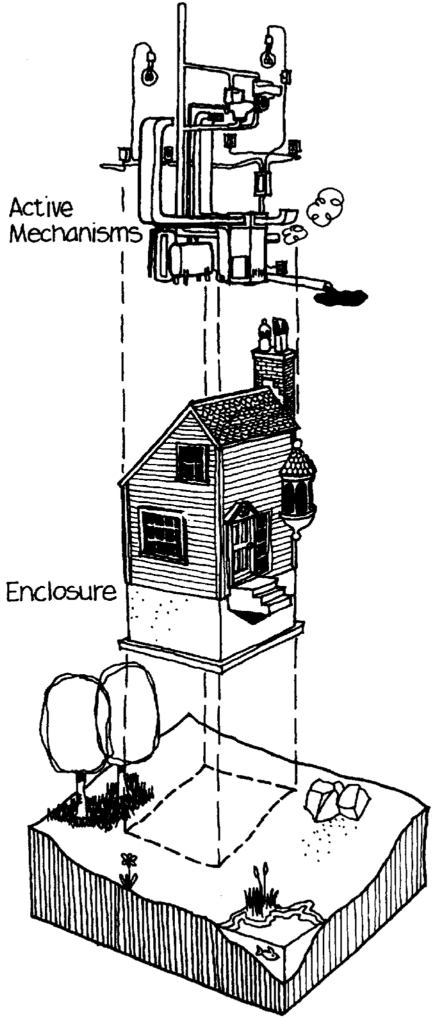
Assist. Professor
Dolaana Khovalyg

28 November 2024

Course Information

Week	Date	Topic	Timing	Teacher	Project (AS, MF)
9	07/11	Building envelope, thermal performance of building elements	45' x 2	DK	Tutorial building envelope
		Exercises	45'		
10	14/11	Heating and cooling demand in buildings	45' x 2	DK	Free work
		Exercises	45'		
11	21/11	Thermal systems for heating and their effect of human comfort	45' x 2	JY	Free work
		Exercises	45'		
12	28/11	Thermal systems for cooling and their effect of human comfort	45' x 2	DK	Tutorial heating systems (emission systems)
		Exercises	45'		

JY – Jaafar Younes, a postdoc from the ICE lab



Source: Edward Allen «How Buildings Work» (2005)

CONTENT:

- Introduction
- Passive Cooling Strategies
- Overview of Active Cooling Systems
  - All-air, refrigerant-based, hydronic systems
  - Radiant Cooling Systems:
    - Heat transfer overview
    - Limiting heat flux
    - Radiant ceiling panels
  - Evaporative cooling
  - Dehumidification
- Summary

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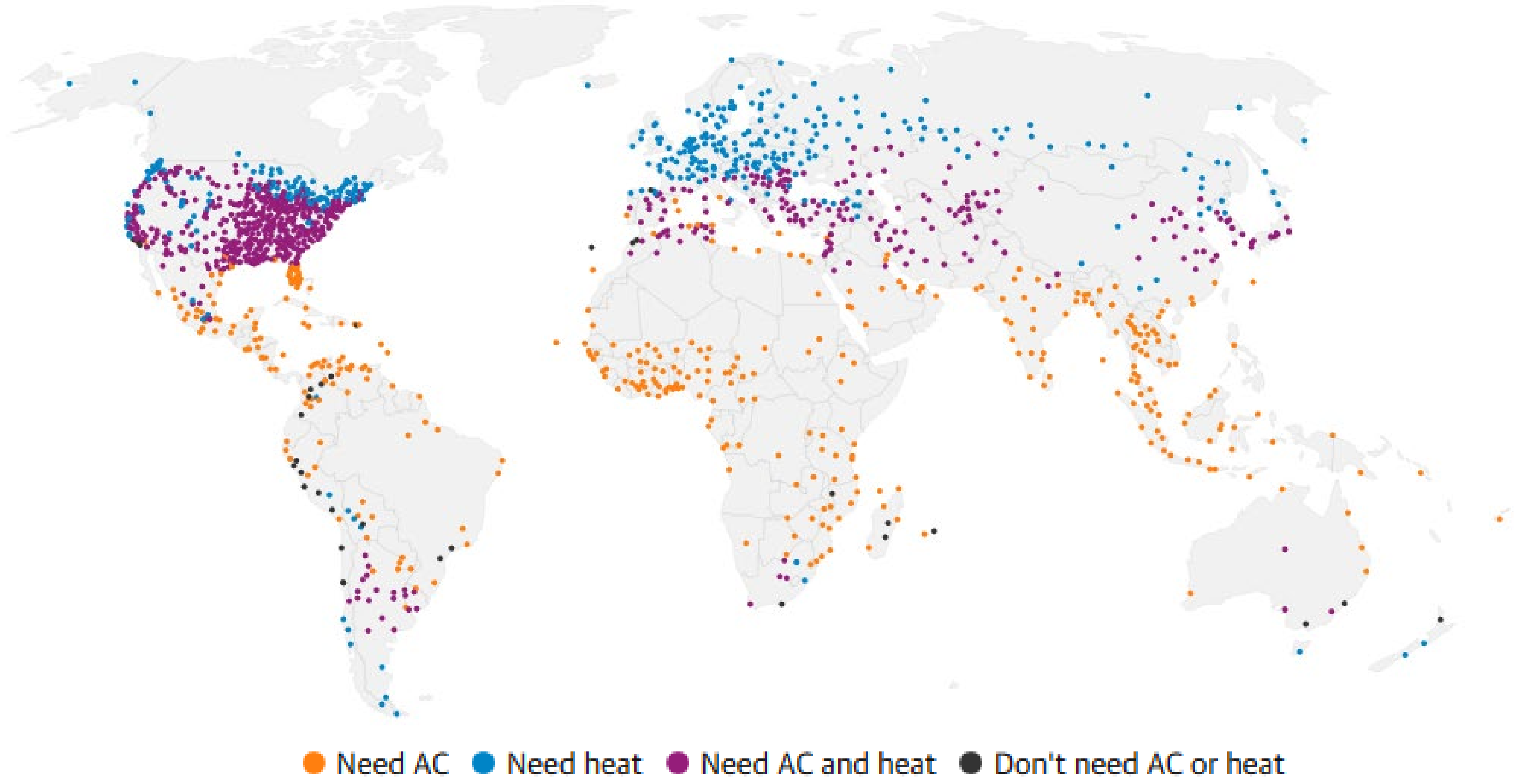
Indoor Thermal Conditioning: Overview



Source: https://www.theguardian.com

Indoor Cooling: Increasing Needs

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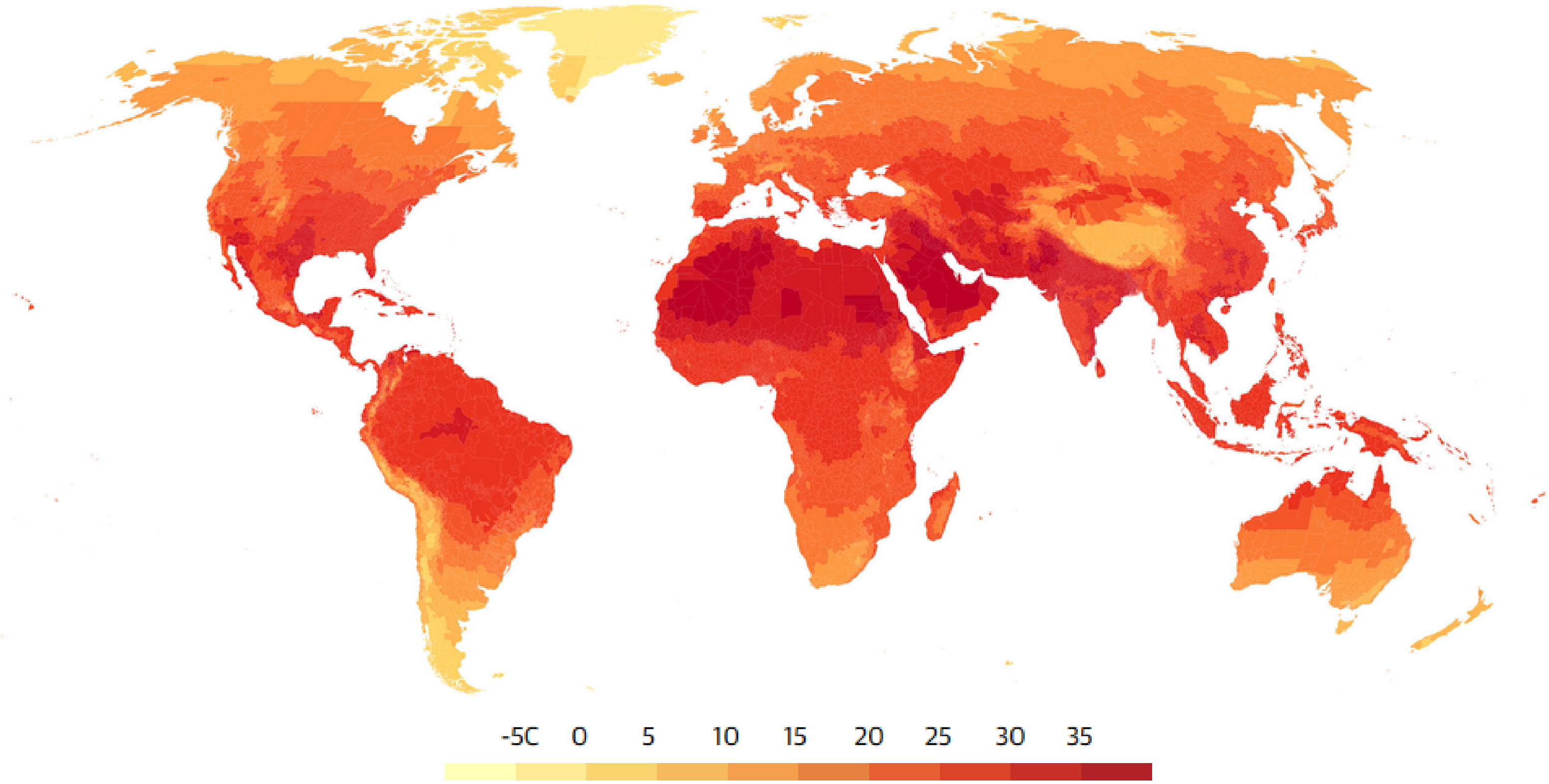
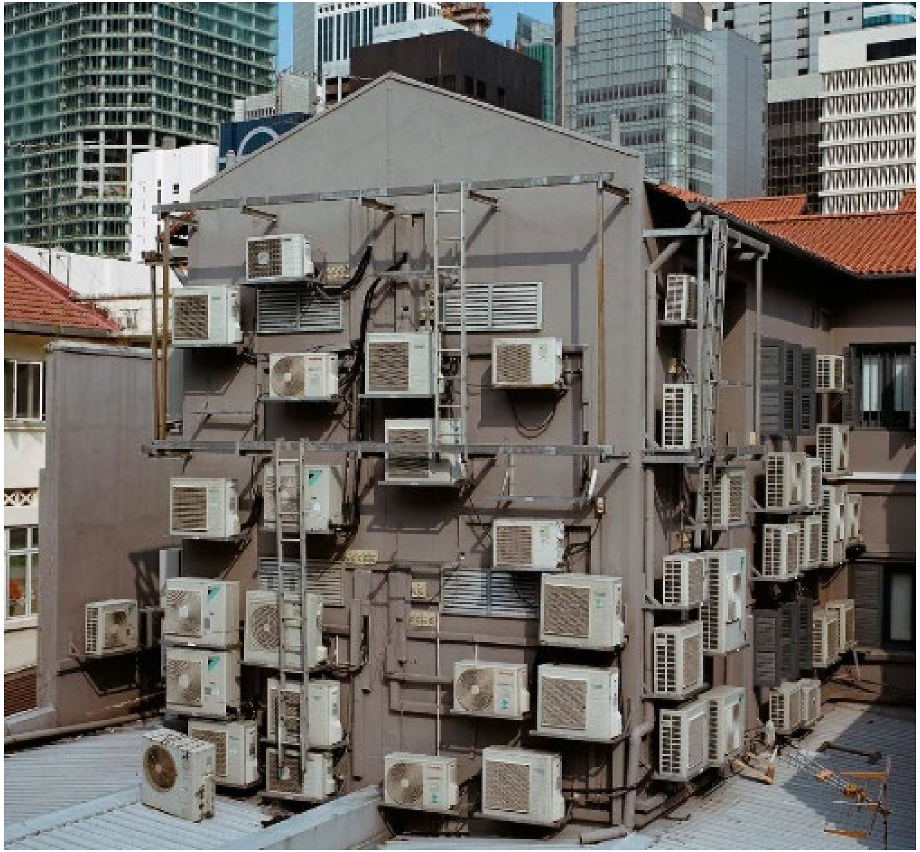
Average temperature between June and August, **2040-2059**



Source: https://www.theguardian.com

Indoor Cooling: Increasing Needs



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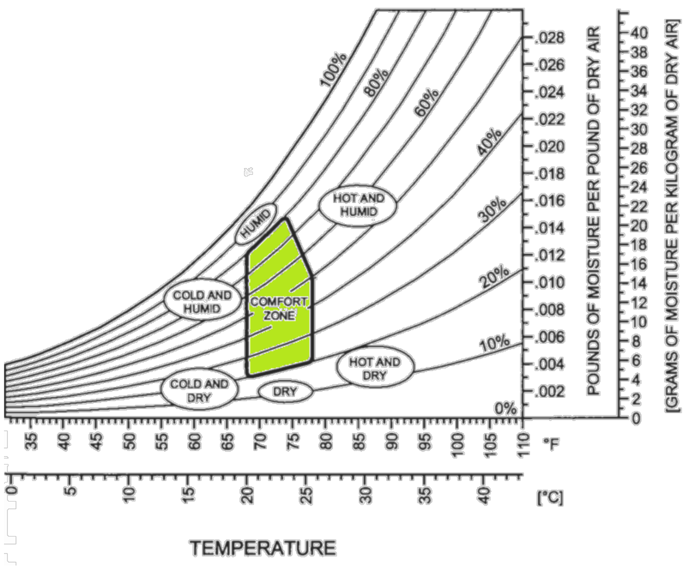
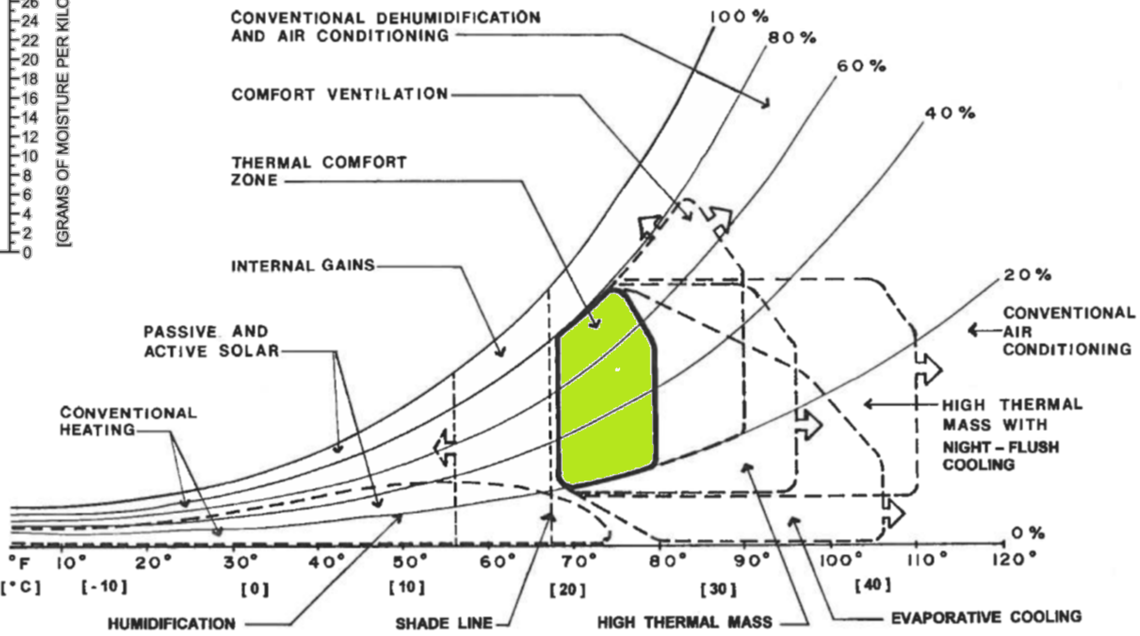
Building Bioclimatic Chart

From Week 10



Climate analysis is necessary due to the *intrinsic* relation between **climate** and **energy demand for thermal comfort in buildings**



Source: Lechner, Norbert, *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, Wiley, 2008.

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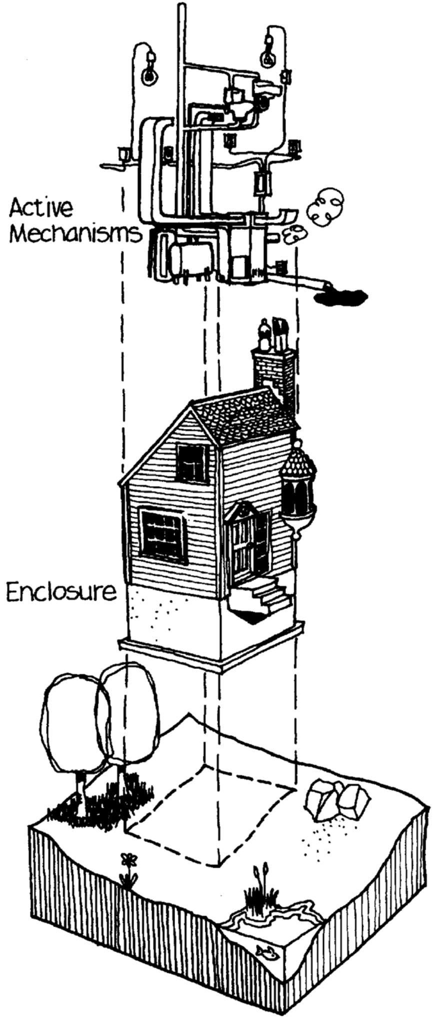

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- Summary

Passive Cooling Strategies

Source: *Valladares-Rendónetal L.G. (2017) Energy and Buildings*

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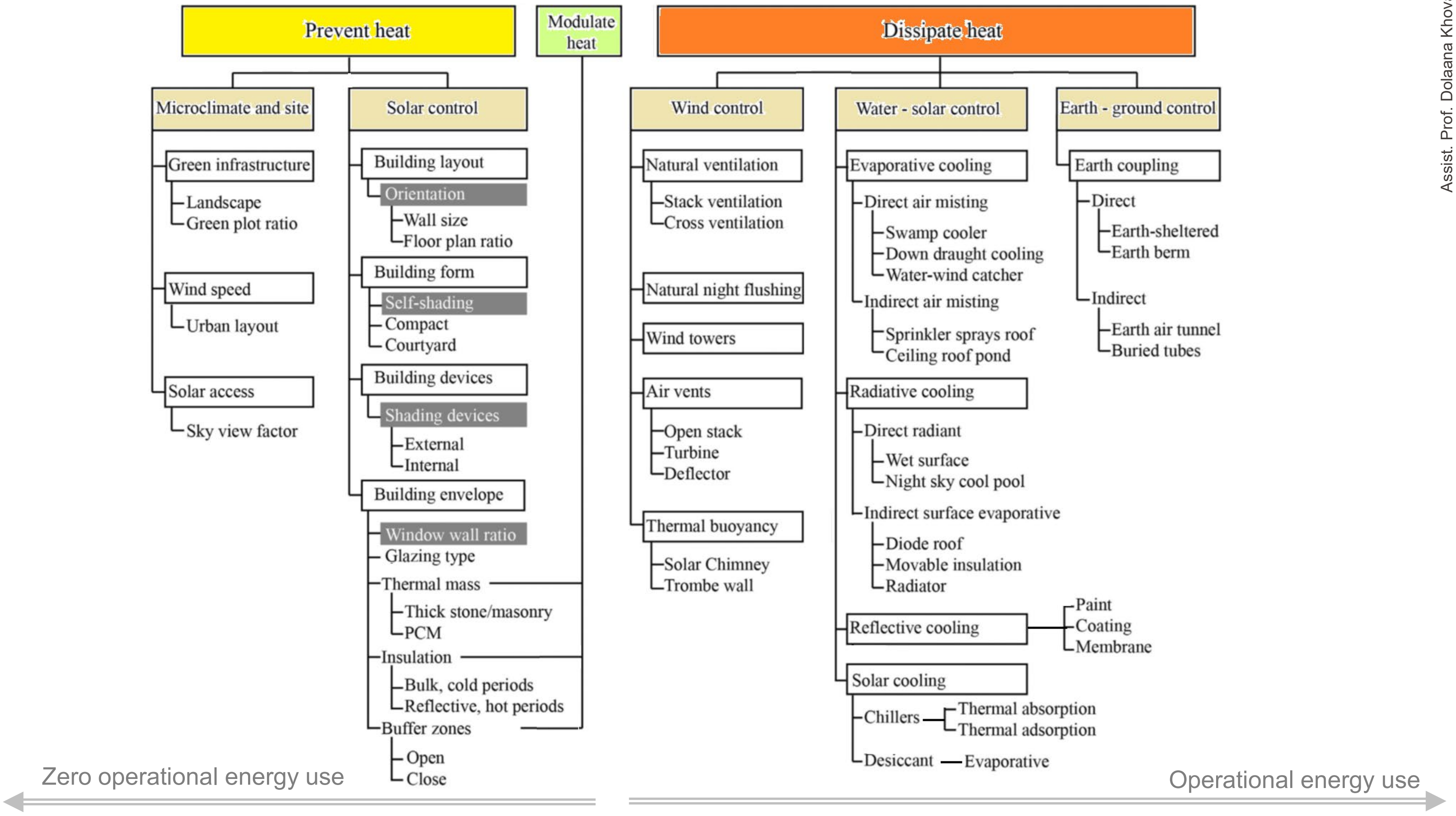
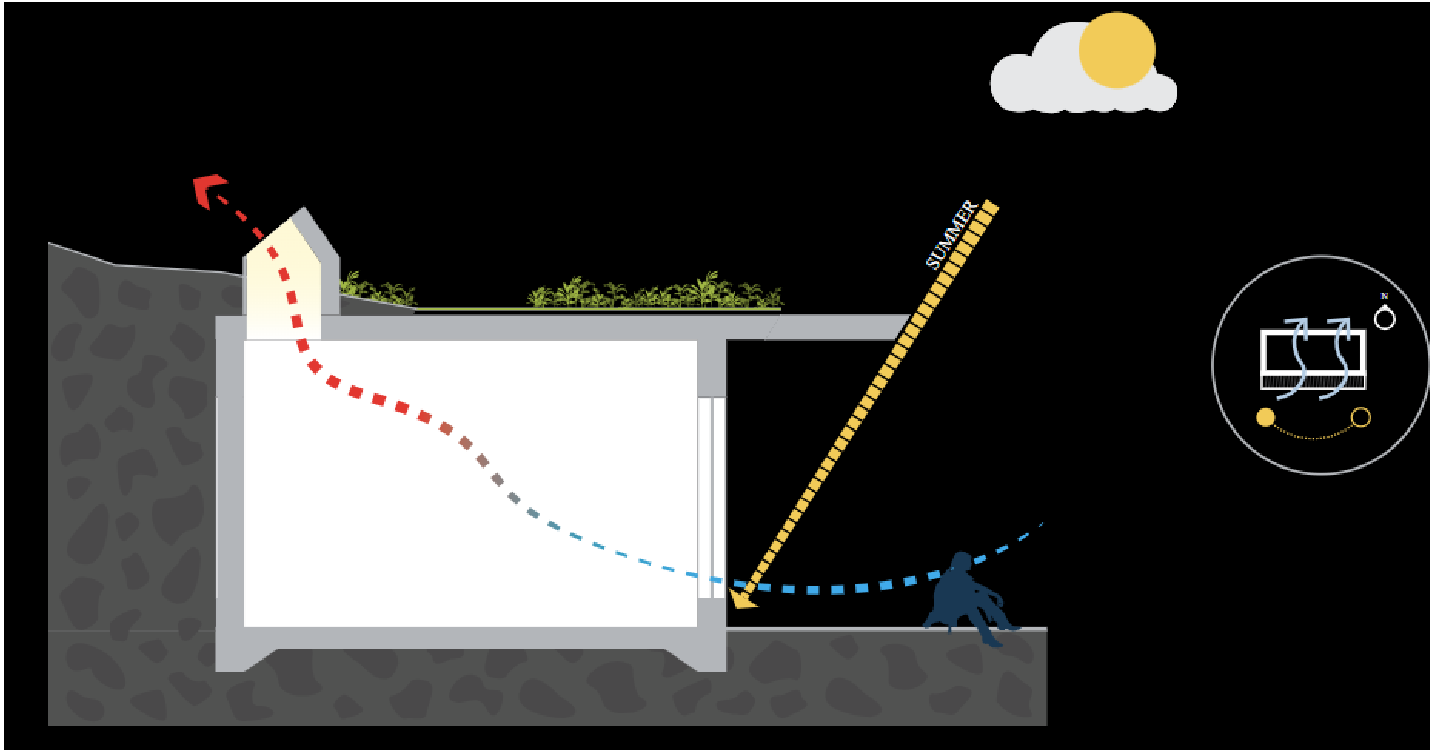


Passive Cooling Strategies: Demonstration

https://climatescout.arcadis.com/



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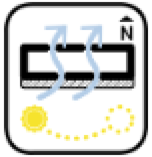
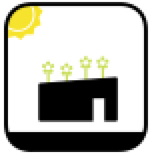
EPFL Passive Cooling Strategies: Demonstration

https://climatescout.arcadis.com/



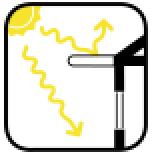
Form for Cooling

Cool Roof



Green Roof

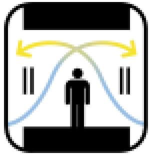
East/West Shading



Solar Shading

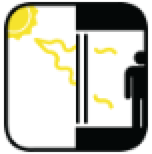
Shading Devices

Stack Ventilation

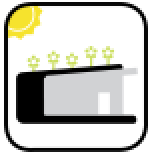


Cross Ventilation

Night Vent Cooling



Building Facades



Earth Sheltering

Evaporative Cooling Towers

What kind of building shape is preferable for warm locations?

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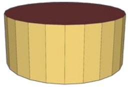
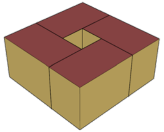
A.



B.



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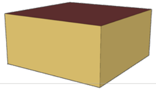

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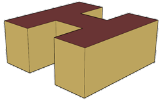

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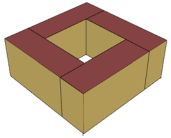

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What are the conditions to keep buildings cool using the thermal mass?

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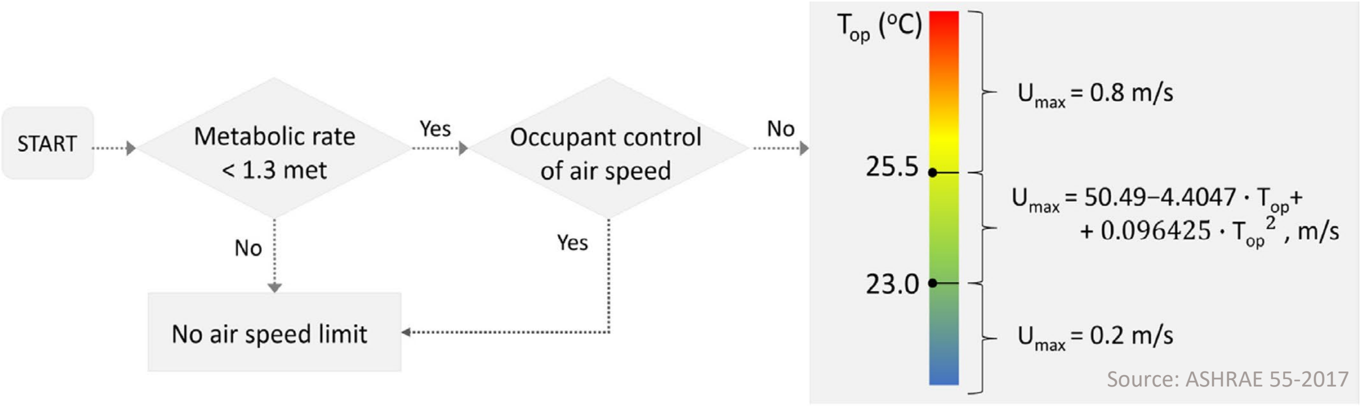
Discuss this question with your neighbors

A. Sufficient diurnal outdoor temperature fluctuations
B. Use concrete in building structure
C. Insulate building envelope
D. Avoid heat gains during the day
E. Enable nighttime flashing
F. All above

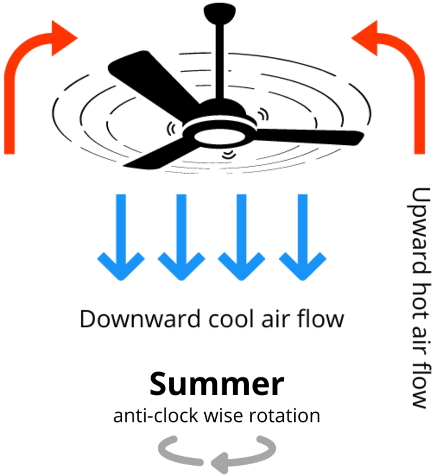
Low Energy Cooling Design

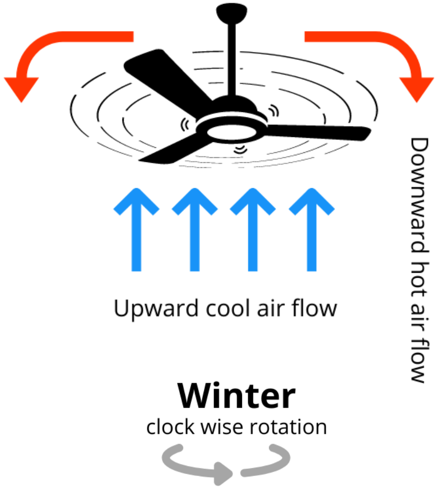
1. Choose **the building envelope configuration** that **reduces** heat gains
2. Reduce solar heat gains:
   - by choosing **clear colors/reflective surfaces** for external opaque surfaces
   - by **shading** the building with vegetation
   - by planning **windows with reasonable sizes** according to their orientations
   - by planning efficient **solar protections for fenestration**
3. Reduce **internal heat gains** from **indoor electric appliances**
4. Precisely define **thermally conditioned zones** and **position** the **thermal boundary** accordingly
5. Ensure *enough indoor elements* with **high thermal inertia** within thermal boundary zone in order **to reduce instantaneous overheating** the space
6. Remove the *excess heat* from the building using *passive means* (*e.g.*, deploy **night-time cooling using natural ventilation** by planning openings)
7. Introduce simple cooling systems (e.g., **fans**, **evaporative cooling**)
8. Consider **active cooling *only to deal with overheated periods*** that cannot be reasonably avoided after applying steps (1)-(7)

Heat Dissipation: Fans



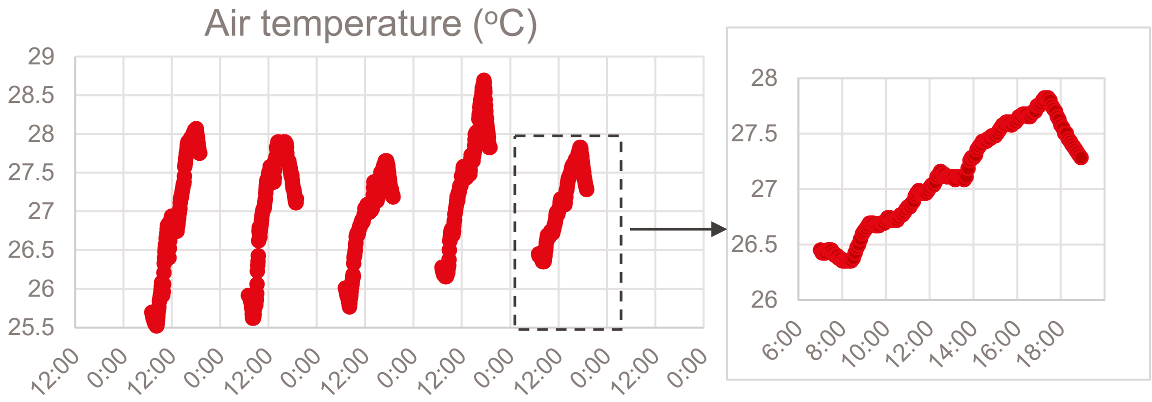
Source: reviewsofairpurifiers.com

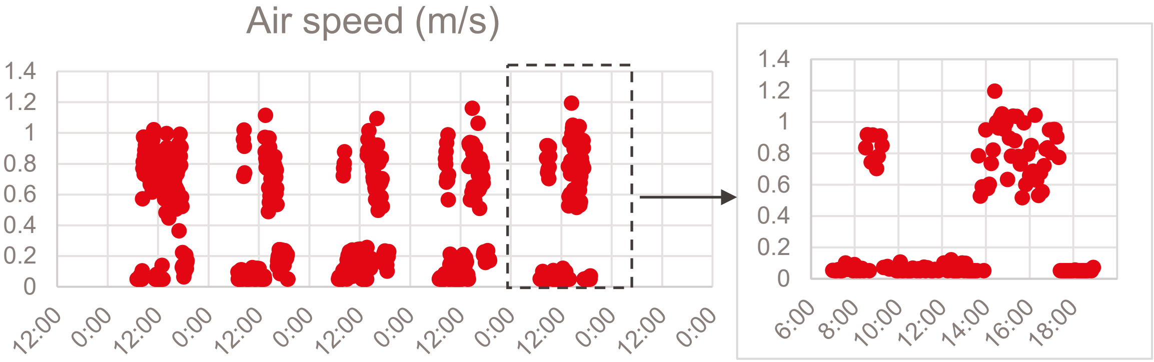




Heat Dissipation: Fans

- Example of **elevated air speed** created **by a person** to improve the comfort
- Office monitoring in Geneva, summer 2020 (**eCOMBINE** project)
- **2 weeks** of measurements
- **1/30** person was using a desk fan
- Maximum air speed was between **0.6-1.2** m/s

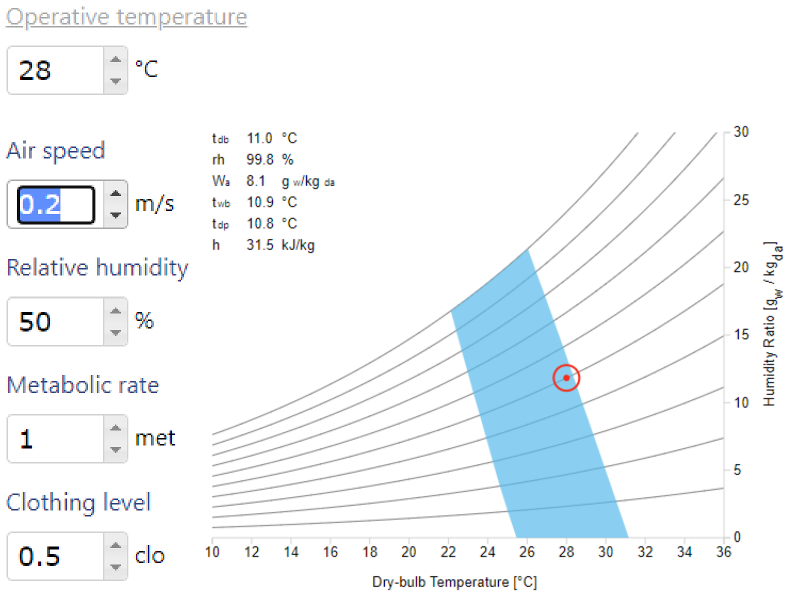


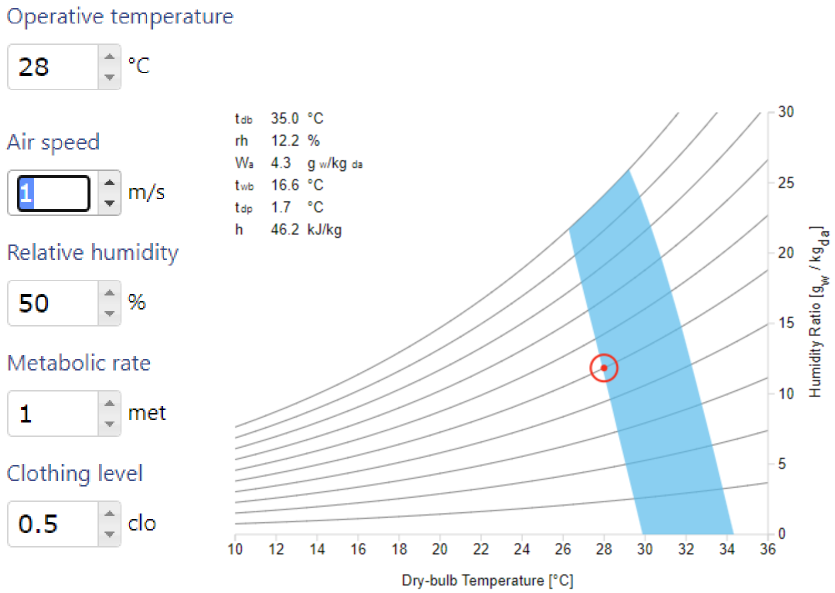


Final report: https://www.aramis.admin.ch/Texte/?ProjectID=45287

Heat Dissipation: Fans

- Fans elevate air flow around the human and increase convective heat removal from the skin
- Increased convection helps also to increase latent heat removal (via evaporation)
- Sensation scale correction up to 1 point (from PMV= +0.43 to PVM= - 0.48)





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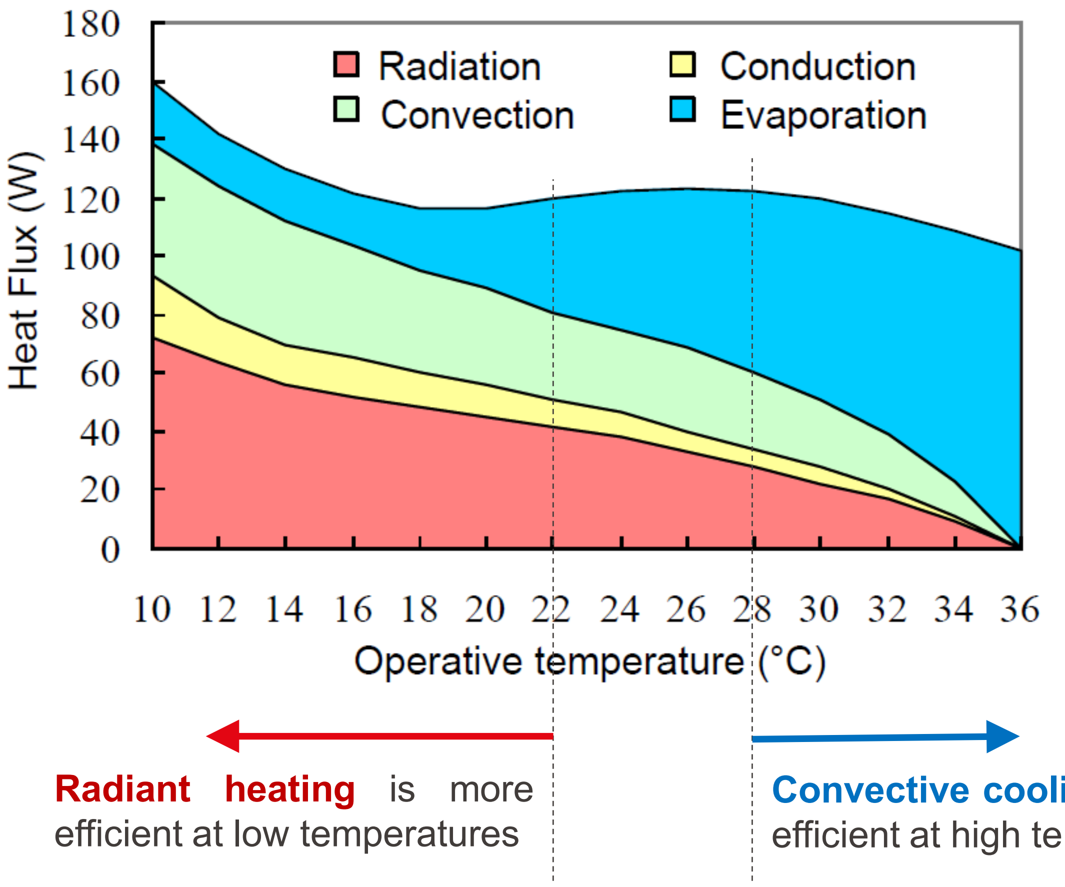
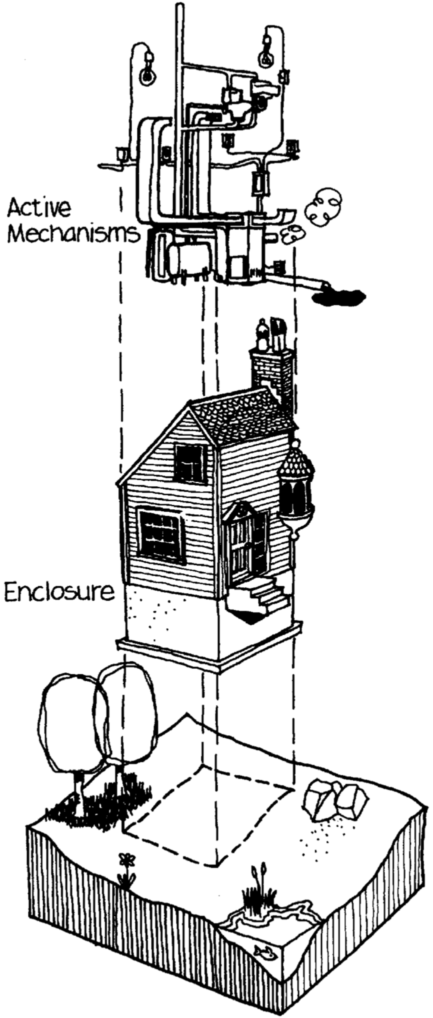
Heat Dissipation from Occupants

From Lect. 03:



Radiant heating is more efficient at low temperatures

Convective cooling is more efficient at high temperatures



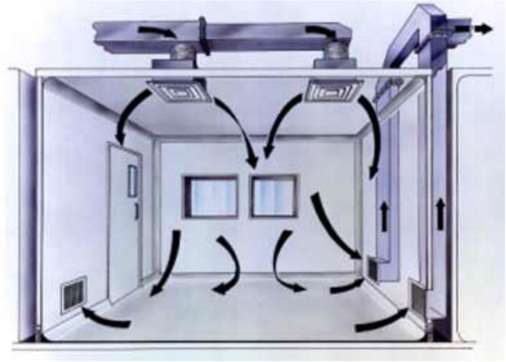
Source: Edward Allen «How Buildings Work» (2005)

CONTENT:

Emission Systems: Overview

From Week 11

All-Air Systems		Radiant systems
centralized air conditioning	**localized** air conditioning	**centralized** water conditioning
heat extraction using: **air**	heat extraction using: **refrigerant**, **water**	heat extraction using: **water**



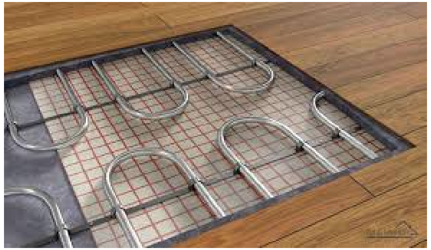
- *Air supply through **grills** (no air deflection)*

- *Air supply through **diffusers** (diffuses air)*

***Fancoils**, **indoor units** (air recirculation)*

***Chilled beams** (**active** and **passive**)*
thermal conditioning +
fresh air supply (active only)

Radiant ceiling



Floor/Wall systems

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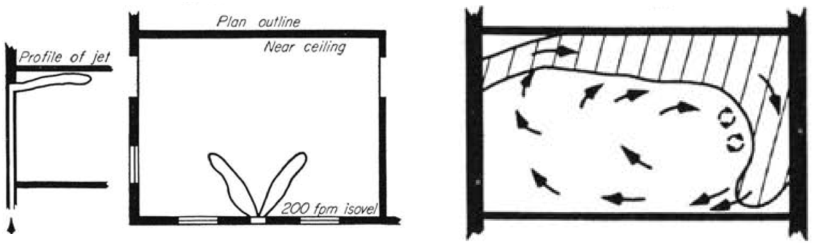
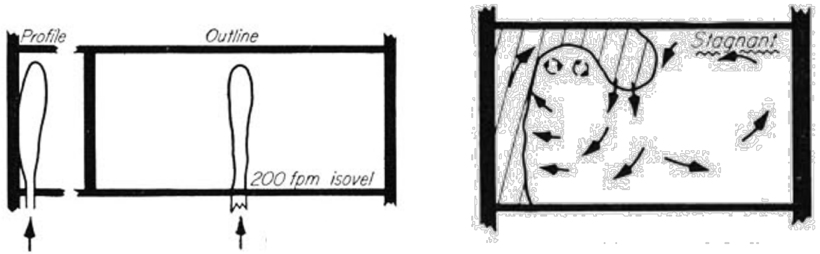
Convective (All-Air) Cooling: Airflow

Distinct groups of air patterns:

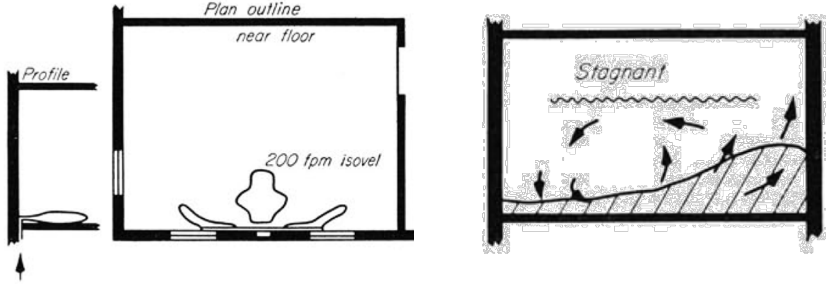
- Air is discharged *at the ceiling level*



- Air is discharged *vertically* from floor grill (non-spreading floor outlet)



- Air spread *horizontally across the floor* (long baseboard units that spread air over a wide floor area)

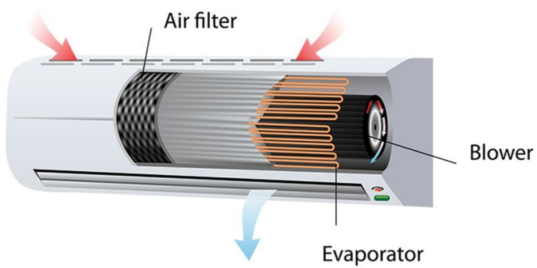


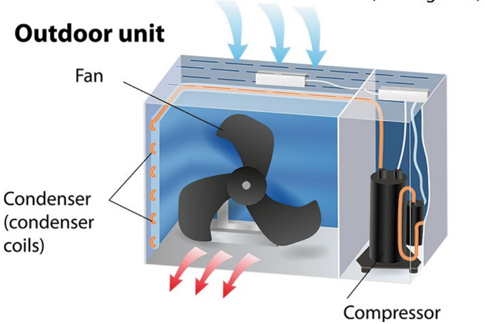
Source: H Straub (1956)

Split System

- **A split system** is *the most common* **cooling equipment** that serves **a single zone** (room)
- Indoor air cooling is based on **the vapor-compression cycle**.

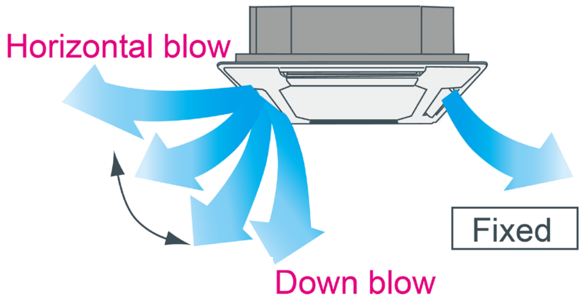
  Each split system has 2 units:
  - **indoor unit** (an evaporator in a casing, with a fan blower)
  - **outdoor unit** (a condenser with a fan, and a compressor in a casing)

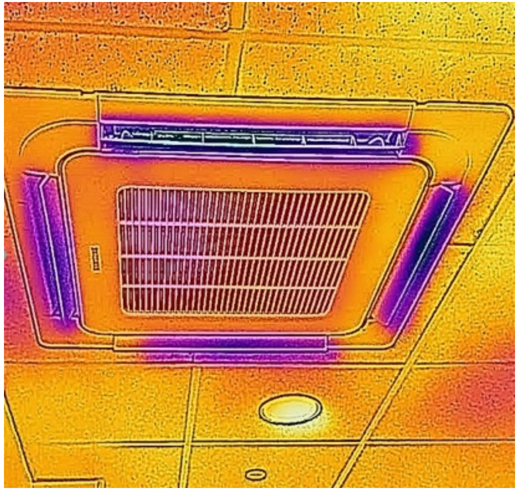




Fancoils

- Indoor terminal units that **remove heat from the space locally** *mainly* due to the **forced convection**
    - *a* room air *is cooled* by passing through *a fin-and-coil heat exchanger* that is filled with *circulating cold refrigerant*, *a fan* is used to force the airflow through the coil
- They **recirculate indoor air** (fresh air is provided by the separate ventilation system)
- A fancoil is **an evaporator** of the **vapor-compression cycle** that is used to "*generate*" cooling
- There can be multiple designs that can fit different space types, cold air is typically directed towards occupied zone:





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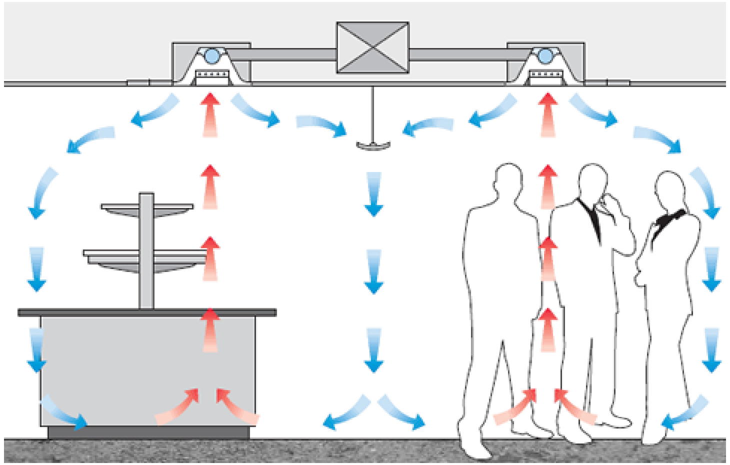
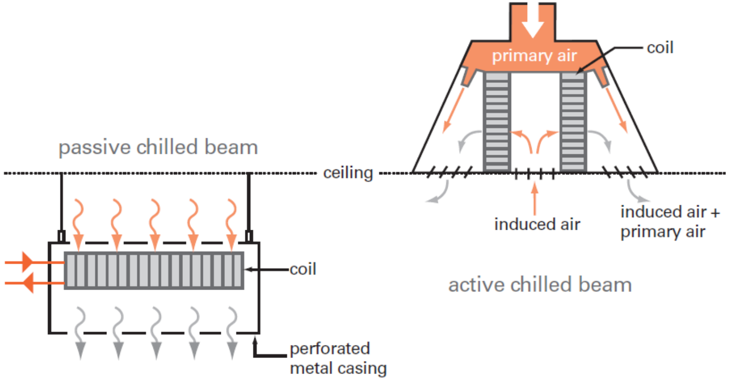
Chilled Beams

- Indoor terminal units that **remove heat from the space** *mainly* due to **convection**
- There are **2 types** of **chilled beams**:
  - **passive** (no fresh air supply, airflow circulation based on the buoyancy effect)
  - **active** (with integral air supply through nozzles)
- Both types have *a fin-and-tube type heat exchanger* which provides *air cooling* by removing heat using circulating cool water in pipes.
- The purpose of the **primary air system** for **active chilled beams** is to:
  1. Deliver *at least* **the required amount of outdoor air** to each space **for ventilation**
  2. Deliver **air** which is *dry enough* to **offset the space latent load** and **maintain the indoor dew point** *low enough* **to avoid condensation** on the chilled beams
  3. Deliver *enough air* to **induce sufficient room airflow** to *offset* the *space sensible cooling load*.



Source: *TRANE, Engineering Newsletter, V38-4*



Hydronic Radiant Systems: Typology

From Week 11

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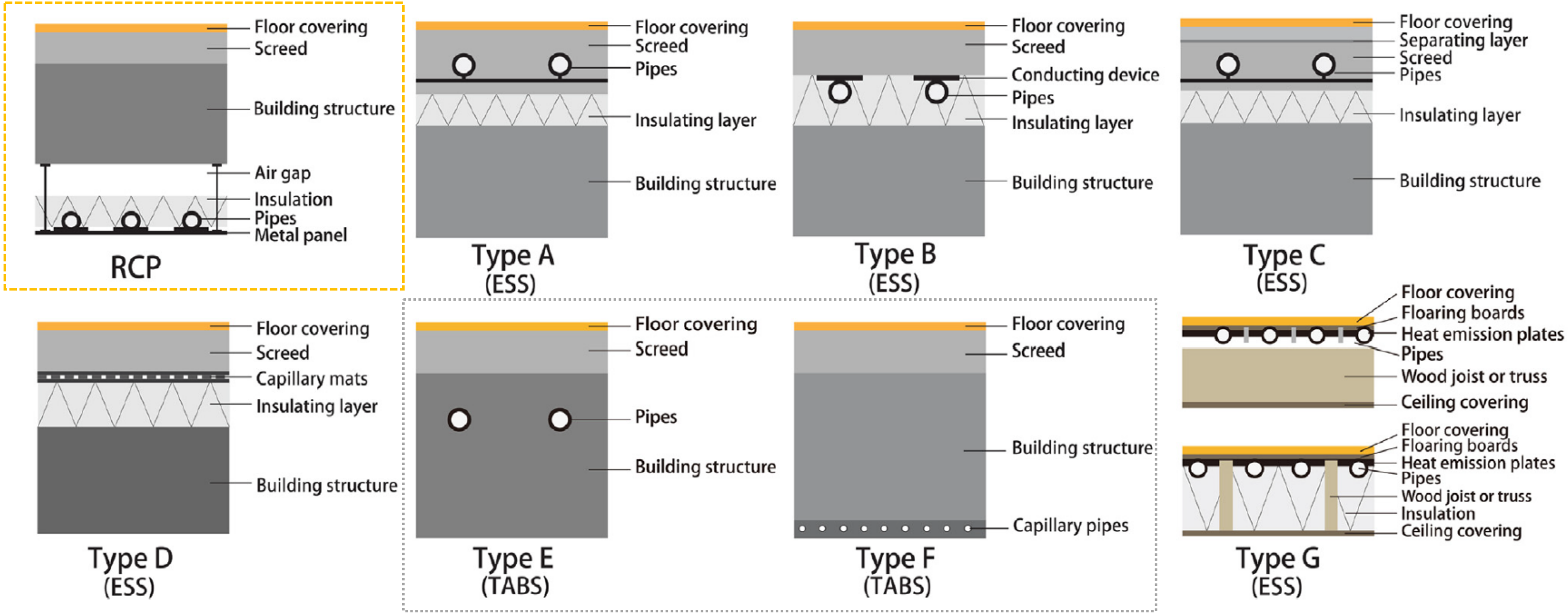
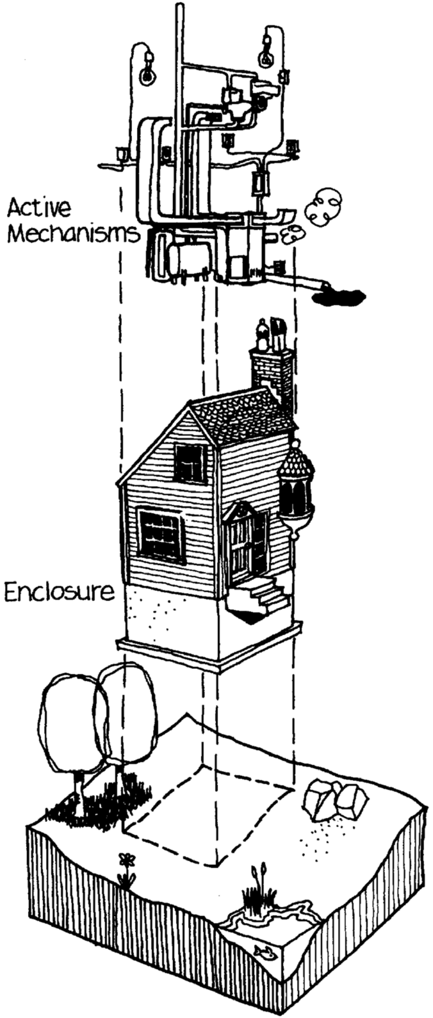
- Three **main categories** of hydronic systems:
  - **radiant ceiling panels** (**RCP**),
  - **embedded surface systems** (**ESS**)
  - **thermally activated building systems** (**TABS**)



Source: Ning et al. (2017) http://dx.doi.org/10.1016/j.enbuild.2016.12.013



Source: Edward Allen «How Buildings Work» (2005)

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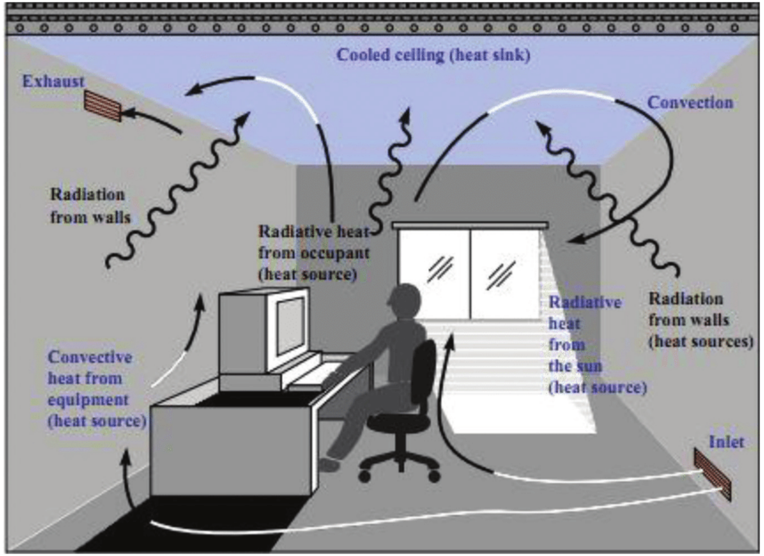
All-Air Cooling vs. Radiant Cooling

- **Cooling** (rate of sensible and latent energy *removal/extraction*) required **to maintain an indoor environment** *at* **a desired temperature** and **humidity**

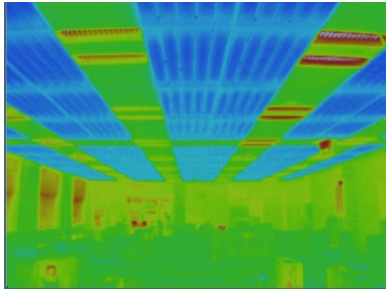
- **Heat extraction rate** – the **rate** at which **heat** is **removed** from a **space** by the **emission system** (terminal device)

  - **For an all-air system**: the *enthalpy difference* between airflow *supplied* to the space and airflow *leaving* the space

  - **For a radiant system:** the *sum of convective and radiant heat transfer rates* at the indoor face of internally cooled surface



Source: Woolley et al. (2018) Energy & Buildings 176, pp 139–150



Source: SANKEN

Source: Izzet Yüksek

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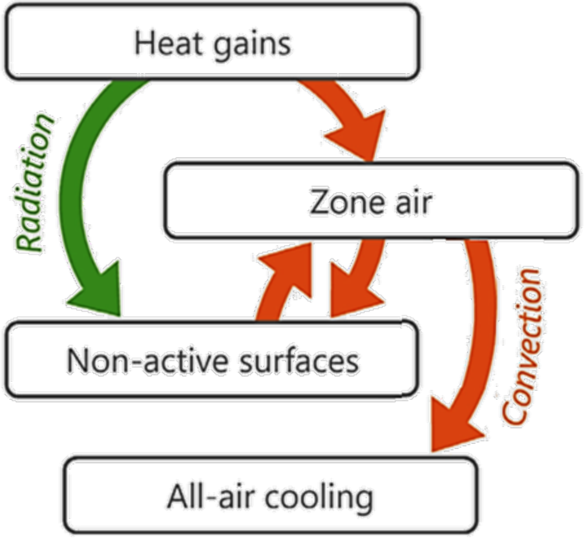
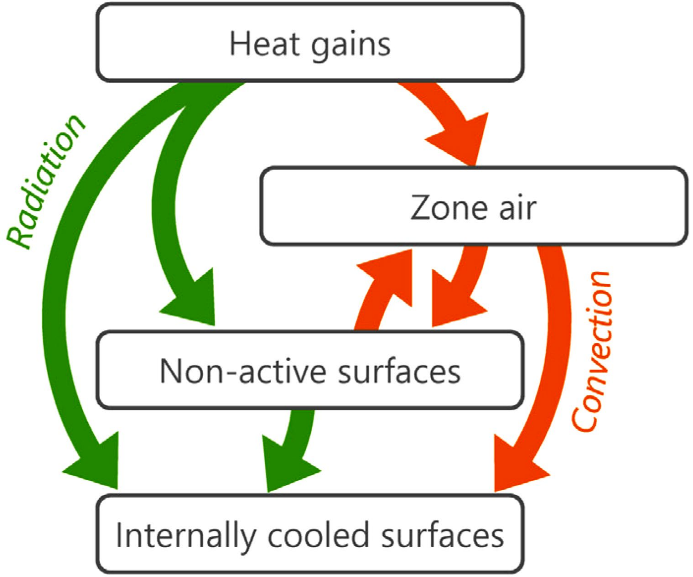
Heat Transfer Pathways for Cooling

- In a space with **all-air cooling**, all radiant heat gains *are absorbed* by *non-active surfaces*.
- In a space with **radiant cooling**, *a portion* of the *radiant heat gains* is absorbed by *non-active surfaces* and *a portion* is absorbed by the *internally cooled surfaces*.



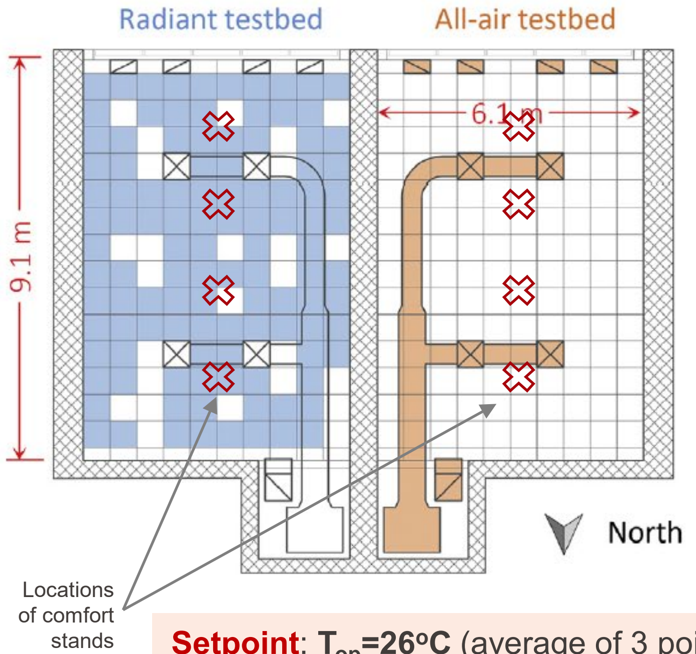
(a) all air cooling



(b) radiant surface cooling

Source: Woolley et al. (2019) Energy & Buildings 200, pp. 68–85

All-Air Cooling vs. Radiant Ceiling Cooling



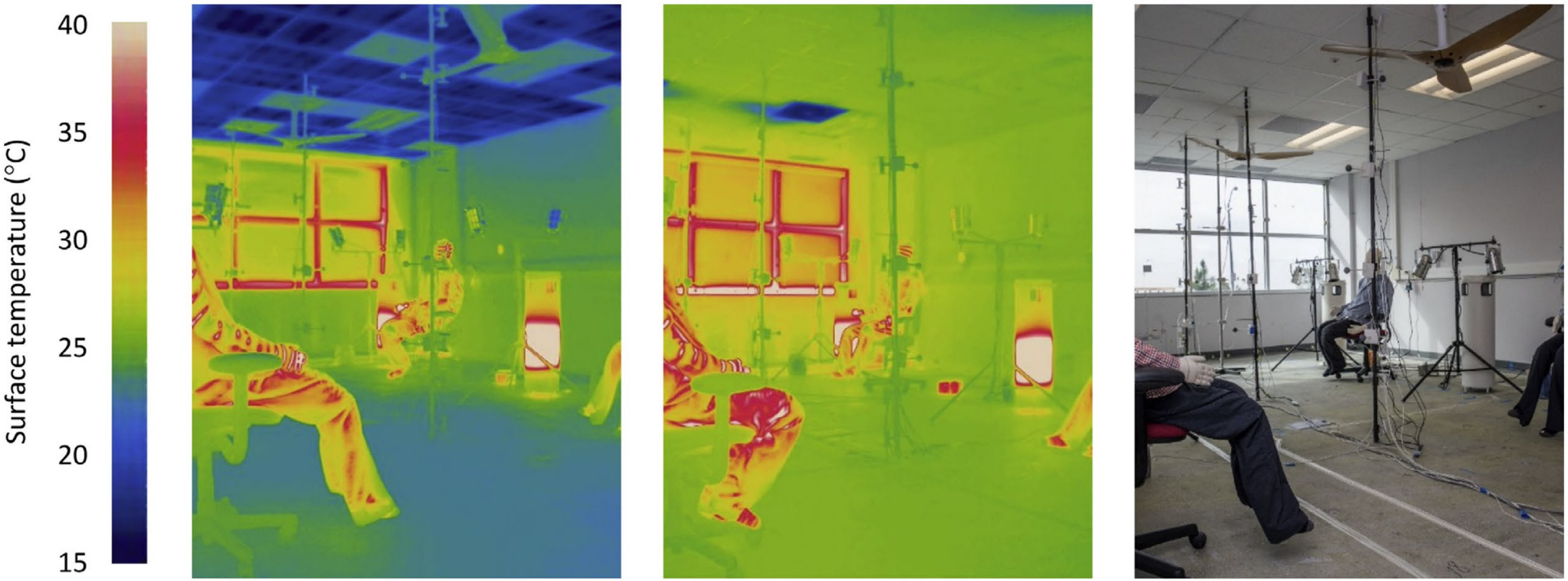
Setpoint: T_{op}=26°C (average of 3 points at 0.6m height: 3.45 m, 5.3 m and 7.16 m from the south wall)

Equal comfort conditions

Radiant		All-air
26 °C	Operative temperature	26 °C
≈ 26.5 °C	Air temperature	≈ 25.5 °C
≈ 25.5 °C	Mean radiant temp.	≈ 26.5 °C

Source: Woolley et al. (2018) Energy & Buildings 176, pp 139–150

All-Air Cooling vs. Radiant Ceiling Cooling



Infrared image of radiant testbed	Infrared image of all-air testbed	Visual image of testbeds

Equal comfort conditions

Radiant		All-air
26 °C	Operative temperature	26 °C
≈ 26.5 °C	Air temperature	≈ 25.5 °C
≈ 25.5 °C	Mean radiant temp.	≈ 26.5 °C

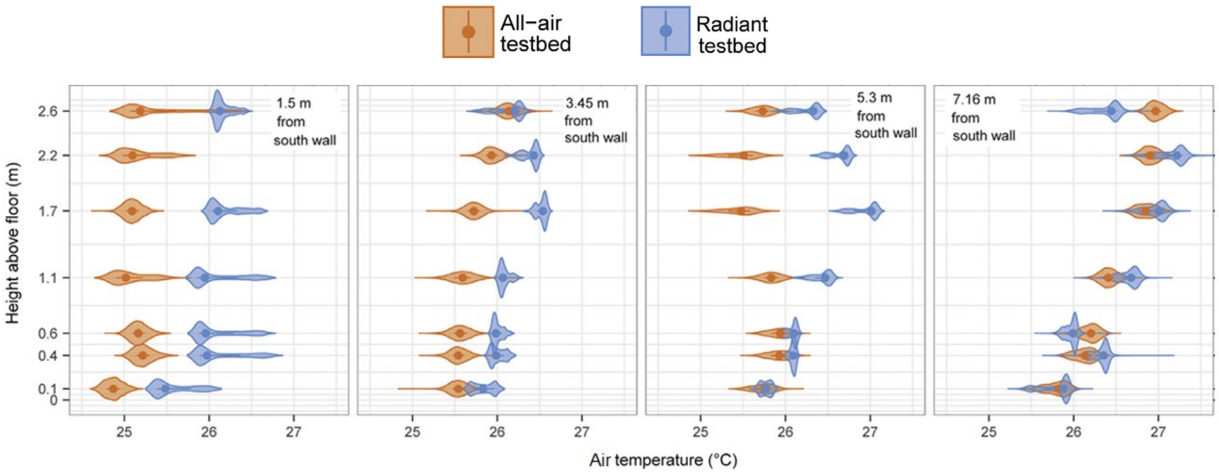
Environmental conditions

Outdoor air temp. ≈ 30 °C
Exterior surface temp. ≈ 60 °C
11:00-13:00@ 7 Sept. 2016

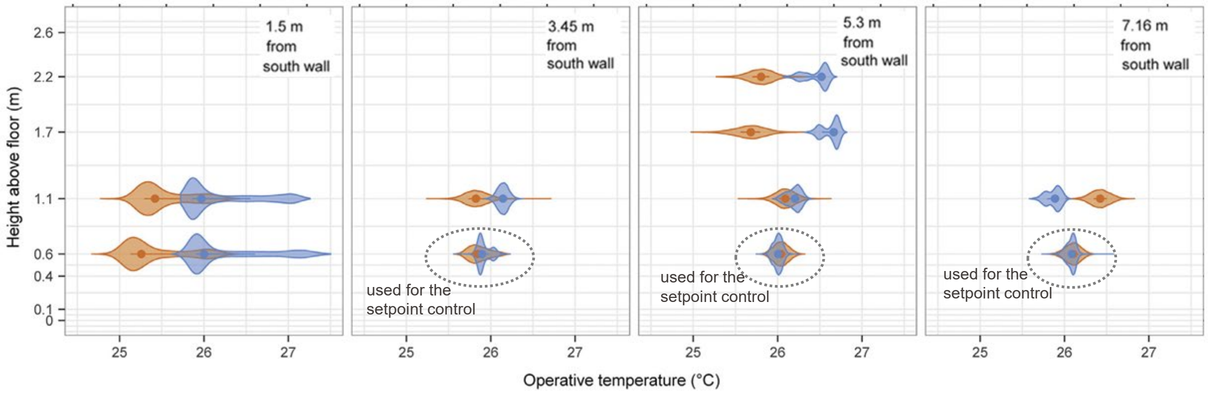
Source: Woolley et al. (2018) Energy & Buildings 176, pp 139–150

All-Air Cooling vs. Radiant Ceiling Cooling

- **Air Temperature:**
  air temperature **is higher in a radiant cooled case** than in *all-air cooled case* at *equivalent comfort conditions*→ radiant cooling could **reduce heat gain from ventilation** if supplied air is warmer.



- **Operative Temperature:**
  variation throughout a room (in non-controlled locations) is a consequence of **non-uniform distribution** of **heat gains** and **distribution of cooling**

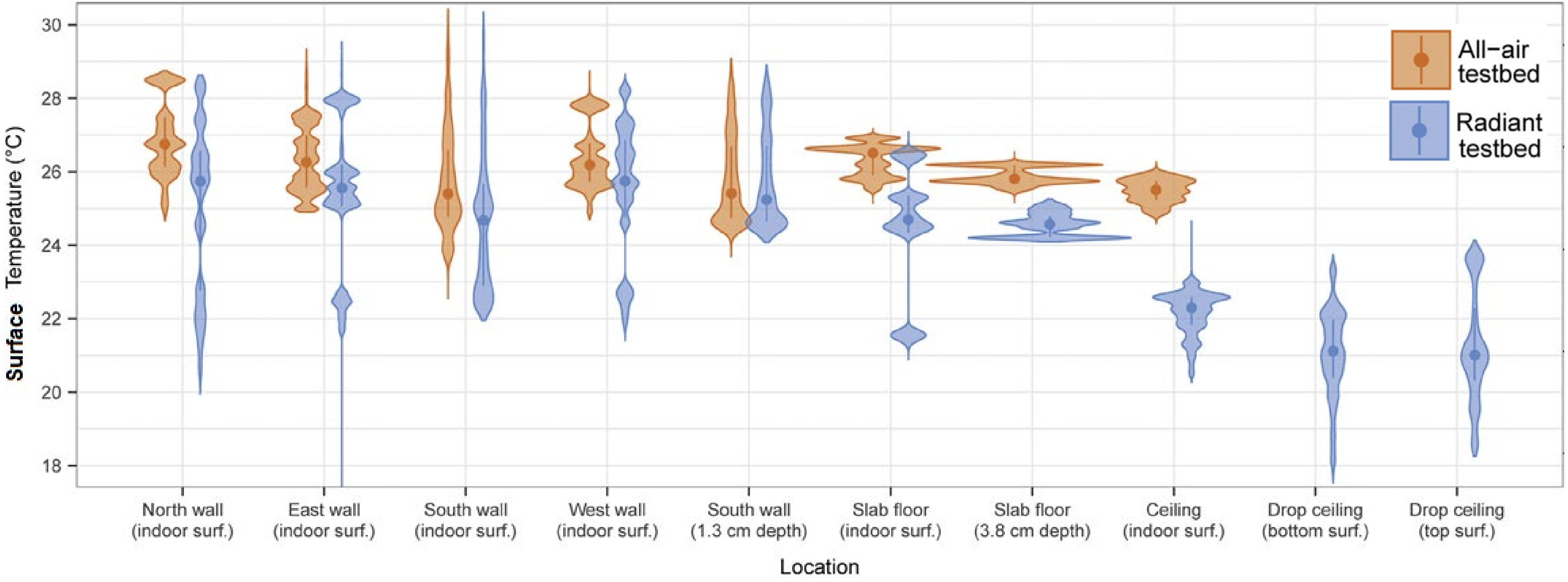


Source: *Woolley et al. (2018) Energy & Buildings 176, pp 139–150*

* Measurements from constant internal heat gains experiments

All-Air Cooling vs. Radiant Ceiling Cooling

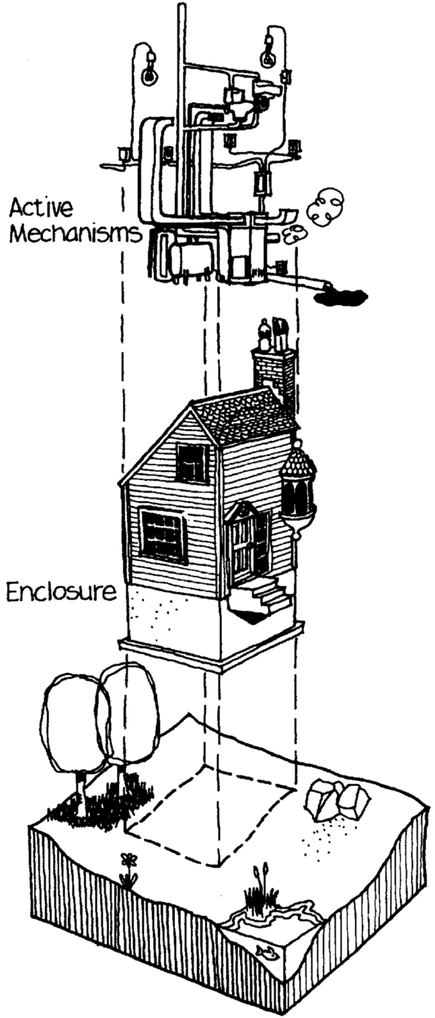
- **Surface Temperature:** All **interior surfaces** in a space **with radiant cooling** are **cooler** than in *a similar space* with **all-air cooling** → **net heat gain** by **heat transfer** *through the envelope* can **be higher**



Source: Woolley et al. (2018) Energy & Buildings 176, pp 139–150

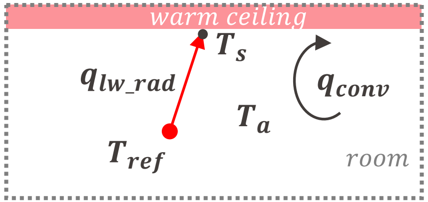
* Measurements from constant internal heat gains experiments

CONTENT:



Source: Edward Allen «How Buildings Work» (2005)

Embedded Radiant Systems: Rated Heat Flux



- Surface convective heat transfer: $q''_{conv} = h_c \times (T_a - T_s)$
- Longwave radiation heat transfer: $q''_{lw\_surf} = h_{rad} \cdot (T_s - T_{ref})$
- Total surface heat flux*: (heat flow density, W/m²) $q'' = h_t \cdot |T_s - T_{ref}|$

$T_s = T_{m,s}$ *mean surface temperature*
$T_{ref} = T_{op}$ *operative temperature (per ISO 18555)*

- **Heat transfer coefficient** between radiant surface and room condition:

Combined convection and (longwave) radiation heat transfer coefficient h_t:

Heating:		Cooling	
Floor heating (FH)	**11** W/m²K	Floor cooling (FC)	**7** W/m²K
Wall heating (WH)	**8** W/m²K	Wall cooling (WC)	**8** W/m²K
Ceiling heating (CH)	**6** W/m²K	Ceiling cooling (CC)	**11** W/m²K

Radiant (longwave) heat transfer coefficient h_{rad} = **5.5** W/m²K
(less than **4%** error for surface temperatures in the range of **15-30°C**)

- **Heat flow density (W/m²):** at steady-state
  - ***floor heating*** / ***ceiling cooling:*** $q = 11 \cdot |T_{m,s} - T_{op}|$
  - ***wall heating*** / ***wall cooling:*** $q = 8 \cdot |T_{m,s} - T_{op}|$
  - ***ceiling heating:*** $q = 6 \cdot |T_{m,s} - T_{op}|$
  - ***floor cooling:*** $q = 7 \cdot |T_{m,s} - T_{op}|$

Source: ISO 11855-2:2012

* Shortwave radiation heat transfer **is not considered** in the *standard approach* of defining total heat flow density which might become problematic **for floor cooling** with direct sunlight

What is the comfort-related limiting heat flux for CEILING cooling in the case of indoor operative temperature 26ºC if the surface temperature limit is 17ºC?

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A. 100 W/m^2
B. 42 W/m^2
C. 72 W/m^2
D. None above

What is the comfort-related limiting heat flux for FLOOR cooling in the case of indoor operative temperature 26ºC if the surface temperature limit is 20ºC?

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A. 100 W/m^2

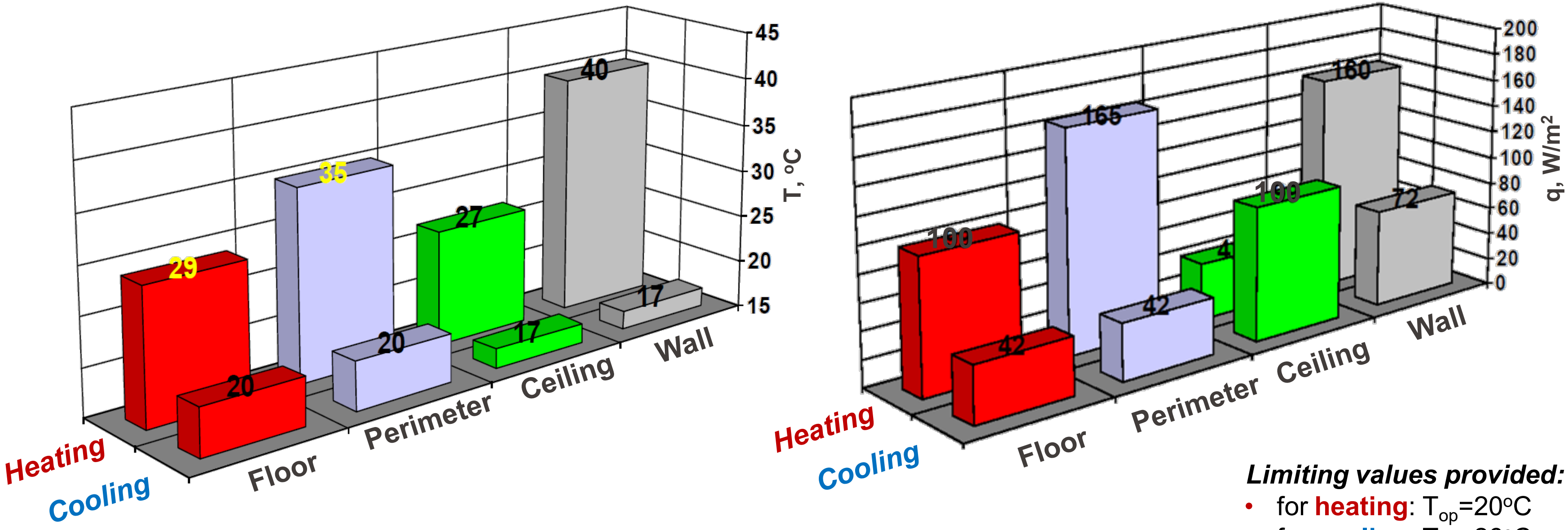
B. 42 W/m^2

C. 72 W/m^2

D. None above

Radiant Systems: Maximum Heat Output

- **Maximum** heating and cooling capacity depends *on the position* of the radiant surface
- The heating/cooling capacity *is limited* by **relatively small convective heat transfer coefficient** between *the surface* and *air*, risk of condensation and concerns about surface temperature, radiant asymmetry, vertical air stratification and draft from comfort perspective

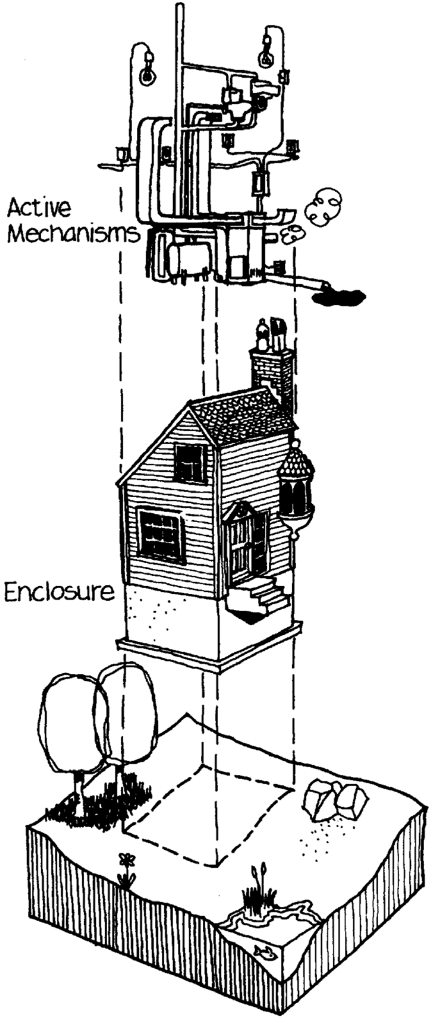


Limiting values provided:

- for **heating**: T_{op}=20°C
- for **cooling**: T_{op}=26°C

(for V_{air} < 0.2 m/s)

Source: Olesen (2018), Radiant heating/cooling dimensioning

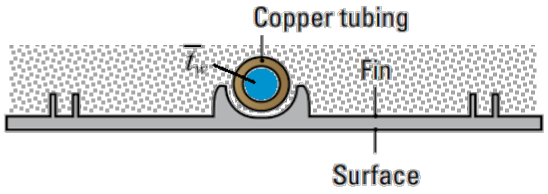


Source: Edward Allen «How Buildings Work» (2005)

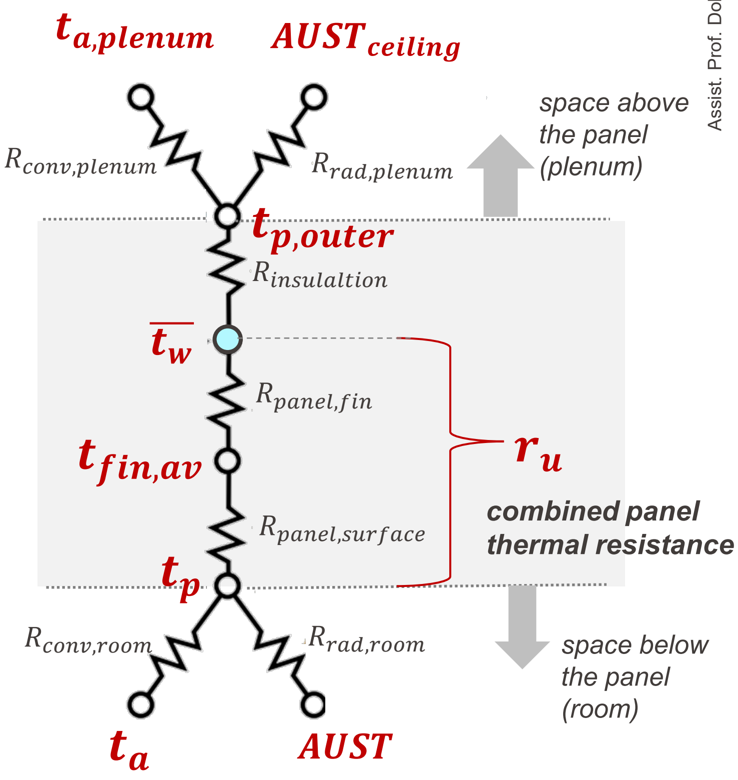
CONTENT:

Radiant Systems: Ceiling Panels

- A radiant ceiling is **a large heat exchanger suspended** from **a room's ceiling**



- **Thermal resistance** in the panel **to heat transfer from** or **to its surface** *reduces* the *performance of the system by affecting water temperature* ($\overline{t_w}$)
- **Average water temperature:** $\overline{t_w} = (T_{wi} + T_{wo})/2$
- **Combined thermal resistance of the panel** (r_u) considers *architecture of the panel* (type of the bond between the piping and the panel material, spacing, piping, covering material presence, etc.)
  - When the *back side of the panels is insulated* using an insulation material, the **heat exchange toward the plenum** *could be ignored*



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Radiant Systems: Ceiling Panels

Thermal resistance of panels $(m^2 \cdot K)/W$:

$$r_u = r_t \cdot M + r_s \cdot M + r_p + r_c$$

- r_u - **combined panel thermal resistance** for a given spacing ***M*** of adjacent tubes
- r_t - thermal resistance **of tube wall** per unit tube spacing:

Circular pipes:

$$r_t = \frac{\ln(D_o/D_i)}{2\pi k_t}$$

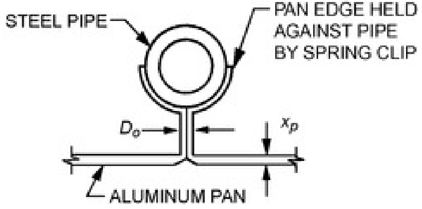
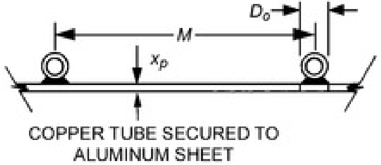
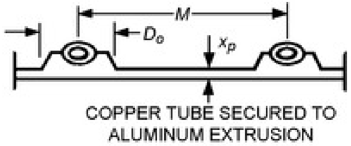
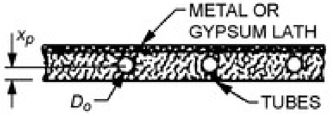
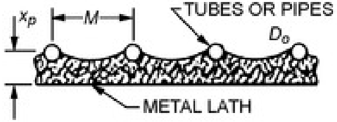
Elliptical pipes:

$$r_t = ln\frac{(a_o + b_o)/(a_i + b_i)}{2\pi k_t}$$

- r_s - thermal resistance **between tube** and **panel body** per unit spacing between adjacent tubes (see the tabulated values)
- r_p - thermal resistance **of a panel body** (see the table)
- r_c - thermal resistance of the **active panel surface covering** (i.e., pads, carpets, etc.), for thickness of x_c :

$$r_c = x_c/k_c$$

- k_t, k_p, k_c - thermal conductivity of **tubing**, **panel**, and **covering** materials, $W/(m \cdot K)$

	Thermal Resistance	
Type of Panel	r_p	r_s
	$\frac{x_p}{k_p}$	0.32
	$\frac{x_p}{k_p}$	0.38
	$\frac{x_p}{k_p}$	0.1
	$\frac{x_p - D_o/2}{k_p}$	≈ 0
	$\frac{x_p - D_o/2}{k_p}$	≤ 0.12

Source: ASHRAE Handbook 2020, HVAC Systems and Equipment, Chapter 6

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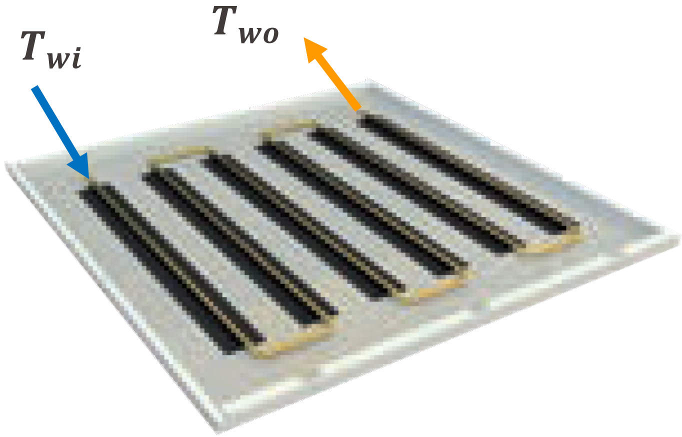
Surface Cooling: Condensation Issues

- **To prevent condensation** on the room side of cooling panels, **the panel water supply temperature** (T_{wi}) should be maintained at least **1 K** above **the room design dew-point temperature** (T_{dp}):

$$(T_{wi} - T_{dp}) > 1K$$

- *This minimum* difference is recommended to *allow for the normal drift of temperature controls* for the water and air systems, and also to provide a factor of safety for temporary increase in space humidity.

- **Precooling** and **dehumidification** of **outdoor fresh air** before it gets mixed up with the return air from the air-conditioned space, **is recommended** *to prevent the surface condensation* at *panel surface*



Source: ASHRAE Handbook 2020

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EPFL

What is the dew point temperature when dry-bulb temperature is 26°C and relative humidity is 50%?

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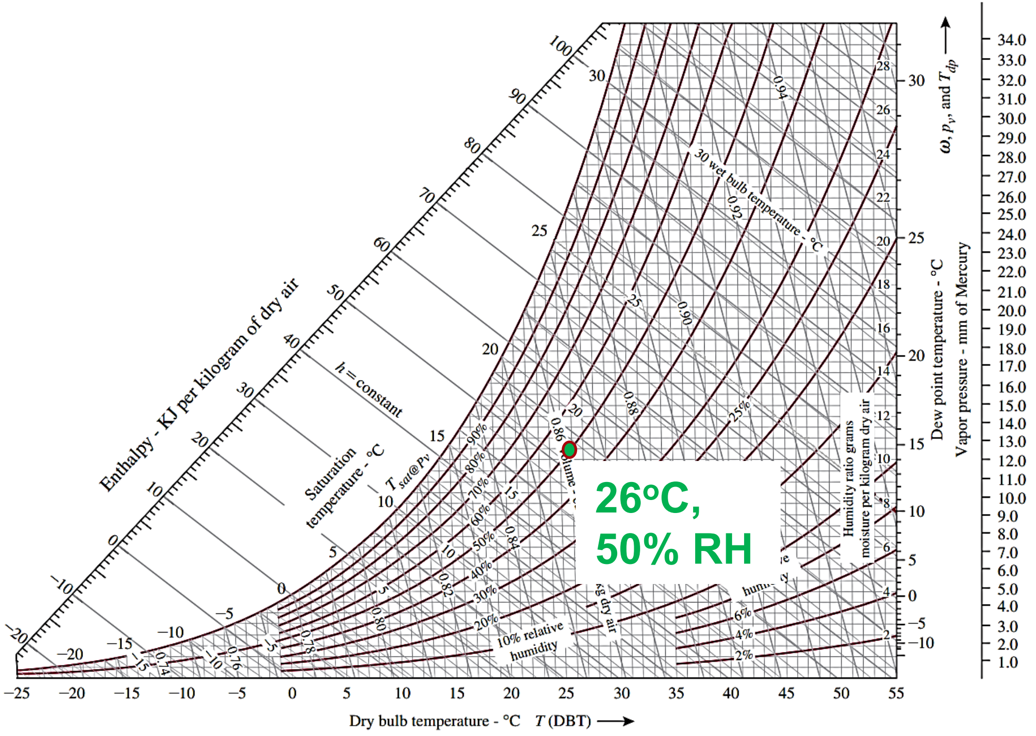
A. 13.8
B. 14.8
C. 15.0
D. 26.0



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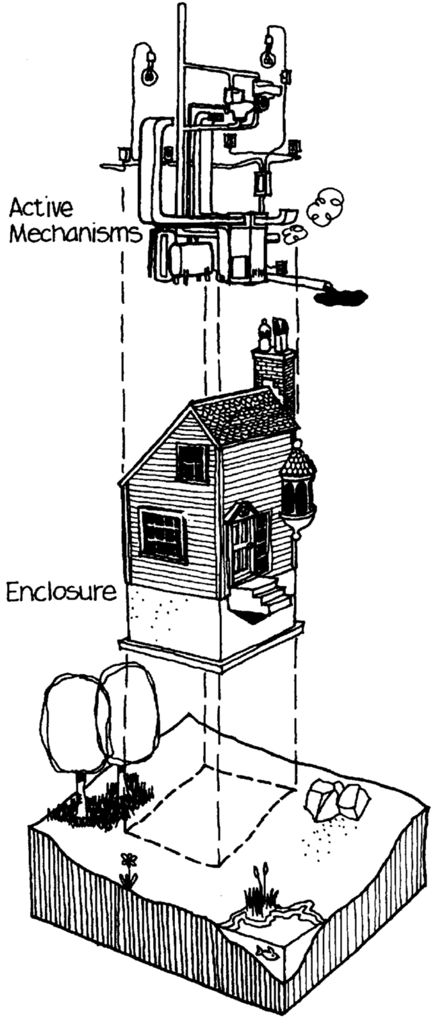


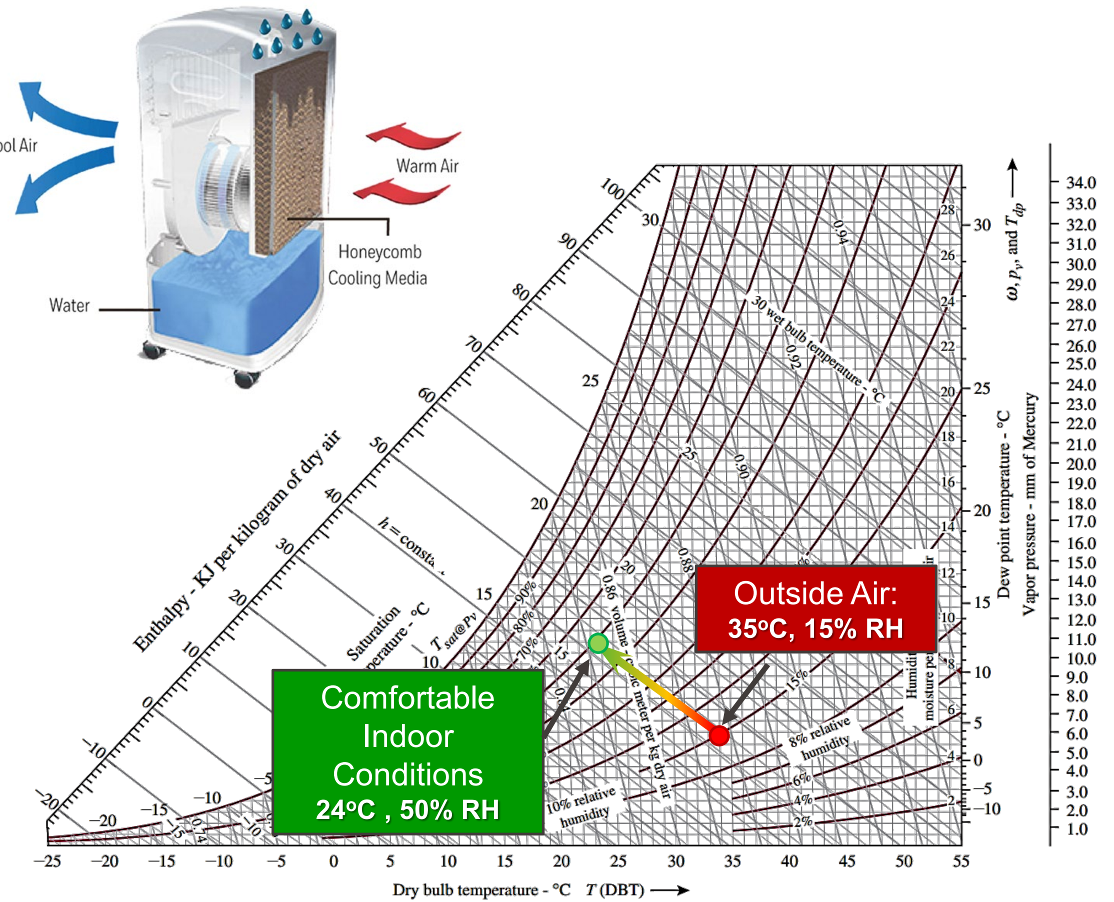
Source: Edward Allen «How Buildings Work» (2005)

CONTENT:

- Introduction
- Passive Cooling Strategies
- Overview of Active Cooling Systems
  - All-air, refrigerant-based, hydronic systems
  - Radiant Cooling Systems:
    - Heat transfer overview
    - Limiting heat flux
    - Radiant ceiling panels
  - **Evaporative cooling**
  - **Dehumidification**
- Summary

Evaporative Cooling

- *Simultaneous* **heat** and **mass transfer** process, or **adiabatic cooling**, and follows **a constant enthalpy line** on the psychrometric chart.
- The *cooling potential for evaporative cooling* is dependent on **the wet-bulb depression** (difference between the **dry-bulb** temperature and the **wet-bulb** temperature)
- Application is limited to **dry** locations



How much can air temperature drop if evaporative cooling is used for the following conditions:
- Ambient temperature: 28ºC, 40% RH
- Maximum desired RH is 60%

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A. 1ºC

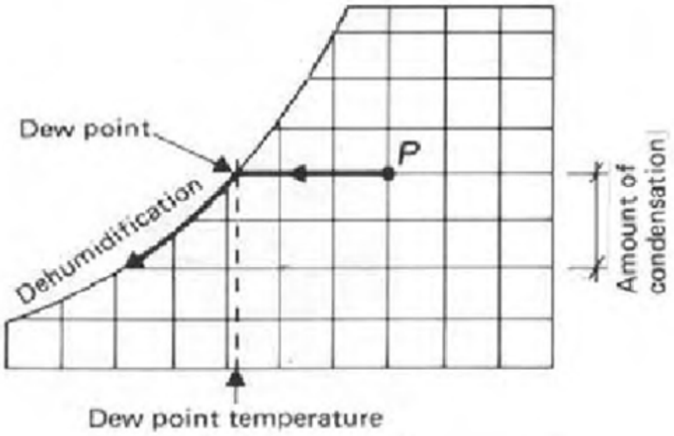
B. 2ºC

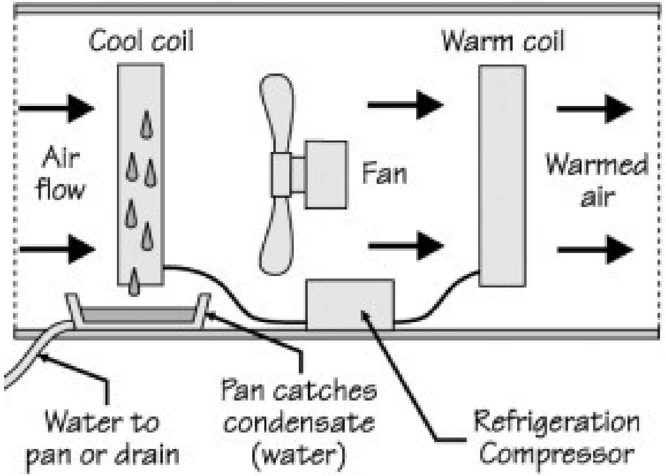
C. 3ºC

D. 4ºC

Dehumidification

- **Dehumidification** – extraction of the water vapor that is contained in air
- *The most common method of dehumidification*: **sub-cooling of air** in **cooling coils** to **condense out moisture** using **chilled water** or **refrigerant**
- **Alternative strategies that** could be more energy efficient for certain climate zones and application types:
  - desiccant dehumidification (solid, liquid)
  - liquid desiccant dehumidification
  - dual wheel, wrapped around coil, *etc.*
- The *pre-cooling* and *dehumidification* of outdoor fresh air can be incorporated into general **air handling units** (AHU).





Dehumidification

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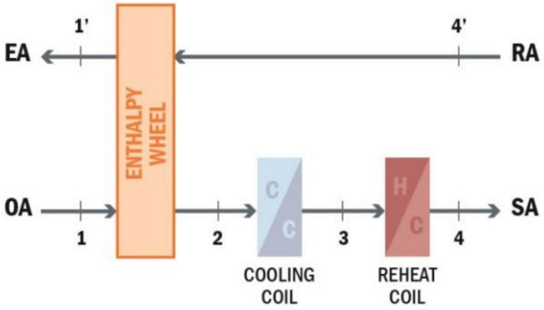
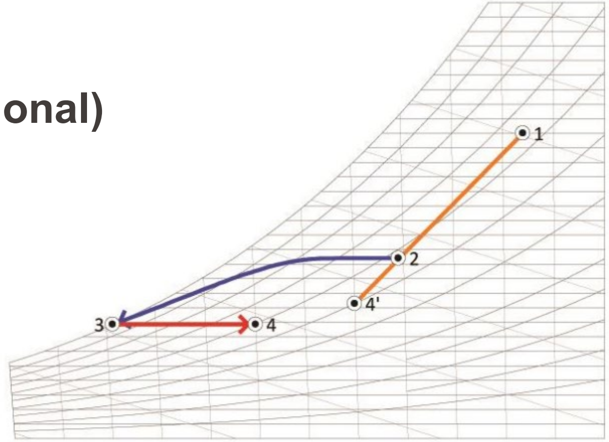
- **Chilled water cooling/ dehumidification** (conventional)

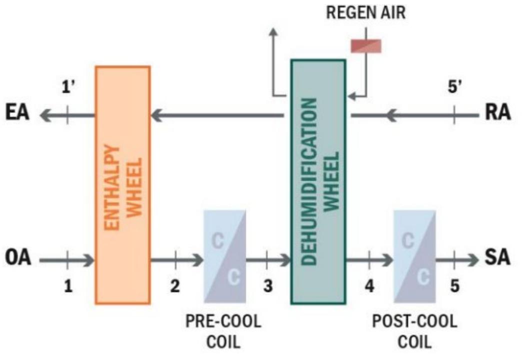
1-2: heat recovery (energy exchange between the used air and entering fresh air)
2-3: air passes over the cooling coil to cool down to the required air humidity ratio
3-4: reheating to the required supply air temperature

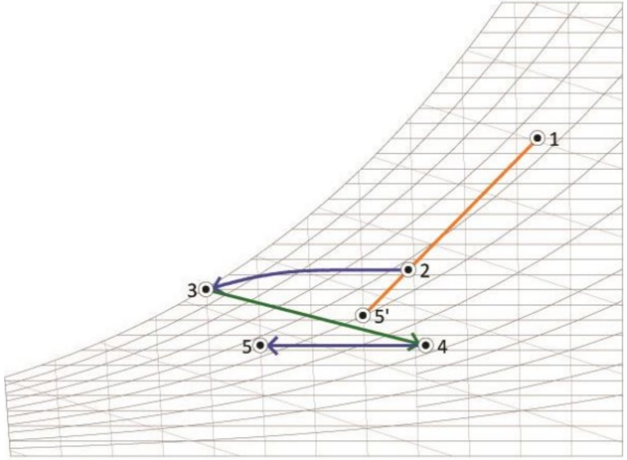




- **Solid desiccant dehumidification**

1-2: heat recovery
2-3: air temperature reduction
3-4: isenthalpic dehumidification, the moisture content of the air reduces while air temperature increases
4-5: warm air passes over a post-cooling coil to cool it down to the required supply air temperature



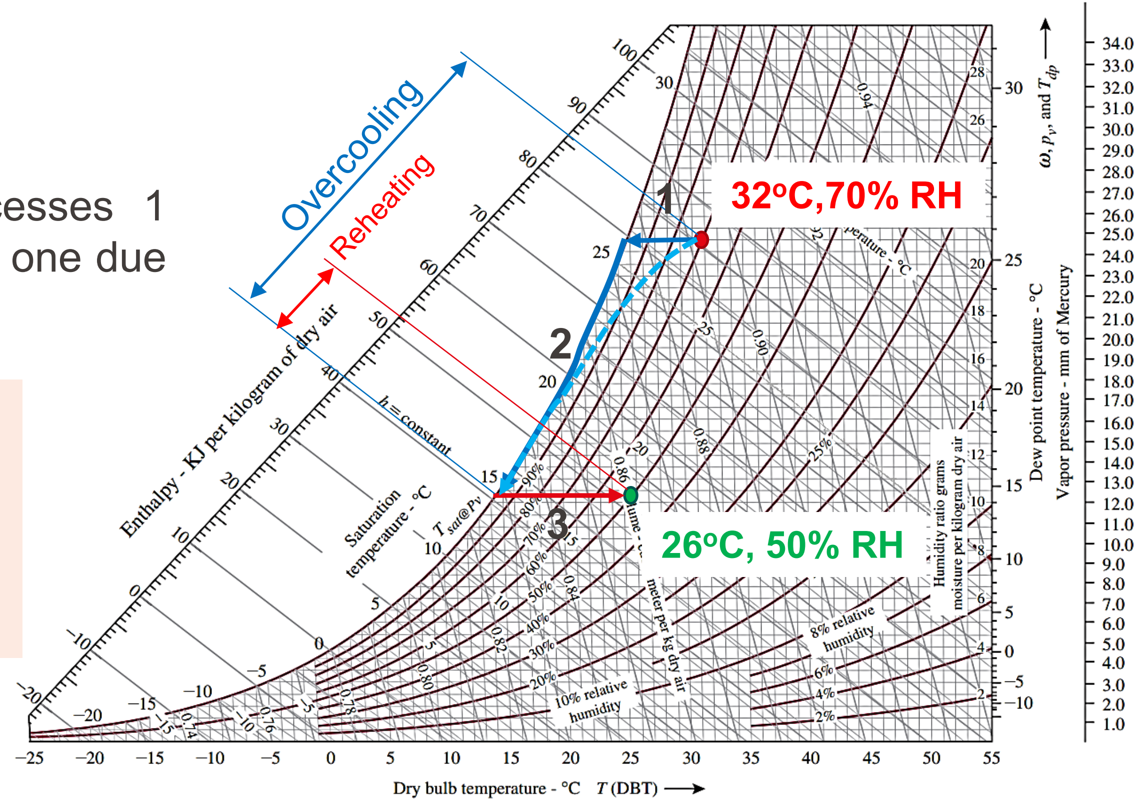


Source: *Pillai et al. (2018) BPAC and SimBuild 2018*

Dehumidification

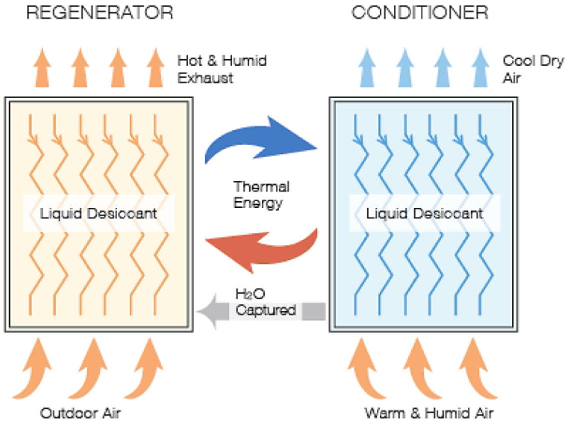
- Conventional dehumidification follows 3 processes:
  1. **Sensible cooling**
  2. **Latent cooling**
  3. **Sensible heating**
- In actual process, processes 1 and 2 deviate from ideal one due to the flow cooling.

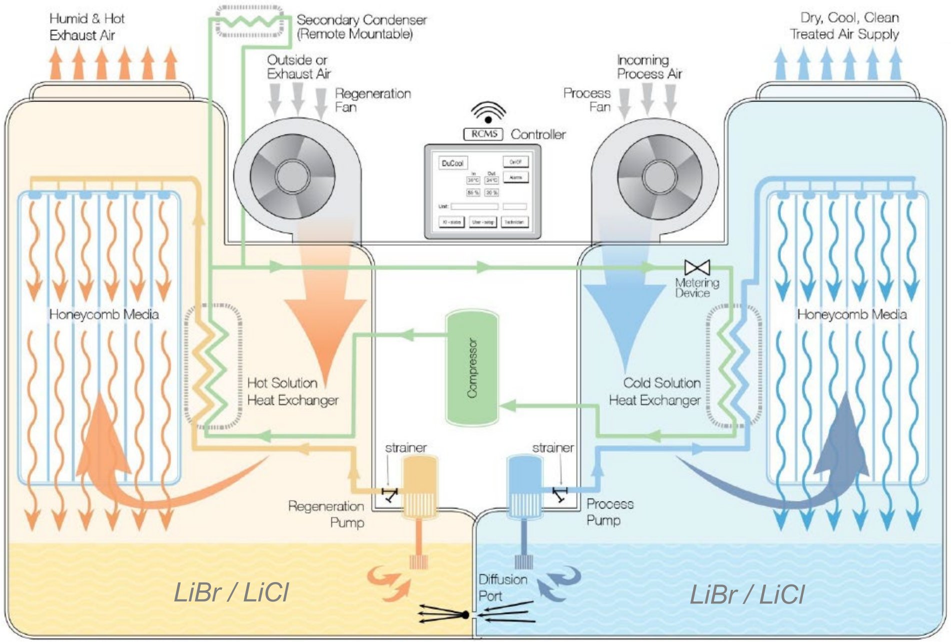
- What is the *alternative more efficient process path* for the same given indoor and outdoor conditions?



Dehumidification

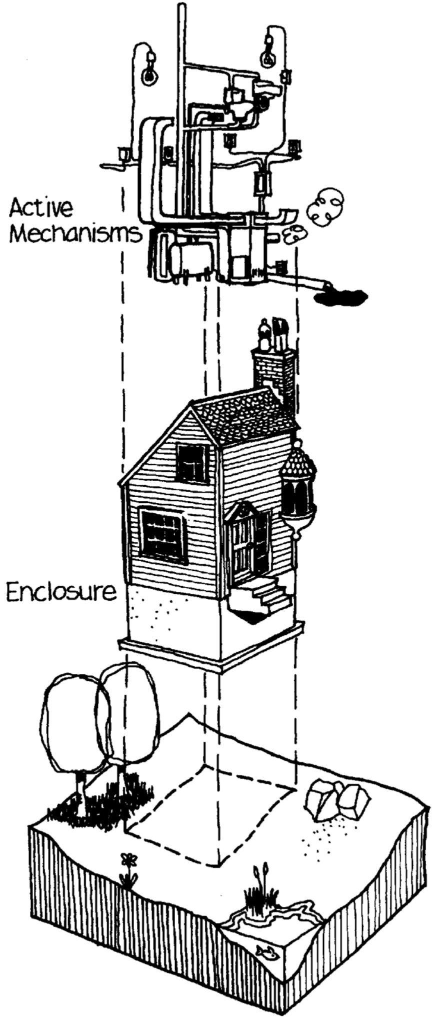
▪ Liquid desiccant dehumidification





Source: Advantix

EPFL



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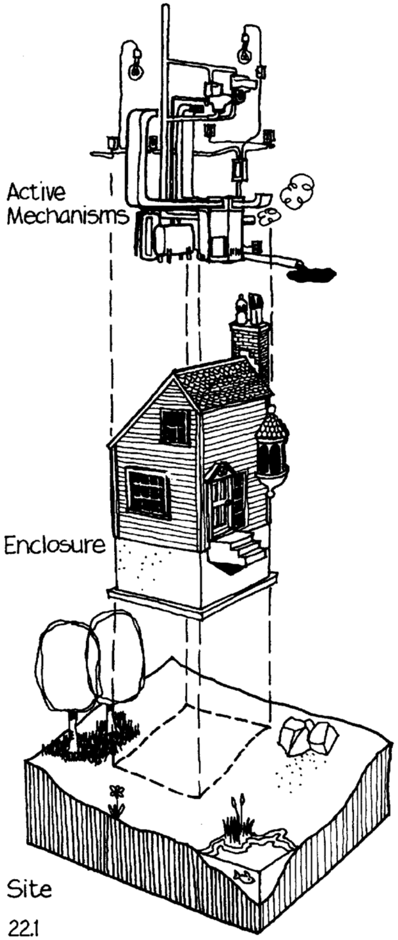
  - Dehumidification
- **Summary**

Main Concepts of this Lecture

- **Passive methods to keep buildings cool**
  Preventing, modulating, and dissipating heat
- **Mechanical cooling emission systems categorization**
  - **All-Air Systems:** flow patterns depending on the supply direction
  - **Refrigerant-based systems:** split system, fancoils, chilled beams
  - **Hydronic Radiant Systems:** radiant ceiling panels
- **Radiant cooling:** heat transfer pathways, effect on the indoor environment, limiting heat flux, thermal resistance of radiant ceiling panels, condensation consideration
- **Evaporative cooling basics**
- **Dehumidification:** differences between conventional approach, solid vs. liquid desiccant dehumidification



Source: Edward Allen «How Buildings Work» (2005)

Thank you for your attention!

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