

# 4.401/4.464 Environmental Technologies in Buildings

Christoph Reinhart

L12 Thermal Mass and Heat Flow

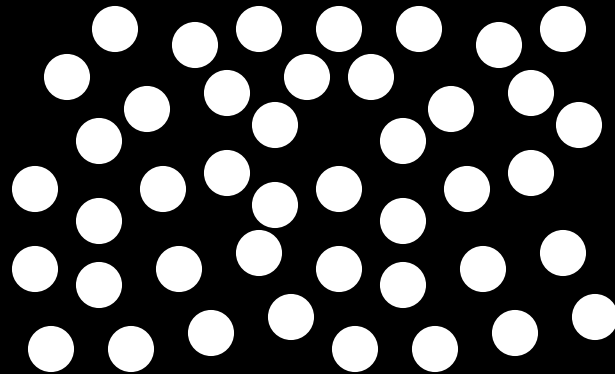
# Thermal Module

- Thermal Mass & Heat Flow I
- Heat Flow II & Insulating Materials
- Window Technologies & Shading
- Ventilation
- Internal Gains & Load Calculations
- HVAC for Small Buildings
- HVAC for Large Buildings
- Simulation Game

# Thermal Mass

# 'Heat' (Internal Energy)

- ❑ **Internal energy** is a form of energy that is stored in a material as molecular motion (sensible energy) or that is associated with the phase of the material (latent energy).
- ❑ **Sensible energy** is measured in temperature (concept of absolute zero, degree Celsius, degree Kelvin, degree Fahrenheit).
- ❑ **Latent energy** is the amount of heat energy released or absorbed by a substance during a change of phase.



# Thermal Material Properties

Table 4 Typical Thermal Properties of Common Building and Insulating Materials—Design Values<sup>a</sup>

Description	Density, lb/ft <sup>3</sup>	Conductivity <sup>b</sup>	Conductance	Resistance <sup>c</sup> (R)		Specific Heat, Btu lb·°F
		(k), Btu·in h·ft <sup>2</sup> ·°F	(C), Btu h·ft <sup>2</sup> ·°F	Per Inch Thickness (1/k), ft <sup>2</sup> ·°F·h Btu·in	For Thickness Listed (1/C), ft <sup>2</sup> ·°F·h Btu	
<b>BUILDING BOARD</b>						
Asbestos-cement board .....	120	4.0	—	0.25	—	0.24
Asbestos-cement board ..... 0.125 in.	120	—	33.00	—	0.03	
Asbestos-cement board ..... 0.25 in.	120	—	16.50	—	0.06	
Gypsum or plaster board ..... 0.375 in.	50	—	3.10	—	0.32	0.26
Gypsum or plaster board ..... 0.5 in.	50	—	2.22	—	0.45	

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Density  
Thermal conductivity  
Specific heat

# Specific Heat

❑ **Specific heat** is the quantity of heat required to increase the temperature of a unit mass of a material by one degree. Its units are J/kg K or BTU/lb °F. The specific heat of water is exactly one since 1 BTU is required raise one pound of water by one degree Fahrenheit. Most other materials have a specific heat or heat capacity lower than water.

❑ Example values :

	Density [kg/m <sup>3</sup> ]	Specific heat [J/kg K]
Water (25°C)	997	4181
Air	1.2	1000
Concrete (dense)	2400	840
Fiberglass batt	12	848
Copper	8900	380
Gypsum board	950	840
Stucco	1858	837

# Volumetric Heat Capacity

□ Since the quantity of a substance is often expressed in terms of its volume rather than its weight, the **volumetric heat capacity [VHC]** describes the ability of a volume of substance to store internal energy under a given temperature change. It may be derived by multiplying the density of a substance by its specific heat.

□ Example values :

	Density [kg/m <sup>3</sup> ]	Specific heat [J/kg K]	Volumetric heat capacity [kJ/m <sup>3</sup> K]
Water (25°C)	997	4181	4168
Air	1.2	1000	1.2
Concrete (dense)	2400	840	2016
Fiberglass batt	12	848	10
Copper	8900	380	3382
Gypsum board	950	840	798
Stucco	1858	837	1555

Note: moving heat using air makes little sense.

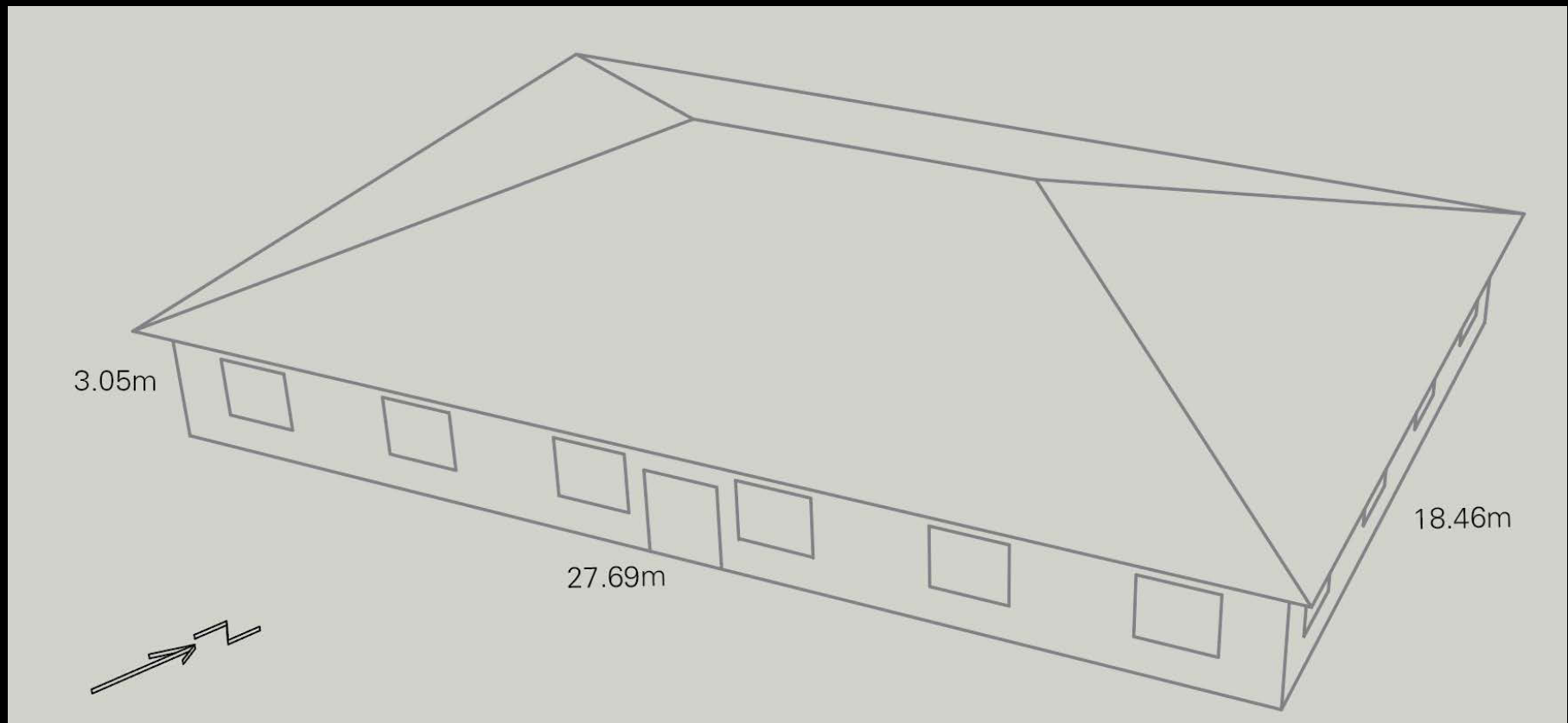
# Thermal Mass

Thermal Mass [TM] is the ability of a building component to store heat while experiencing a temperature change. The thermal mass of an element depends on its volume as well as its volumetric heat capacity. It is simply defined as

$$TM = \text{Volume} \times VHC$$



# US DOE Benchmark Small Office Building



Floor area: 511.1 m<sup>2</sup>

Wall area: 225.7 m<sup>2</sup>

Roof area: 511.1 m<sup>2</sup>

Window area: 55.8 m<sup>2</sup>

US Department of Energy Commercial Benchmark Building

URL: <https://www.energy.gov/eere/buildings/commercial-reference-buildings>

# Thermal Mass Example – Building Floor

What is the thermal mass of a concrete floor with a thickness of 0.1 m that extends across the Small Office Building?

$$TM = \text{Volume} \times \text{VHC}$$

$$\text{Volume} = 27.69 \text{ m} \times 18.46 \text{ m} \times 0.1 \text{ m} = 51.1 \text{ m}^3$$

$$\text{VHC} = 2016 \text{ kJ/m}^3\text{K}$$

Resulting in:

$$TM = 10,3049.3 \text{ kJ/K} \sim 28.6 \text{ kWh/K}$$

$$\text{with } 1 \text{ kJ} = 1 \text{ kW}\cdot\text{s} = 1 \text{ kW} \cdot 3600 \text{ s} / 3600 = 1/3600 \text{ kWh}$$

# Thermal Mass Example – Enclosed Air

What is the thermal mass of the enclosed air?

$$TM = \text{Volume} \times VHC$$

$$\text{Volume} = 27.69 \text{ m} \times 18.46 \text{ m} \times 3.05 \text{ m} = 1559 \text{ m}^3$$

$$VHC = 1.2 \text{ kJ/m}^3\text{K}$$

Resulting in:

$$TM = 1870.8 \text{ kJ/K} \sim 0.5 \text{ kWh/K}$$

Thermal mass of air is negligible.

$$\text{with } 1 \text{ kJ} = 1 \text{ kW}\cdot\text{s} = 1 \text{ kW} \cdot 3600 \text{ s} / 3600 = 1/3600 \text{ kWh}$$

# Heat

The heat/internal energy required to raise the temperature of an object (without changing its phase) corresponds to the thermal mass of the object times the temperature difference.

$$Q = TM \times (T_{\text{before}} - T_{\text{after}})$$

What is the energy required to raise the temperature of the concrete floor by 2 K?

$$Q = TM \times \Delta T = -28.6 \text{ kWh/K} \times 2 \text{ K} = -57.2 \text{ kWh}$$

Note: A negative energy value indicates that energy is absorbed by the object.

*Let's build our first  
building.*

# The PASSYS Test Cells

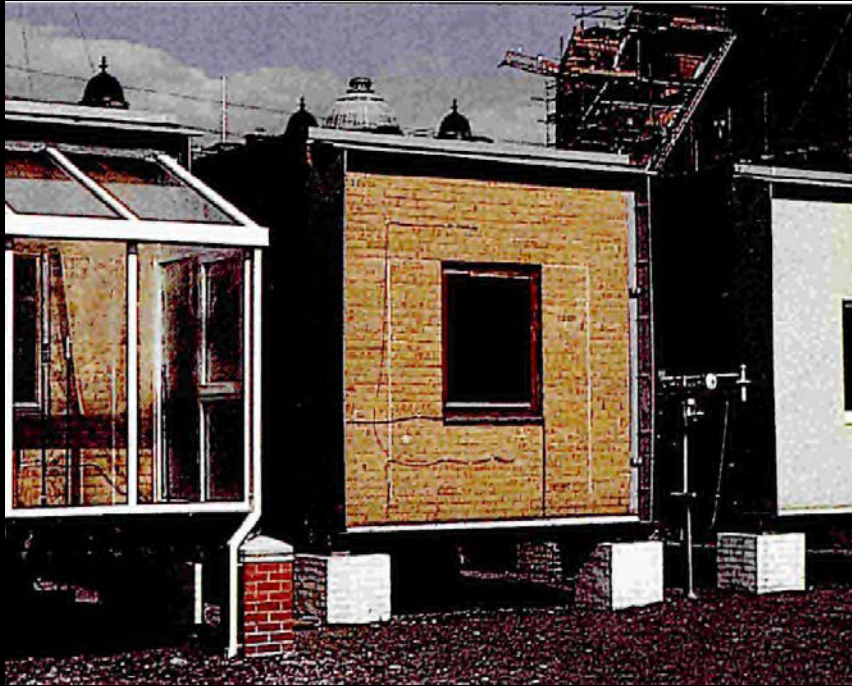
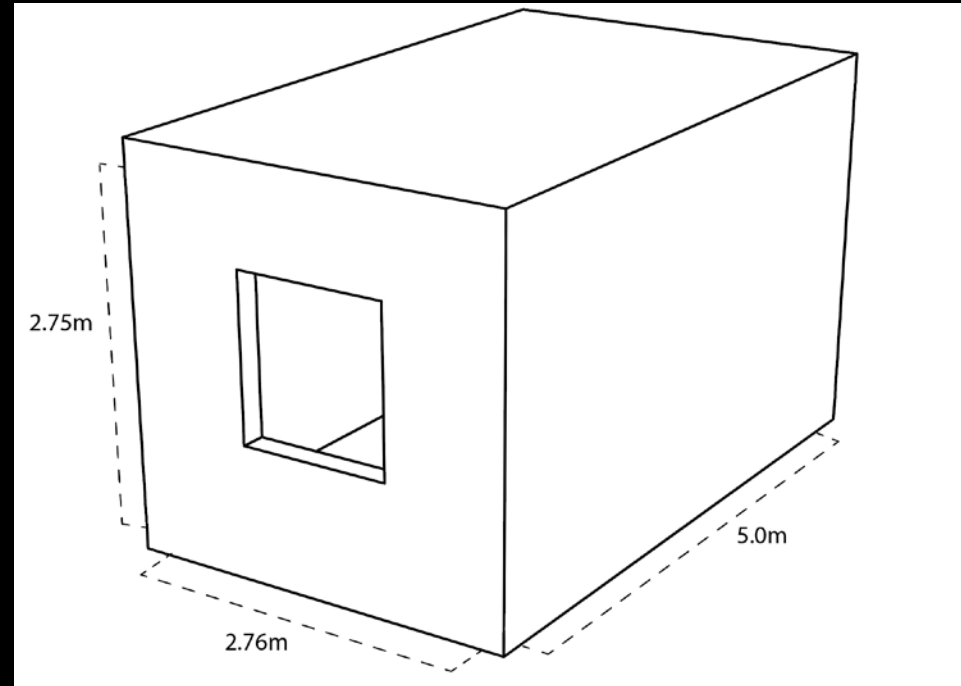


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- ❑ The PASSYS test cells were developed in 1990 in Europe to systematically test the performance of the different solar architectural façade solutions as well as to validate building performance simulation programs (BPS).
- ❑ BPS tools were developed to model the various heat and mass flows in and around buildings. Transient or dynamic PBS can also consider the effect of thermal mass.

# Building Technology Test Cell



# Initial BPS Validation through the PASSYS Test Cells

ESP-r model

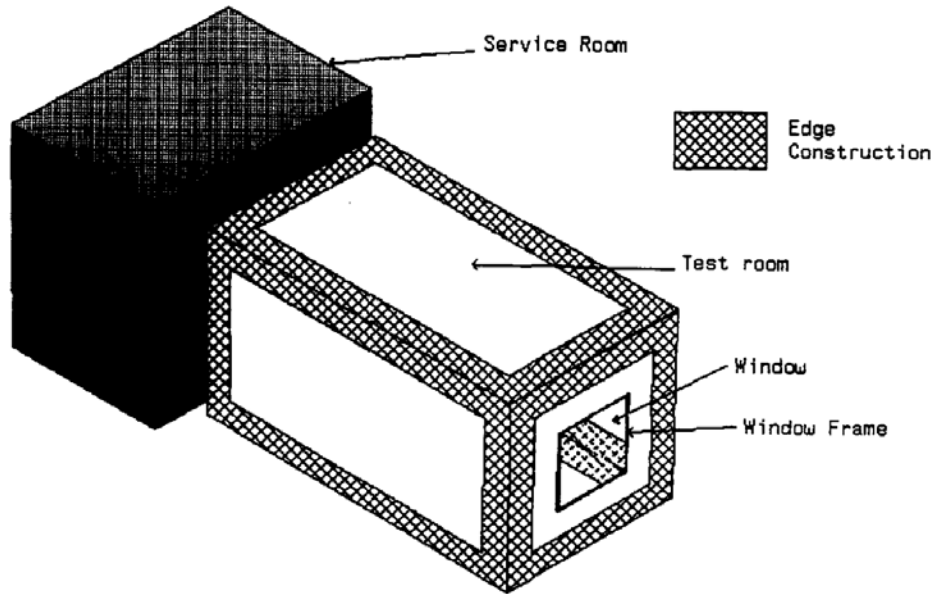
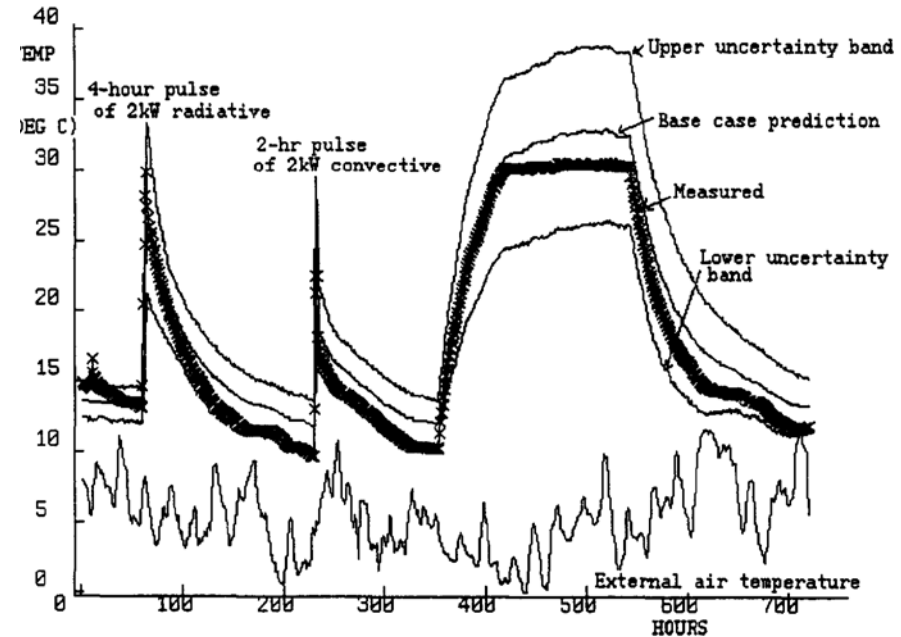


Fig. 3. Model of a test cell fitted with the common reference wall.

ESP-r simulation



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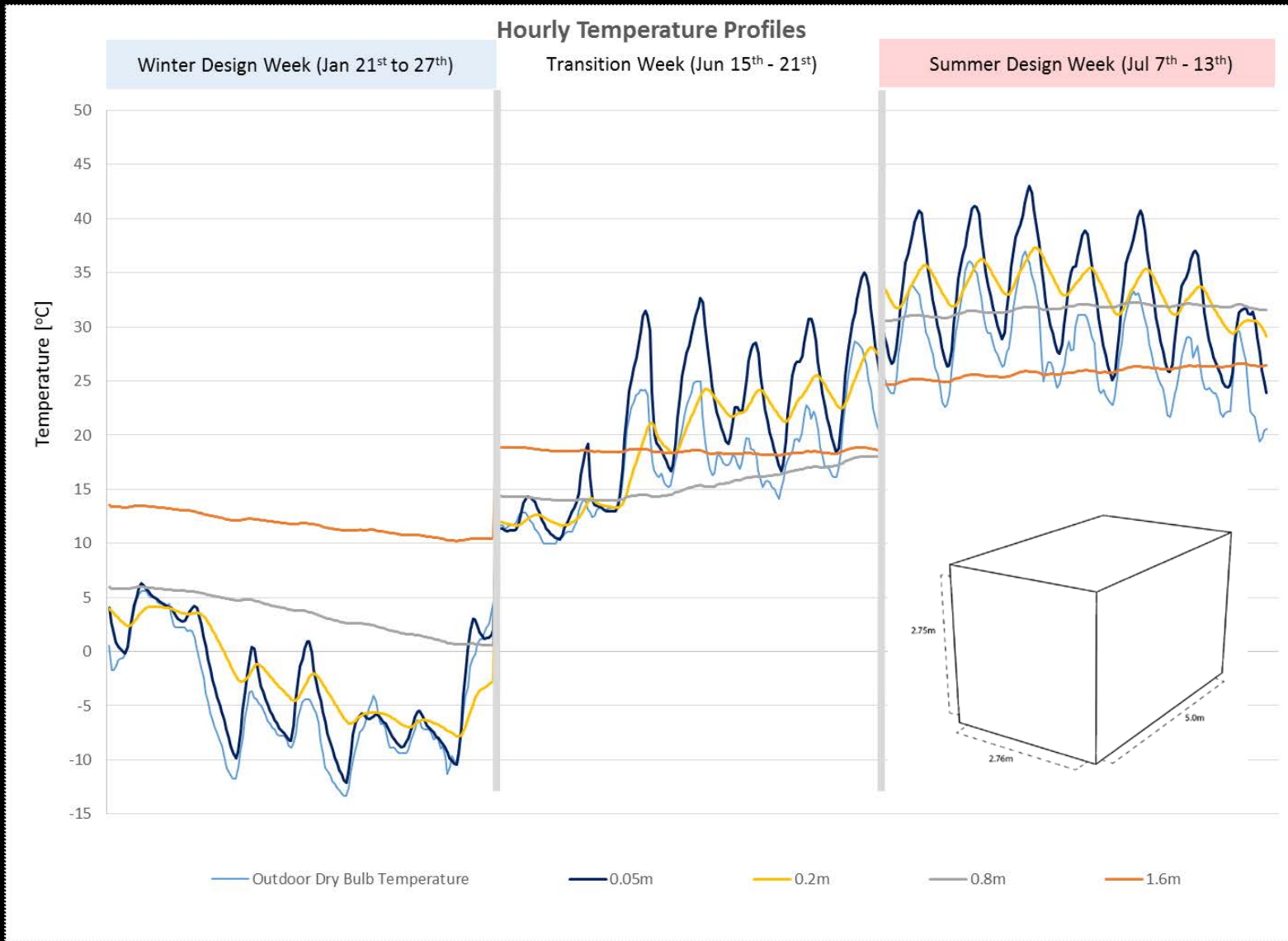
- If carefully calibrated, the ESP-r program was shown to reproduce measured temperature developments within the limits of measurement accuracy for all simulation inputs.
- A future lecture will be dedicated to BPS.

European Commission, "The PASSYS Test Cells: A COMMON EUROPEAN OUTDOOR TEST FACILITY FOR THERMAL AND SOLAR BUILDING RESEARCH," EU Bookshop EU-NA-12882-EN-C, 1990, pp. 1-68.

P. Stachan, Model Validation using the PASSYS Test Cells, Building and Environment, 28:2, pp. 53-165, 1993.

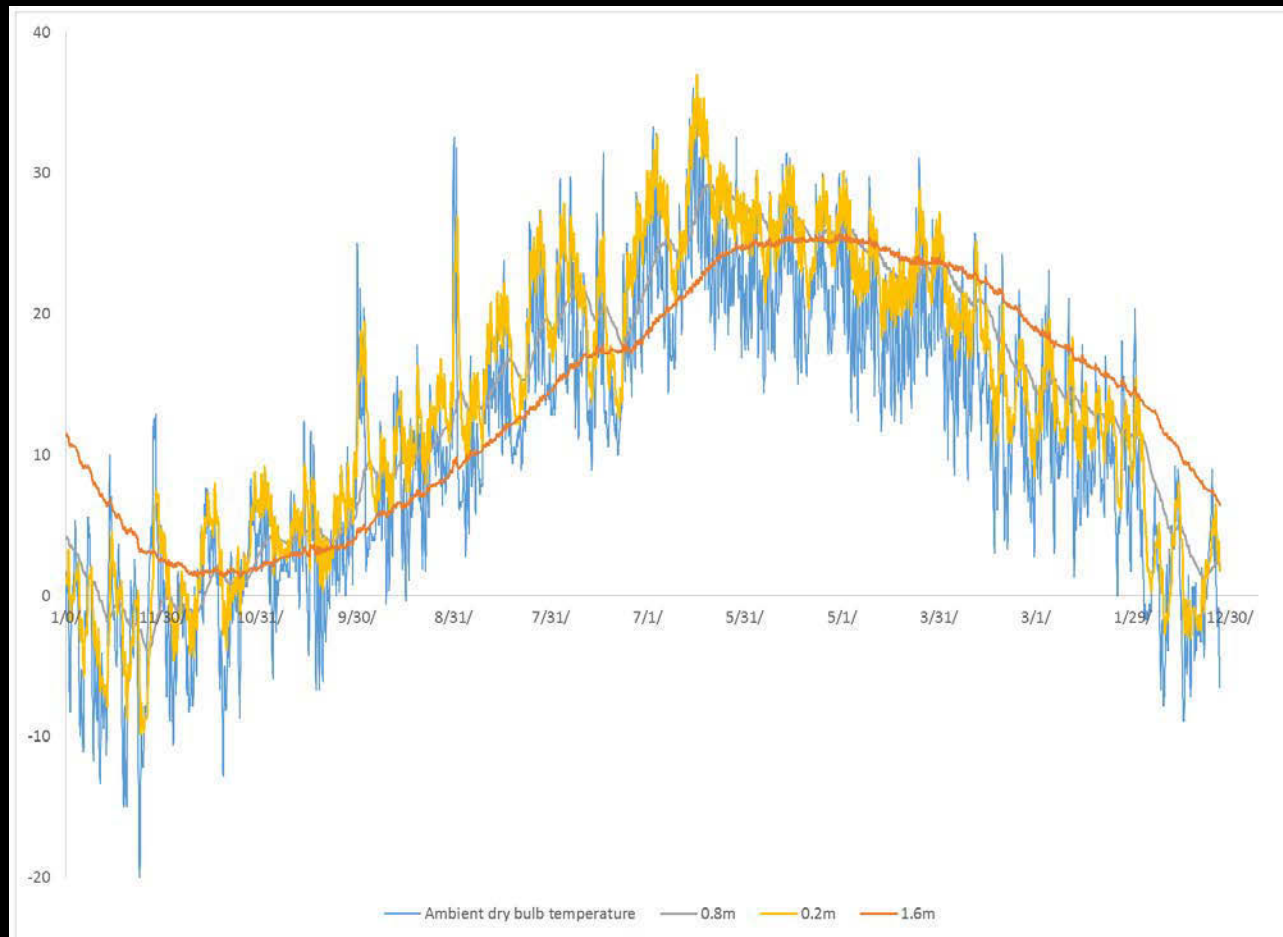


# Thermal Mass Study of a PASSYS Cell



☐ Thermal mass dampens temperature swings and adds "inertia" to a space.

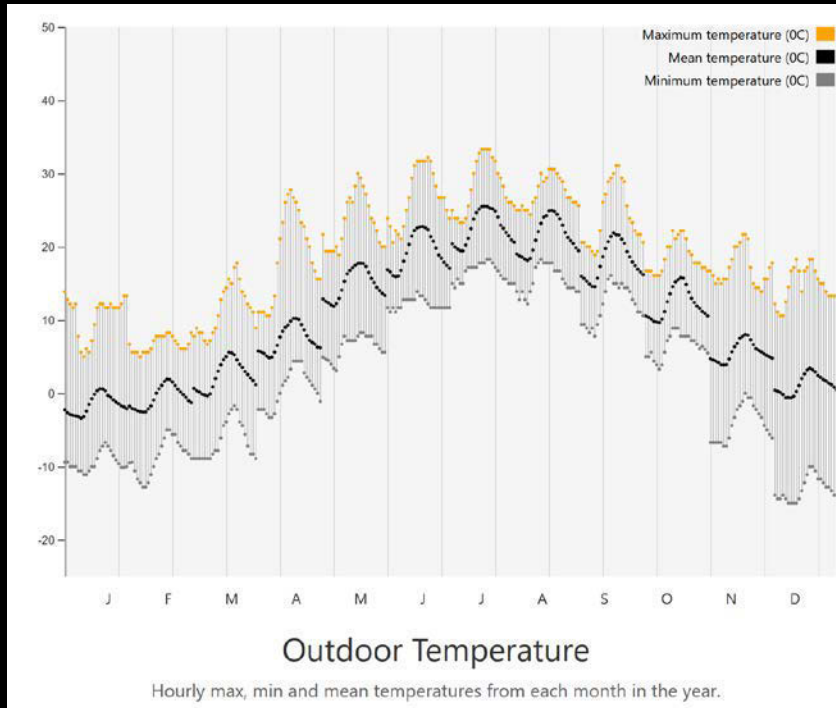
# Annual Temperature Curves for Varying Concrete Thicknesses



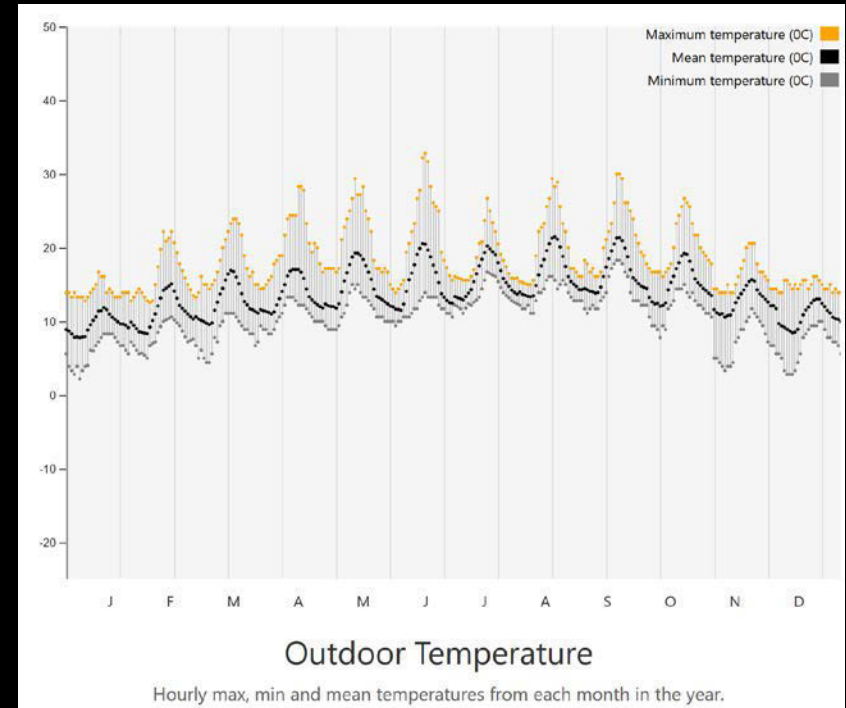
- ❑ As the thermal mass increases, the indoor temperature follows increasingly longer outside DBT trends.
- ❑ For a theoretical 1.6 m thick concrete envelope the lag time of thermal mass becomes visible.

# Thermal Mass in Different Climates

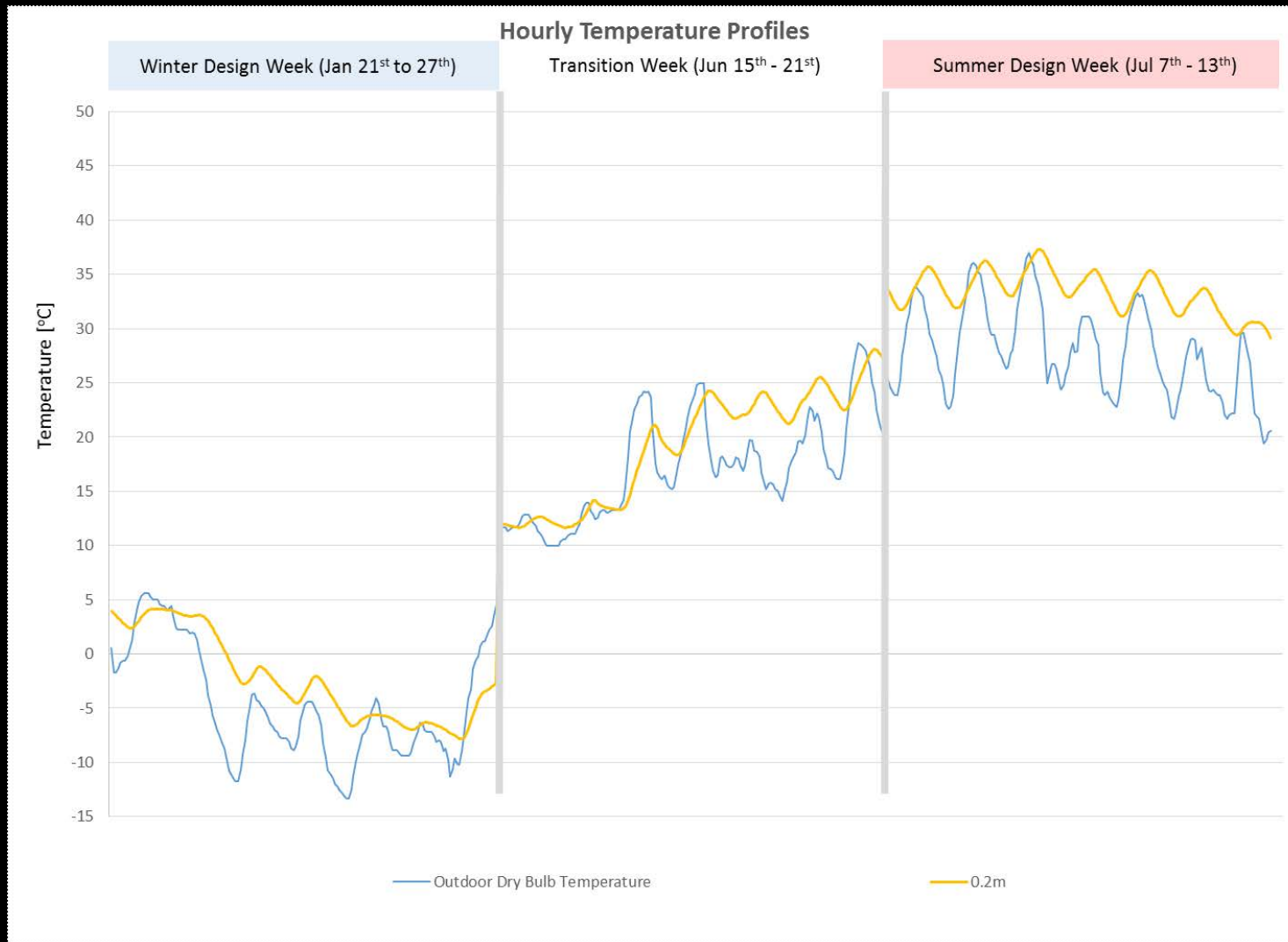
## Boston



## San Francisco

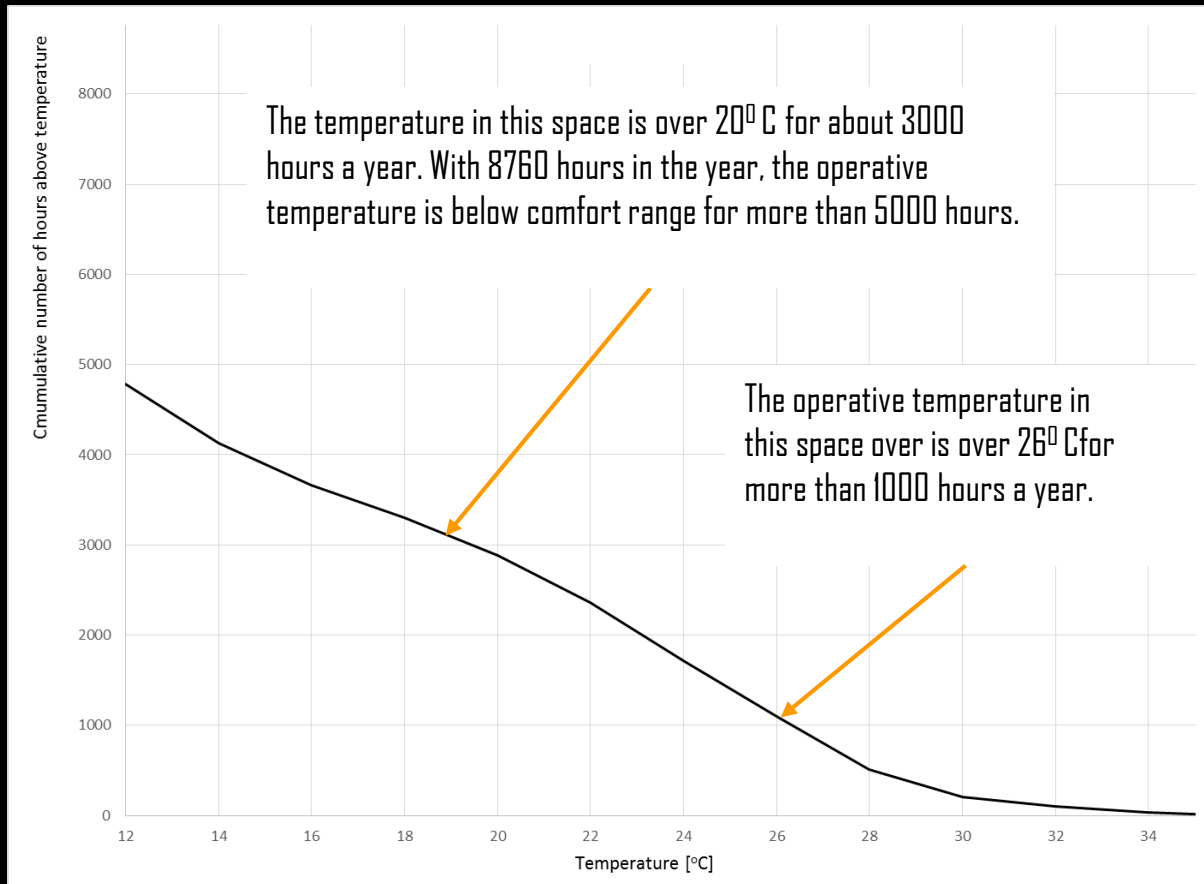


# Towards A More Comfortable Test Cell



- 0.2 m thick concrete seems to be a “practical” thickness.
- Unfortunately, it does not seem to be very comfortable in our test cell.
- Let’s explore what happens over the course of the year.

# Fever Curve – No Insulation



The temperature is in the comfort range between 20°C and 26°C for only 2000 hours a year (3000 hours – 1000 hours).

❑ A fever curve is a graphical method to analyze temperature distributions over the course of a year. The curve shows the cumulative number of all (occupied) hours in a year during which a temperature is above a given temperature.

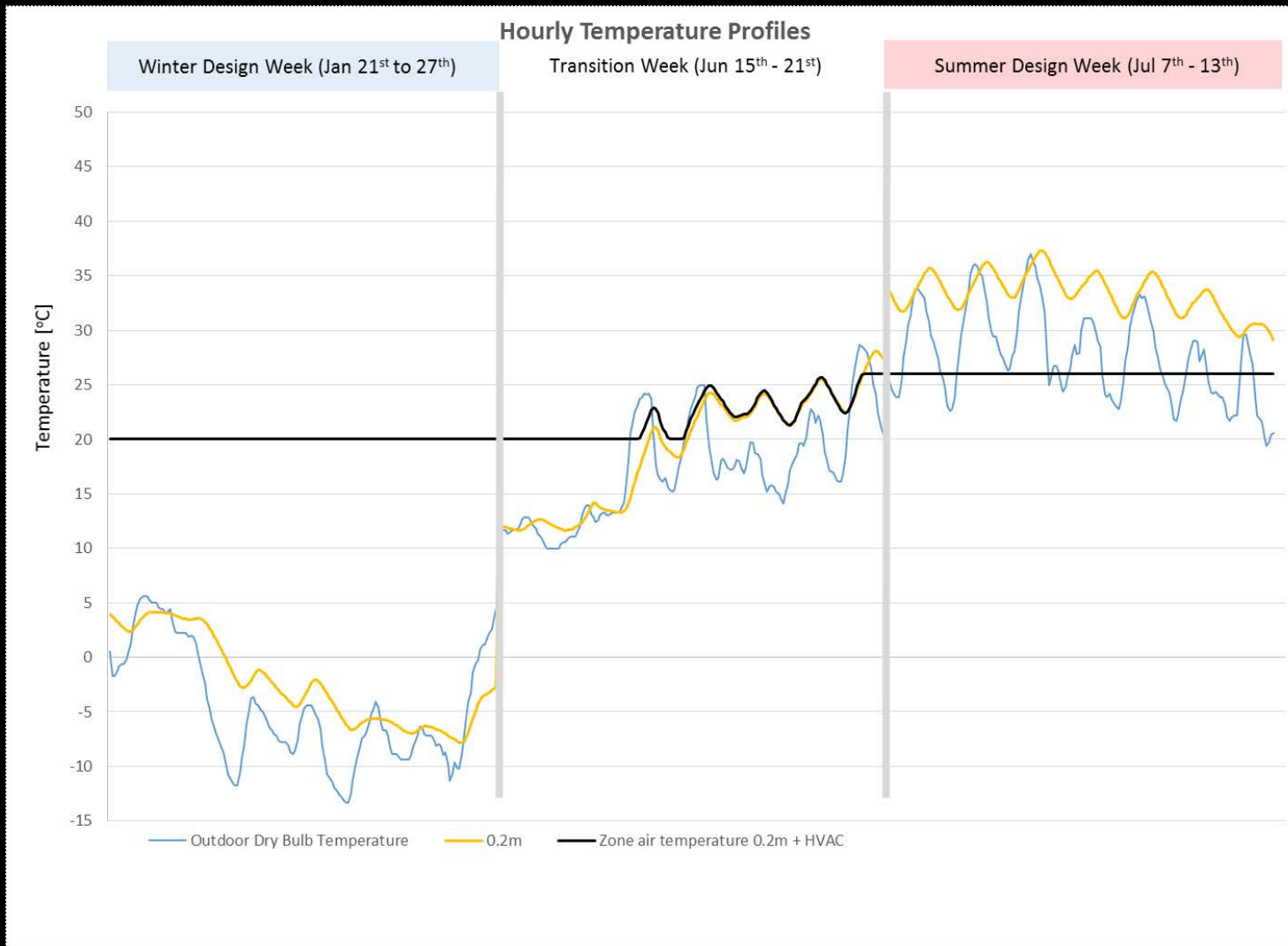
❑ Fever curves are frequently used to test the ability of different design to keep a space within a given comfort range.



Photo by [Dunnock D](#) on Flickr. License CC BY-NC.

❑ Romantic but uncomfortable. What can we do?

# Test Cell Fully Conditioned- No Insulation



- Zone air temperature is controlled between 20° C and 26° C.
- Thermal mass is only activated during the transition week.

# WIPO Conference Hall, Geneva, Switzerland



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- Thermal mass may act as a liability to keep a space comfortable e.g. when it is only used intermittently.



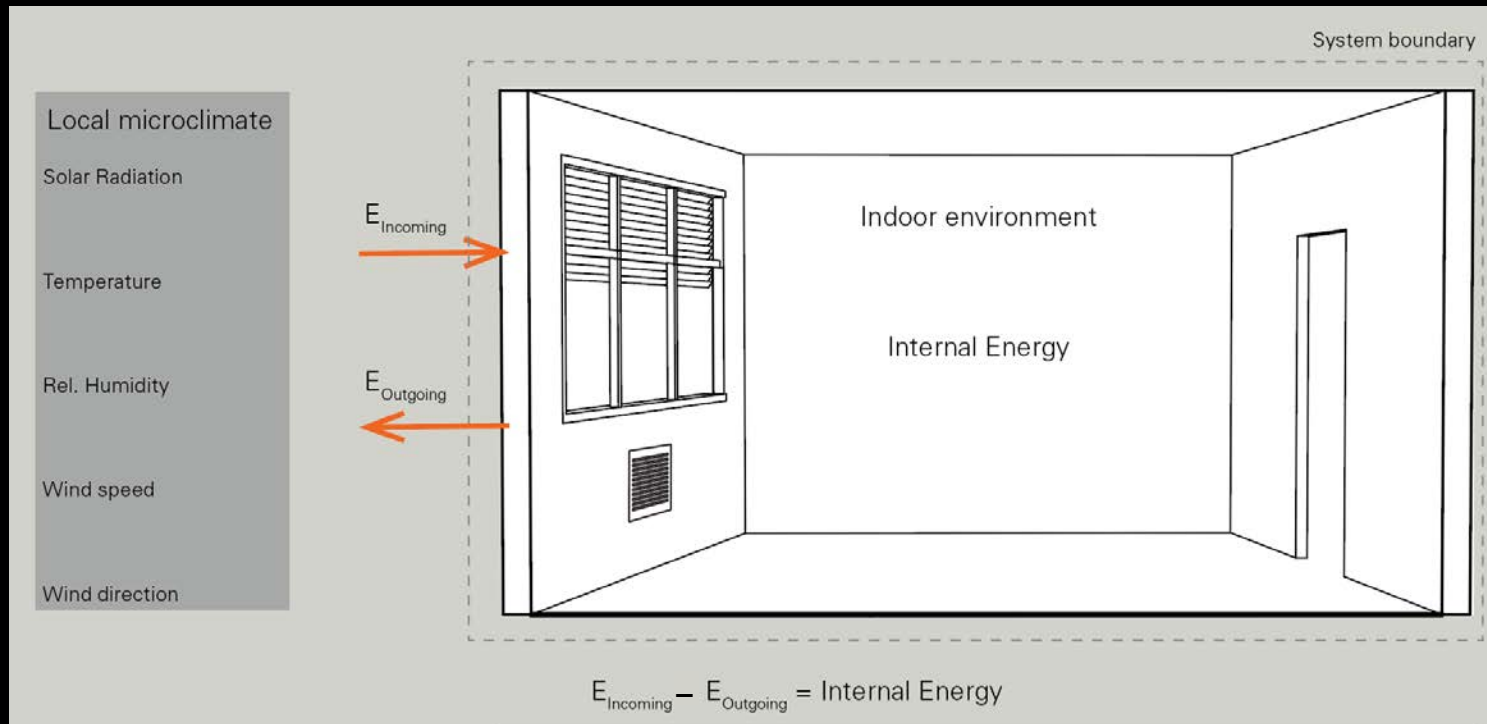
# WIPO Conference Hall



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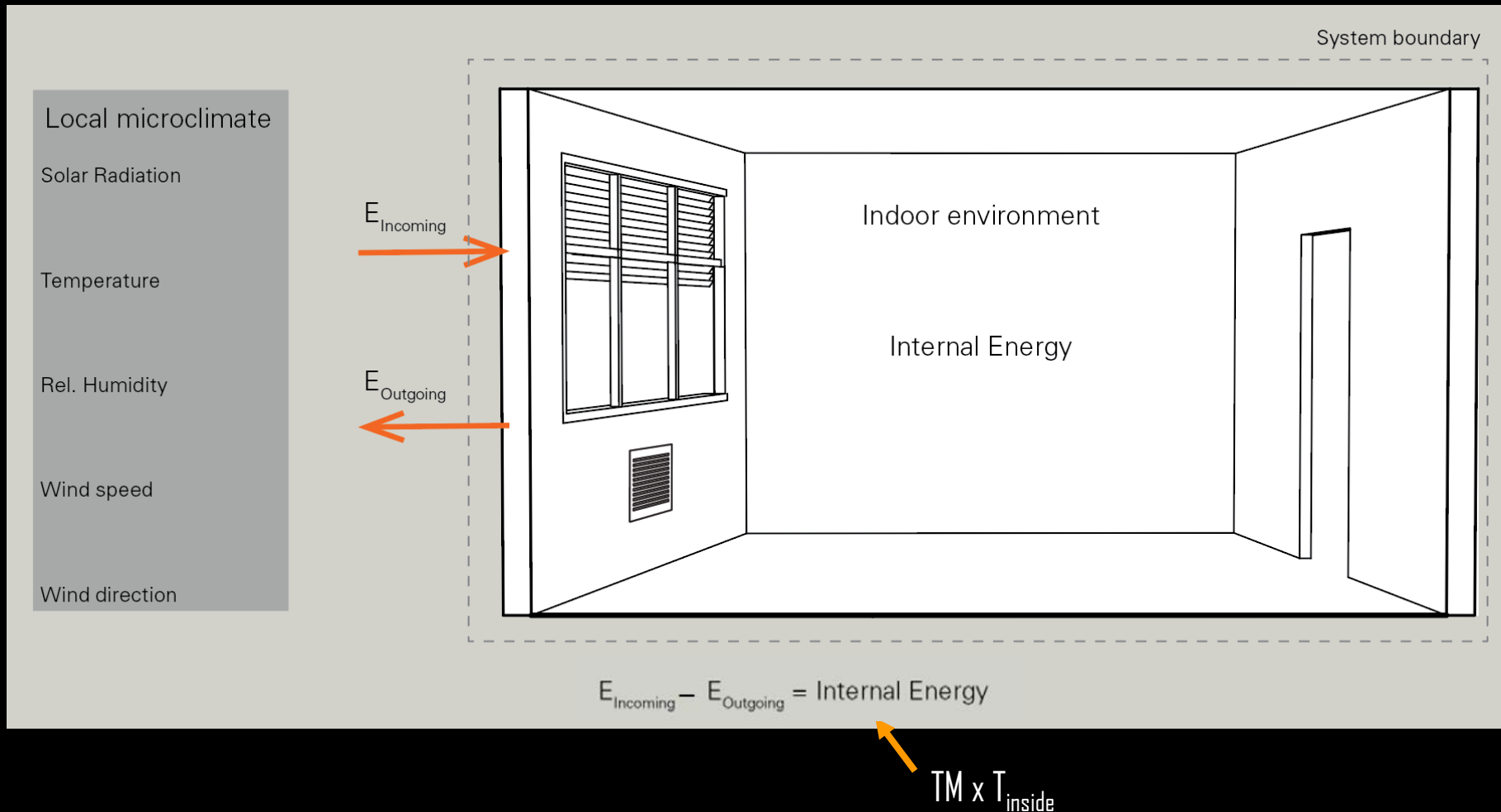
# Heat Balance of a Building

In order to understand the thermal behavior of a building, it is useful to think of the building as a **system with a boundary** with the boundary consisting of the building envelope (basement, external walls and roof). One can predict how a building will behave over time by recalling the first law of thermodynamics, i.e. any excess energy crossing the building envelope is going to be stored in the building's thermal mass.

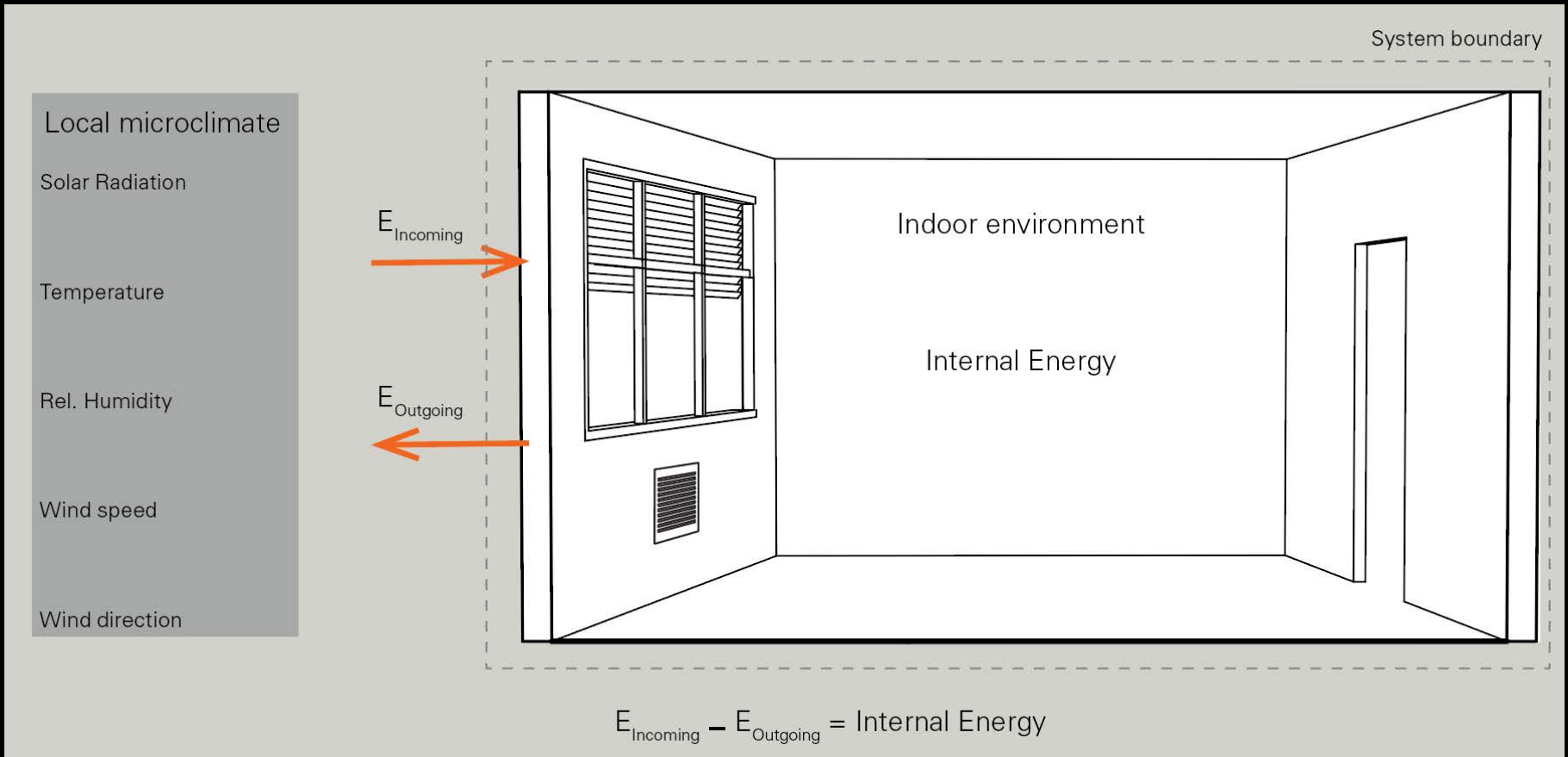


If incoming and outgoing energy flows balance each other, then the system is in equilibrium and no energy is stored.

# Heat Balance Equation

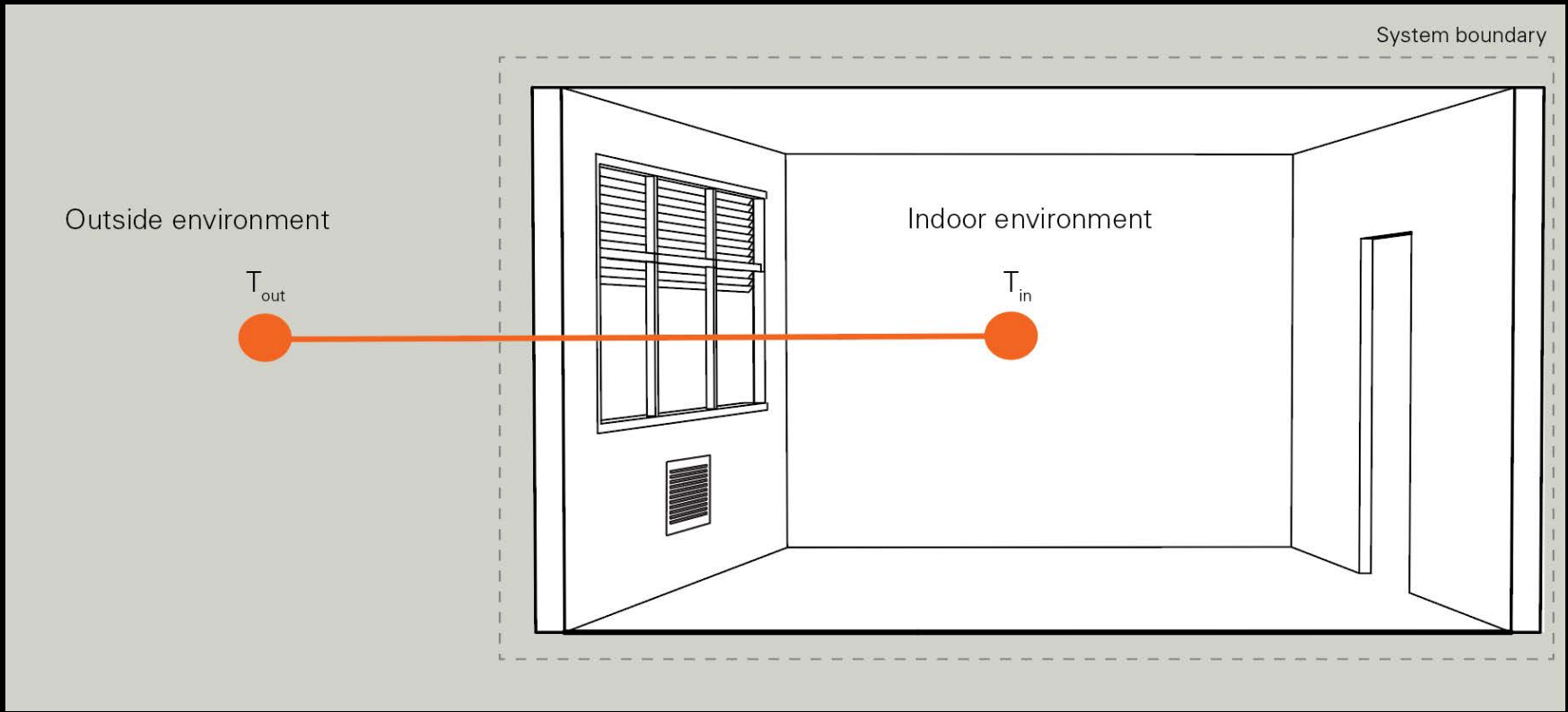


# Heat Flow



What happens to the temperature in the building if incoming and outgoing energy are the same?

**It remains constant.**



What happens over time if  $T_{outside} \neq T_{inside}$ ?

Heat will 'flow' from hot to cold.

# Heat Flow

- ❑ **Heat** is energy in transit from one material to another material.
- ❑ This transfer of energy or **heat flow** only happens spontaneously from an object with a high temperature to an object with a lower temperature.
- ❑ As water flows from a higher to a lower position, so heat flows from a higher temperature zone or object to a lower.
- ❑ This principle is also called the 'Second Law of Thermodynamics'.

*What are the three forms of heat flow?*



# Heat Flow

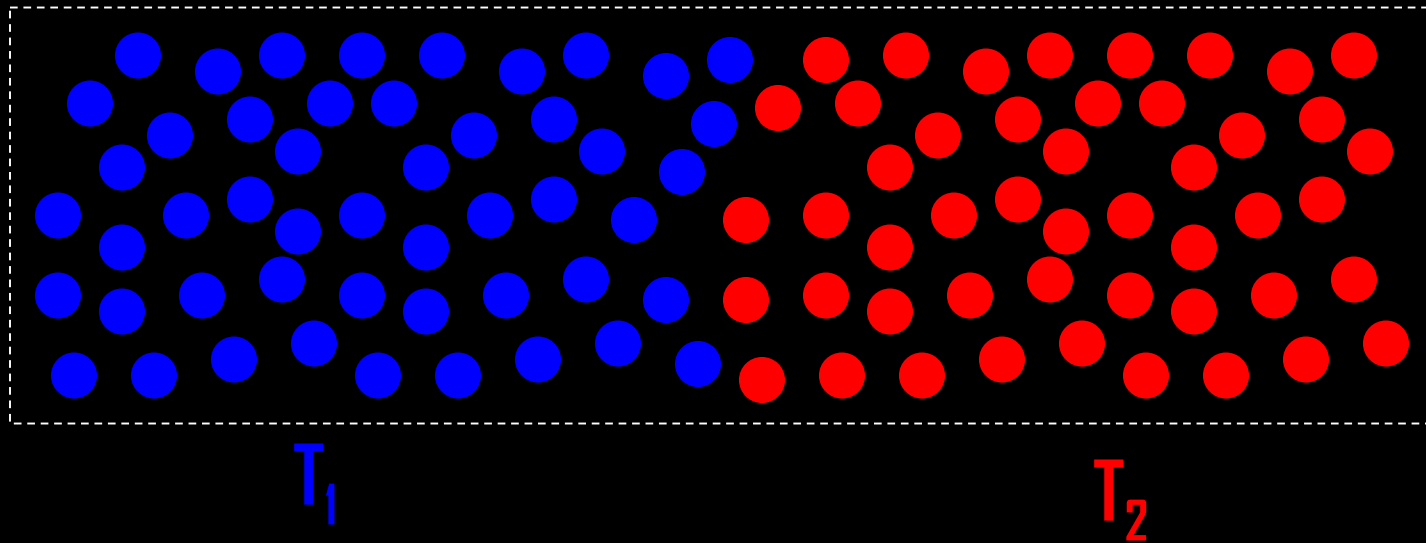
Heat flow can take place in three forms :

- ❑ Conduction: Heat flow within a body or through bodies in contact by the 'spread' of molecular motion.
- ❑ Convection: Heat flow from a solid to a fluid (gas or liquid) or vice versa. Convection involves the transport of heat from one surface to another via a moving fluid.
- ❑ Radiation: Transfer of electromagnetic energy from one body to another.

# Conduction

# Conduction

□ Conduction occurs in solids when warmer molecules, which are vibrating faster than colder molecules, transfer part of their energy to the colder molecules. It is a dynamic process.

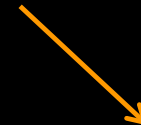


□ In buildings, conduction is a key contributor to heat losses and gains through the building envelope.

# Conduction

The simplest way to mathematically describe conduction through a material is its **thermal conductivity**. In general the conductivity,  $\kappa$ , of a material may vary in different directions within the material. However, in building science one usually assumes that materials have uniform thermal conductivity and that heat flows "one dimensionally" through a construction assembly. Units: W/mK

□ Example values :



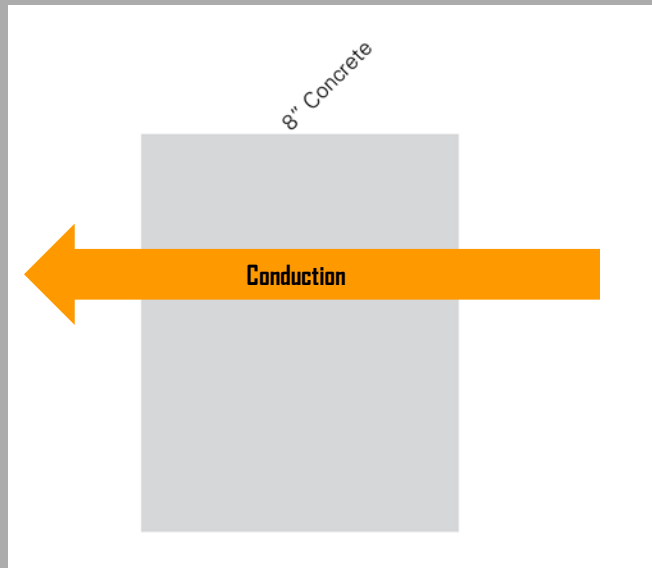
	Density [kg/m <sup>3</sup> ]	Specific heat [J/kg K]	Volumetric heat capacity [kJ/m <sup>3</sup> K]	Conductivity [W/m K]
Water (25°C)	997	4181	4168	0.58
Air	1.2	1000	1.2	0.024
Concrete (dense)	2400	840	2016	1.75
Fiberglass batt	12	848	10	0.043
Copper	8900	380	3382	384
Gypsum board	950	840	798	0.16
Stucco	1858	837	1555	0.69

Note that standing air is an excellent insulator.

# Conductance

Conductance is a material property of a building element that describes how well the element conducts heat. Conductance is measured in  $\text{W}/\text{m}^2\text{K}$  or  $\text{BTU}/\text{h ft}^2 \text{ }^\circ\text{F}$  and is defined as:

$$\text{conductance} = \kappa / \text{material thickness}$$



The conductance through an 0.2 m (8") thick concrete wall is

$$\begin{aligned} U_{\text{wall}} &= 1.75 \text{ W/m K} / 0.2 \text{ m} \\ &= 8.75 \text{ W/m}^2\text{K} \end{aligned}$$

*Conversion:*  $5.67446 \text{ W/m}^2\text{K} \approx 1 \text{ BTU/h ft}^2 \text{ }^\circ\text{F}$

# Resistance

Resistance,  $R$ , is the inverse of conductance,  $C$ .

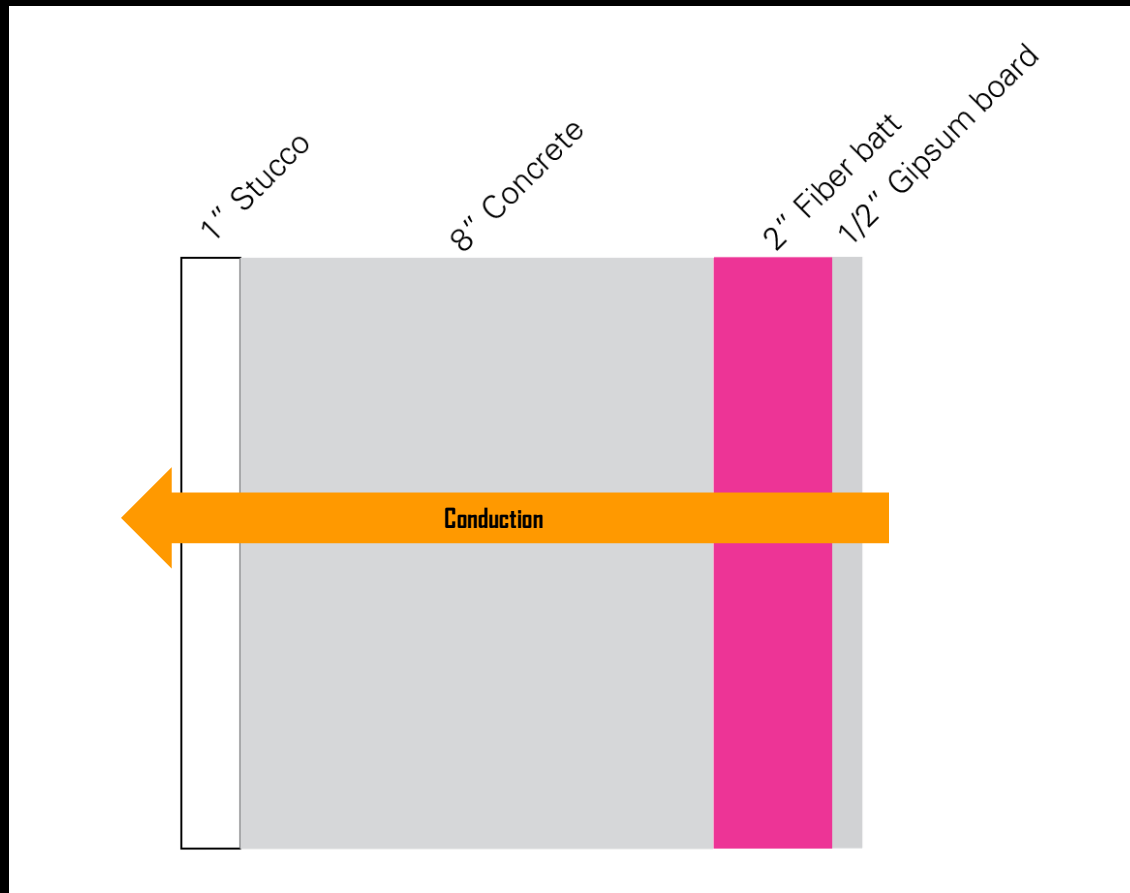
$$R = 1/C$$

- Construction assembly properties are often quoted in resistances since the total resistance of several layers in series can simply be added up.

$$R_{\text{Total}} = R_{\text{Layer 1}} + R_{\text{Layer 2}} \dots + R_{\text{Layer n}}$$

- Note that the order in which different layers are being arranged does not change the overall resistance of a construction assembly.

# Example – Wall Section of the DOE Small Office Building



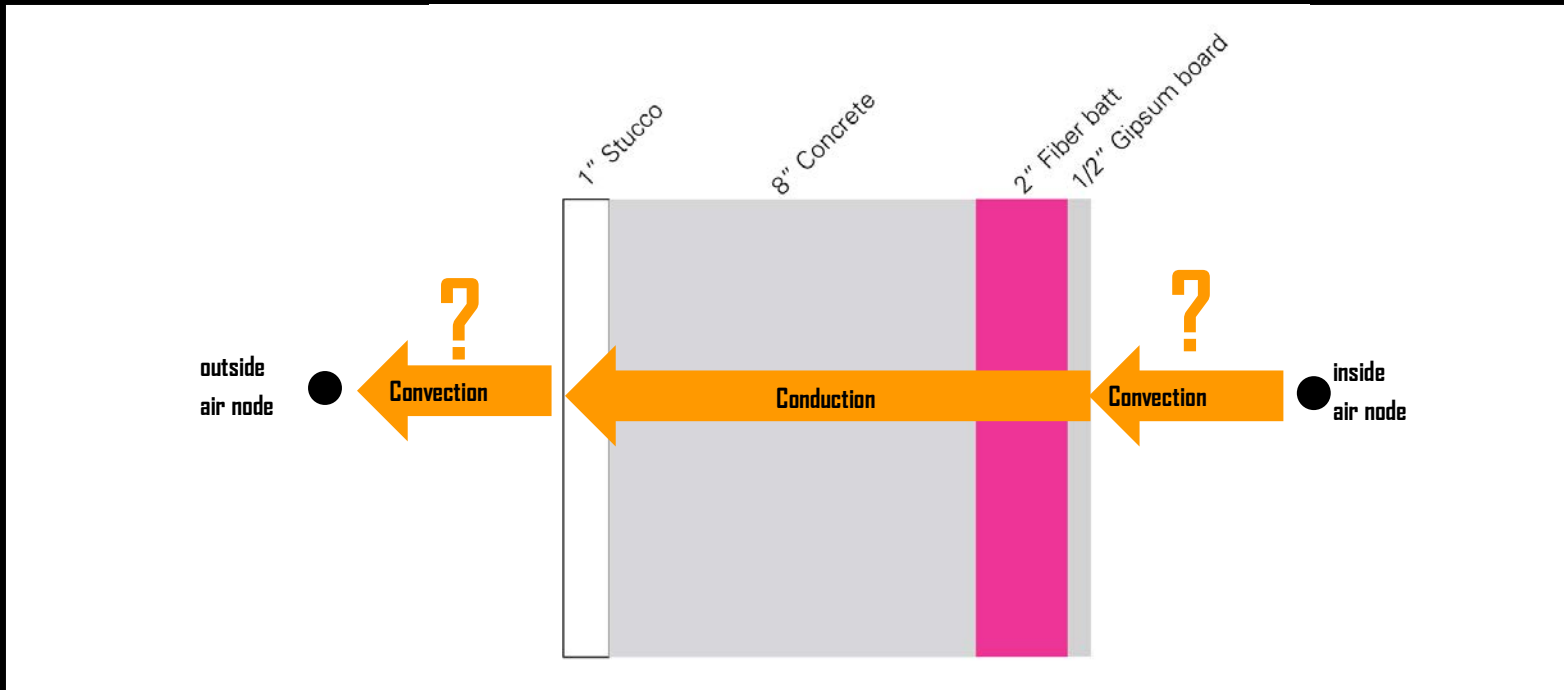
$$R_{\text{Wall}} = R_{\text{concrete}} + R_{\text{fiberglass batt}}$$

$$= 0.025 \text{ m} / 0.69 \text{ W/mK} + 0.2 \text{ m} / 1.75 \text{ W/mK} + 0.05 \text{ m} / 0.043 \text{ m W/mK} + 0.0125 \text{ m} / 0.16 \text{ W/mK}$$

$$= 1.4 \text{ Km}^2/\text{W}$$

# 'R' Value and 'U' Value

Conductance and Resistance are rarely used in building physics. The quantities used instead are the 'U'-value and 'R' value because they also take surface effects (convection) into account. The 'R' value is the inverse of the 'U' value.

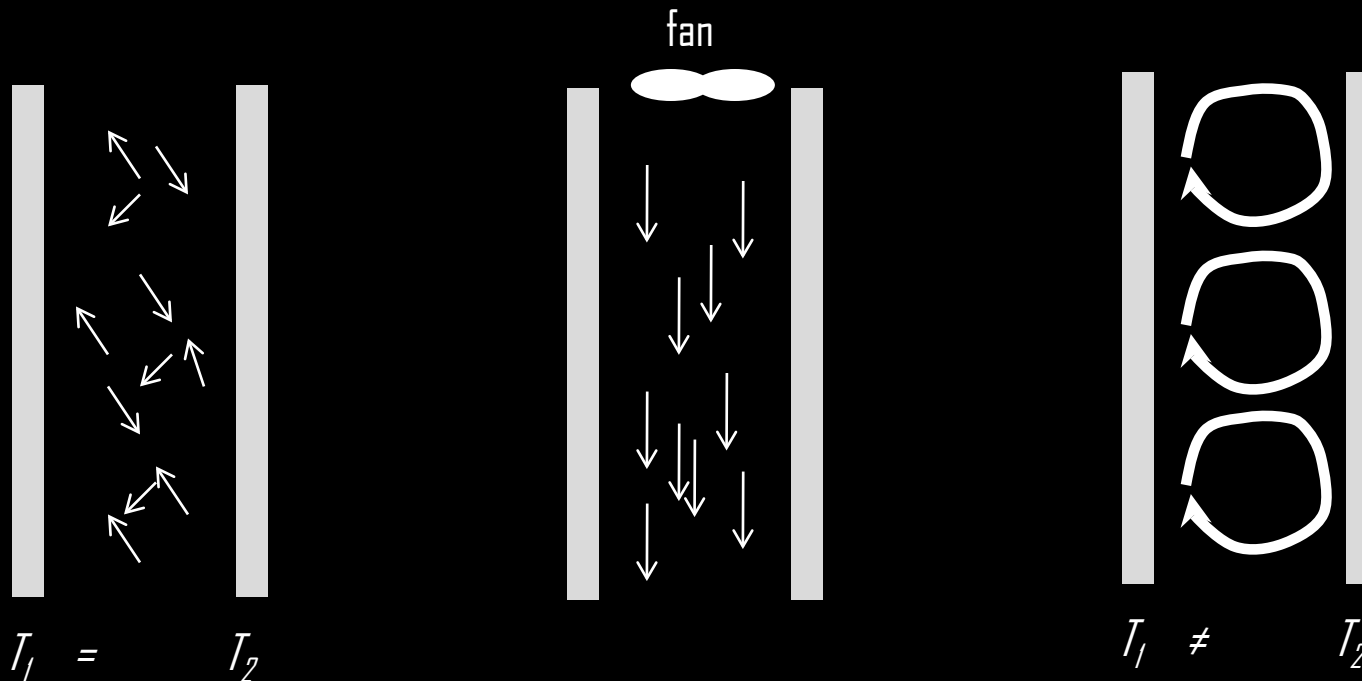




# Convection

# Surface Effects - Convection

- ❑ **Convection** is heat flow through the movement of molecules within fluids (gas or liquid). This movement can take place through diffusion (localized random movements) or larger scale movements (currents) within the fluid. Only the latter type of convection is effectively transporting heat.
- ❑ **Forced Convection** describes a convective heat flow that is externally induced, e.g. through a fan.
- ❑ **Natural Convection** describes convective heat flow that is caused by the act of heating a fluid e.g. buoyancy.



# Natural and Surface Convection

- ❑ **Natural Convection** phenomena are difficult to quantify and can play a major role in naturally ventilated buildings. Natural air movement in buildings occurs through density differences in the air.
- ❑ **Surface Convection** is heat flow from a solid to a fluid (gas or liquid) or vice versa.

# Surface Conductance/Resistance

□ **Surface Conductance** is a measure of the time rate of heat flow across a surface. This heat flow is usually caused by natural and wind-induced convection as well as radiation. Surface conductances are usually measured and can be found in surface property tables. Same as conductance for a material, surface conductance is measured in  $W/m^2K$  or  $BTU/h\ ft^2\ ^\circ F$ .

□ **Surface Resistance** is the inverse of surface conductance.

□ Surface resistances according to ASHRAE Fundamentals Chapter 22 :

Regular Wall:

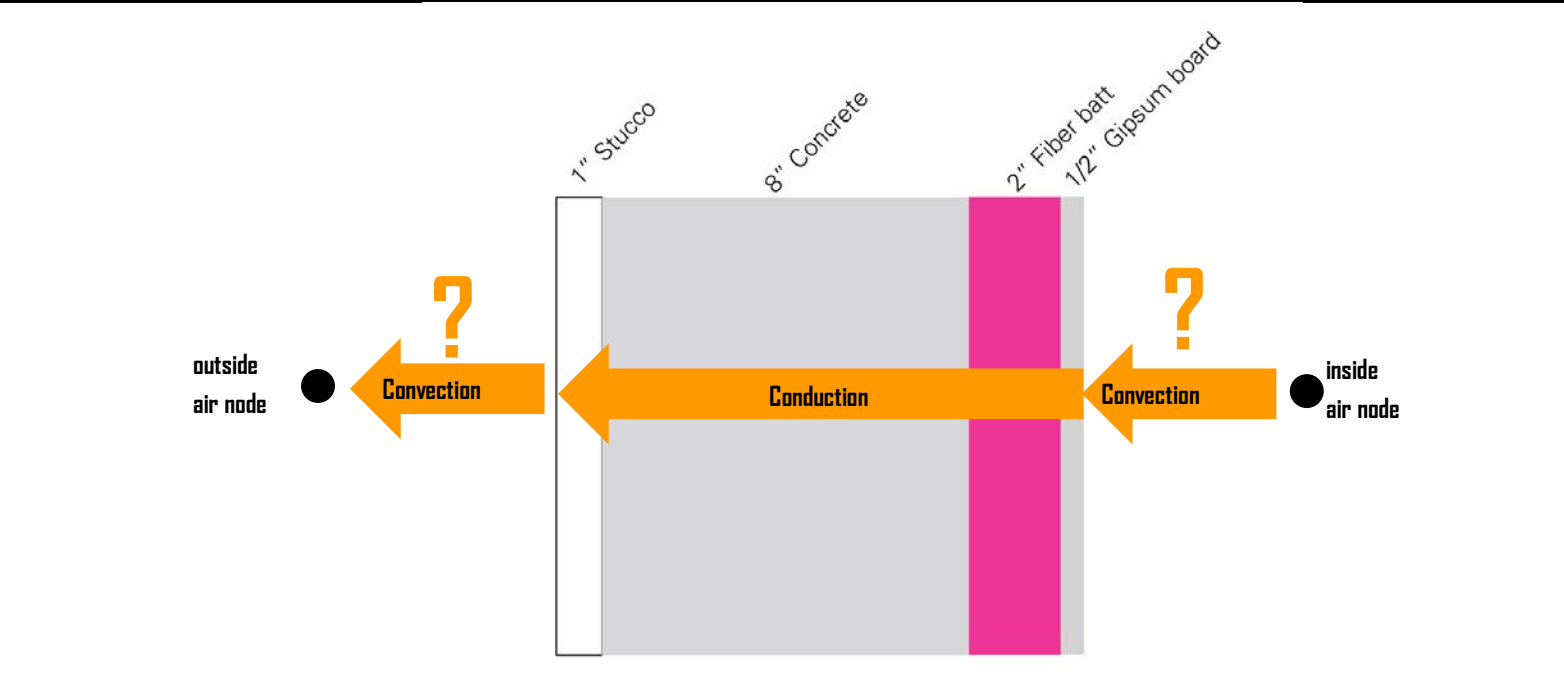
Inner Surface:  $R_{inside} = 0.12\ m^2K/W = 0.68\ h\ ft^2\ F/BTU$

Outer Surface (15 MPH wind):  $R_{outside} = 0.03\ m^2K/W = 0.17\ h\ ft^2\ F/BTU$

Conversion :  $1\ m^2K/W \approx 5.67446\ h\ ft^2\ F / Btu$

# Calculation of the 'R' Value

The air-to-air 'R'-value ( $R_{a-a}$ ) is a measure of the overall thermal resistance of a building element including surface effects. It can be calculated by summing up all the resistances of all building element layers as well as corresponding surface resistances:  $R_{a-a} = R_{inside} + R_{wall} + R_{outside}$



$$R_{a-a} = 0.12 \text{ K m}^2/\text{W} + 1.4 \text{ K m}^2/\text{W} + 0.03 \text{ K m}^2/\text{W} = 1.55 \text{ K m}^2/\text{W} = 8 \text{ h ft}^2 \text{ F}/\text{BTU}$$

$$U_{wall} = 1/R = 0.66 \text{ W}/\text{K m}^2$$

↖ This is an "R-8" wall.

# Online U-Value Calculator

<https://www.ubakus.de/u-wert-rechner/>

Inside:  20 °C 50 % Humidity

From inside to outside: reverse Thickness Width Distance λ μ

#	Material	Thickness	Width	Distance	λ	μ	Icons
1	Resin Plaster	25 mm			0,7	50/200	≡ ✎ + ⏻
2	Concrete	200 mm			2	80/130	≡ ✎ + ⏻
3	Glasswool	50 mm			0,04	1/2	≡ ✎ + ⏻
4	Gypsum Fibreboard	12 mm			0,35	4/19	≡ ✎ + ⏻
5							🗑️

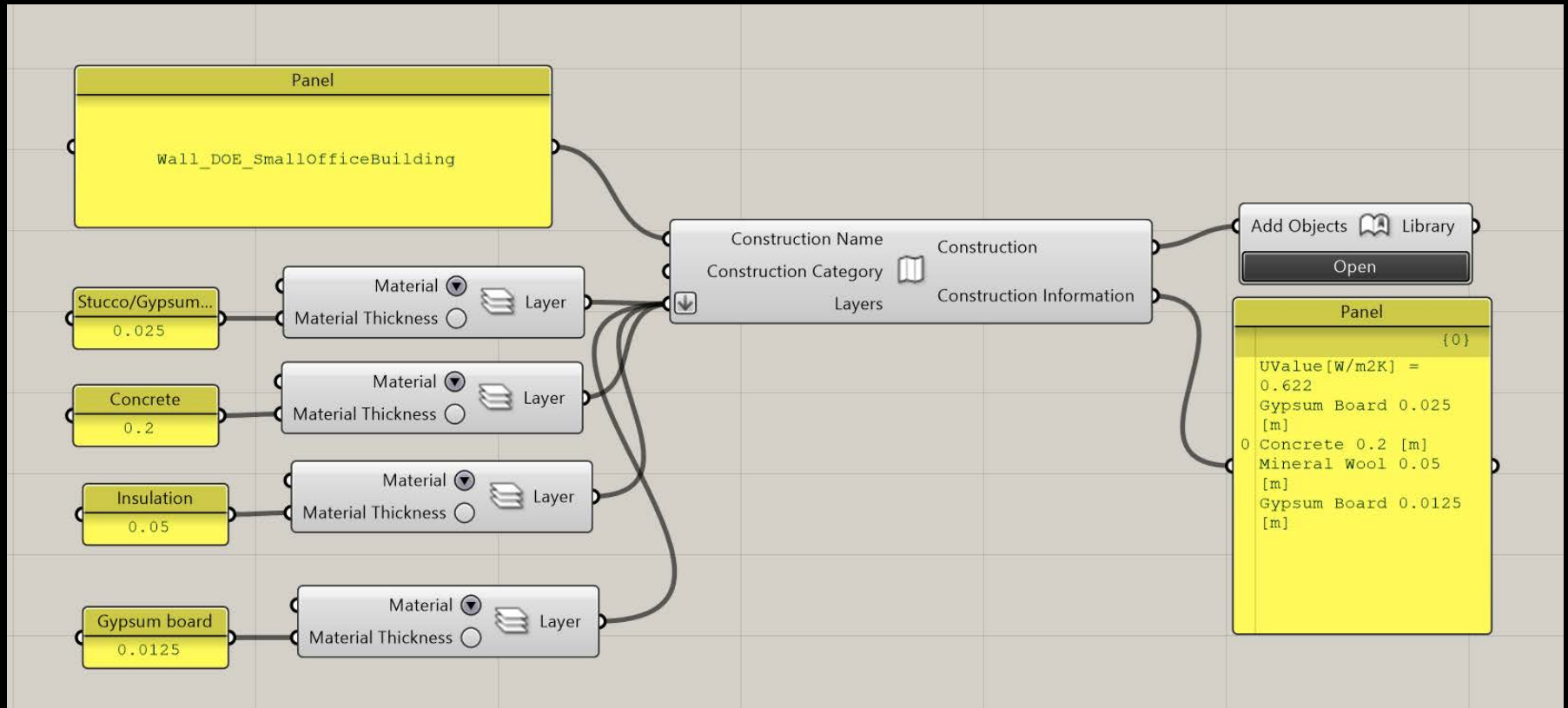
Outside:  -5 °C 80 % Humidity

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<p><b>U-value: 0,629</b> W/m²K </p> <p>EnEV Bestand: U&lt;0.24* <input type="checkbox"/></p> <p>PEI n.e.: 219 kWh/m²</p> <p>excellent insufficient</p>	<p>Condensate: 0 kg/m²</p> <p>moisture content of wood: +0,0 %</p> <p>Drying time: -</p> <p>excellent insufficient</p>	<p>sd-value: 18 m</p> <p>Interior surface: 16,3°C (63%)</p> <p>Drying reserve: 513 g/m²a</p> <p>insufficient excellent</p>	<p>Thickness: 28,7 cm</p> <p>Weight: 525 kg/m²</p> <p>temp. amplitude damping (1/TAV): 49,3</p> <p>phase shift: 8,5 h</p> <p>Heat storage capacity: 394 kJ/m²K</p> <p>insufficient excellent</p>
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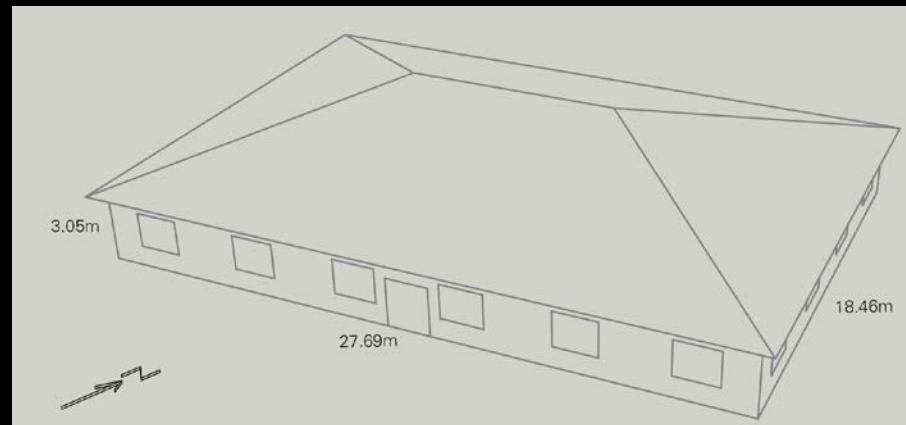
# U-Value Calculator in DIVA/Archsim



# Exercise: Conduction Heat Loss through the Walls of the DOE Small Office Building

What is the heat flow through the insulated wall, assuming an outside temperature of  $-5^{\circ}\text{C}$  and an inside temperature of  $22^{\circ}\text{C}$ ?

$$Q' = \sum UA \times (T_{\text{inside}} - T_{\text{outside}})$$



The U value of the wall is  $U_{\text{wall}} = 0.66 \text{ W/m}^2 \text{ K}$ ; the area is  $A = 225.7 \text{ m}^2$  and so

$$Q' = U_{\text{wall}} \times A \times (22^{\circ}\text{C} - (-5^{\circ}\text{C})) = 0.66 \text{ W/m}^2 \text{ K} \times 225.7 \text{ m}^2 \times 27 \text{ K} = 4 \text{ kW}$$

If this temperature difference remains over the course of an hour, the heat loss through the walls is 4 kWh. Note: For thermal simulations we usually consider temperature changes in one hour increments (using TMY files).



# Exercise: Conduction Heat Loss through the Walls of the DOE Small Office Building

Now consider all heat losses including the roof ( $U_{\text{Roof}} = 0.19 \text{ W/m}^2\text{K}$ ) and windows ( $U_{\text{Window}} = 3.24 \text{ W/m}^2\text{K}$ ). What is the heat flow through the envelope assuming an outside temperature of  $-5^\circ \text{C}$  and an inside temperature of  $22^\circ \text{C}$ ?

$$Q' = \sum UA \times (T_{\text{inside}} - T_{\text{outside}})$$

And so:

$$U_{\text{wall}} \times A \times (22^\circ \text{C} - (-5^\circ \text{C})) = 0.66 \text{ W/m}^2 \text{K} \times 225.7 \text{ m}^2 \times 27 \text{ K} = 4 \text{ kW}$$

$$U_{\text{Roof}} \times A \times (22^\circ \text{C} - (-5^\circ \text{C})) = 0.19 \text{ W/m}^2 \text{K} \times 511.1 \text{ m}^2 \times 27 \text{ K} = 2.6 \text{ kW}$$

$$U_{\text{Window}} \times A \times (22^\circ \text{C} - (-5^\circ \text{C})) = 3.24 \text{ W/m}^2 \text{K} \times 55.8 \text{ m}^2 \times 27 \text{ K} = 4.9 \text{ kW}$$

$$\sum UA = 11.5 \text{ kW}$$

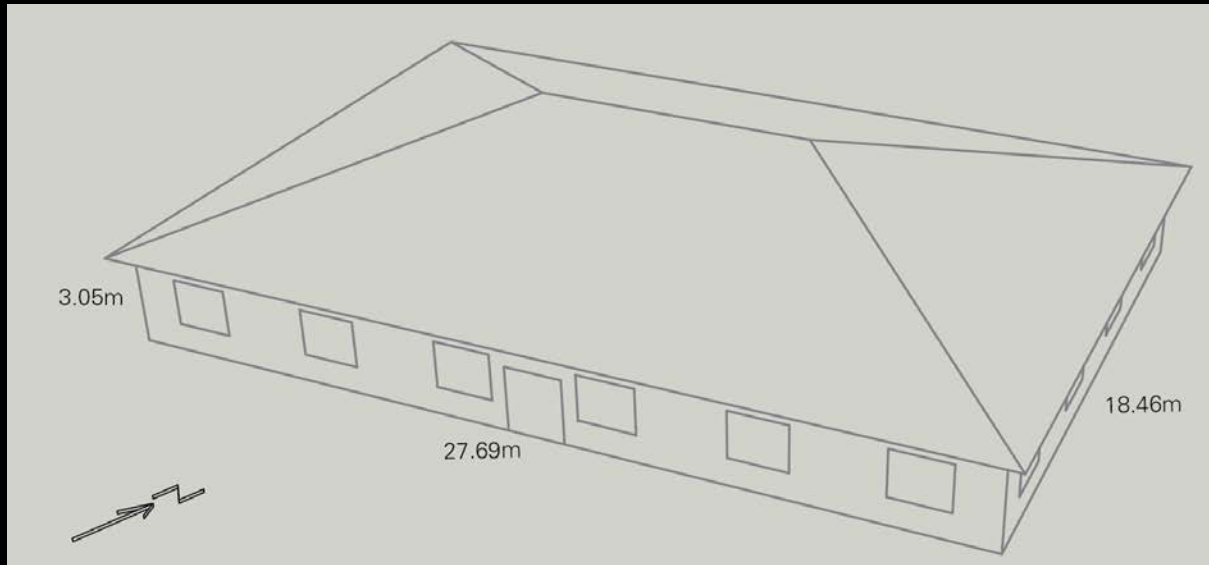
Note that the windows dominate even though their area is small.

# Slab-on-Grade Floors

The concept of the U value is only applicable in assemblies exposed to air on both sides. This includes floors above a crawl space. For other types of floors such as slab-on-grade, it has been found that heat flow scales roughly linearly with floor perimeter length. Accordingly, empirical heat flow coefficients are expressed in  $W/mK$ .

# Example Slab-on-Grade Floor

Assuming a an R-5 slab-on-grade floor for the DOE Small Office Building dimensions 27.69 m x 18.46 m and a heat flow coefficient ( $F_2$ ) of 1.21 W/m K.



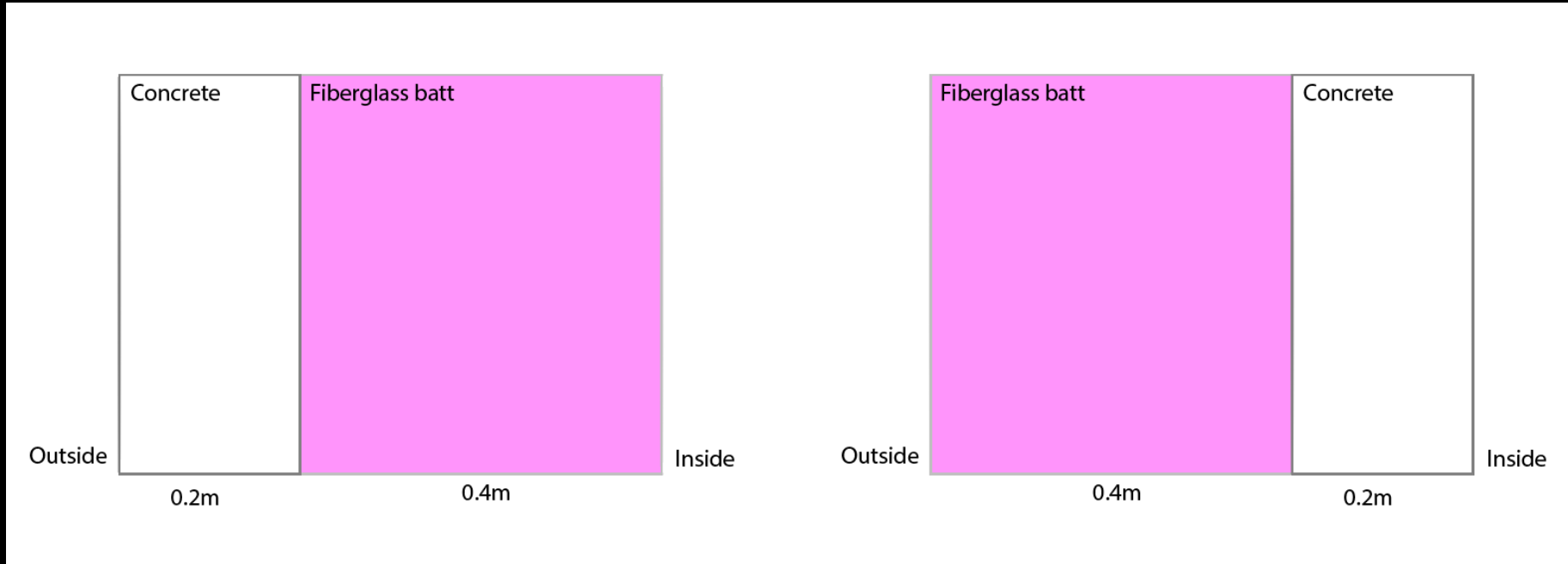
The heat flow is  $2 \times (27.69 \text{ m} + 18.46 \text{ m}) \times 1.21 \text{ W/m K} = 0.1 \text{ kW/K}$

$$\Sigma UA_{\text{Envelope}} = 11.5 \text{ kW} + 0.1 \text{ kW} = 11.6 \text{ kW}$$

*Should the insulation be  
inside or outside of the  
thermal mass/structure?*

# Concept of Active vs Passive Thermal Mass

- ❑ Only the thermal mass inside of the insulation is 'active', i.e. adds thermal inertia to a space.

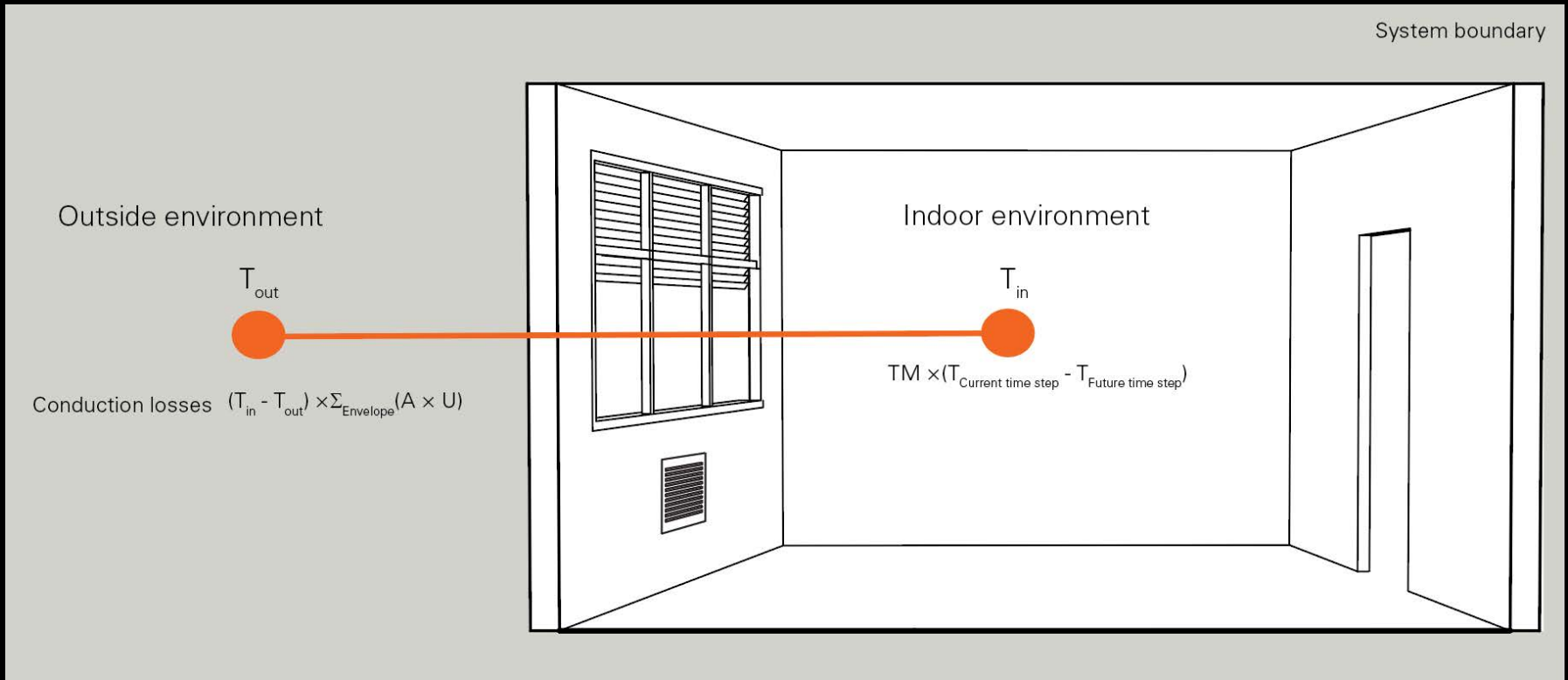


Passive thermal mass

Active thermal mass

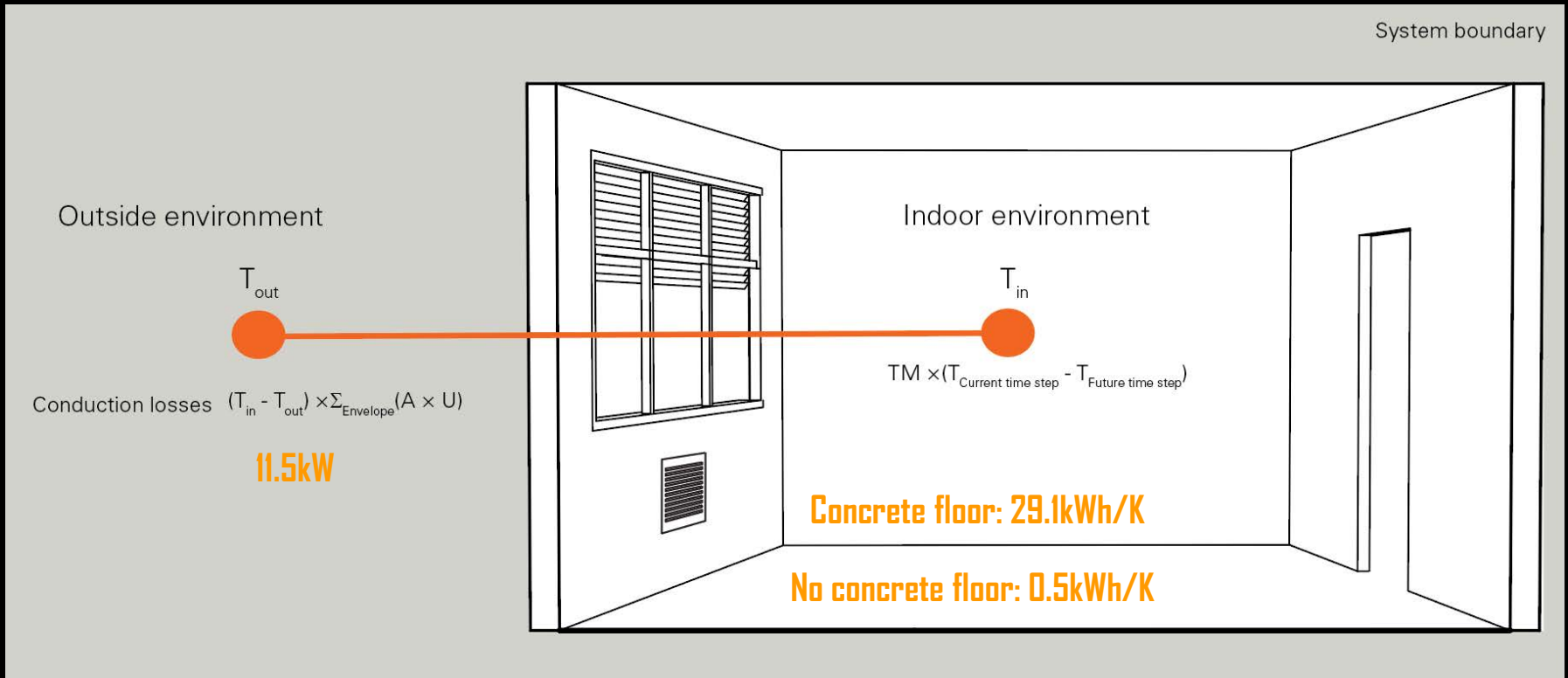
- ❑ Note, the insulation thickness is exaggerated.
- ❑ Note that inside air and insulation also add thermal inertia (albeit generally very little) to a space.

# Heat Balance Equation



Note that this equation only considers one-dimensional heat flow.

# Example - Resiliency



Q: Imagine that during a cold night the heating system in the DOE Small Office Building breaks. It is 22° C in the building and -5° C outside. How fast does the indoor temperature fall with and without the thermal mass floor if one ignores the thermal mass of the walls?

A: With concrete floor, the indoor temperature falls at 11.5 kW/29.1 kWh/K = 0.4 K/h. Without the thermal mass of the floor, the temperature is free-falling at 11.5 kW/0.5 kWh/K = 23 K/h.

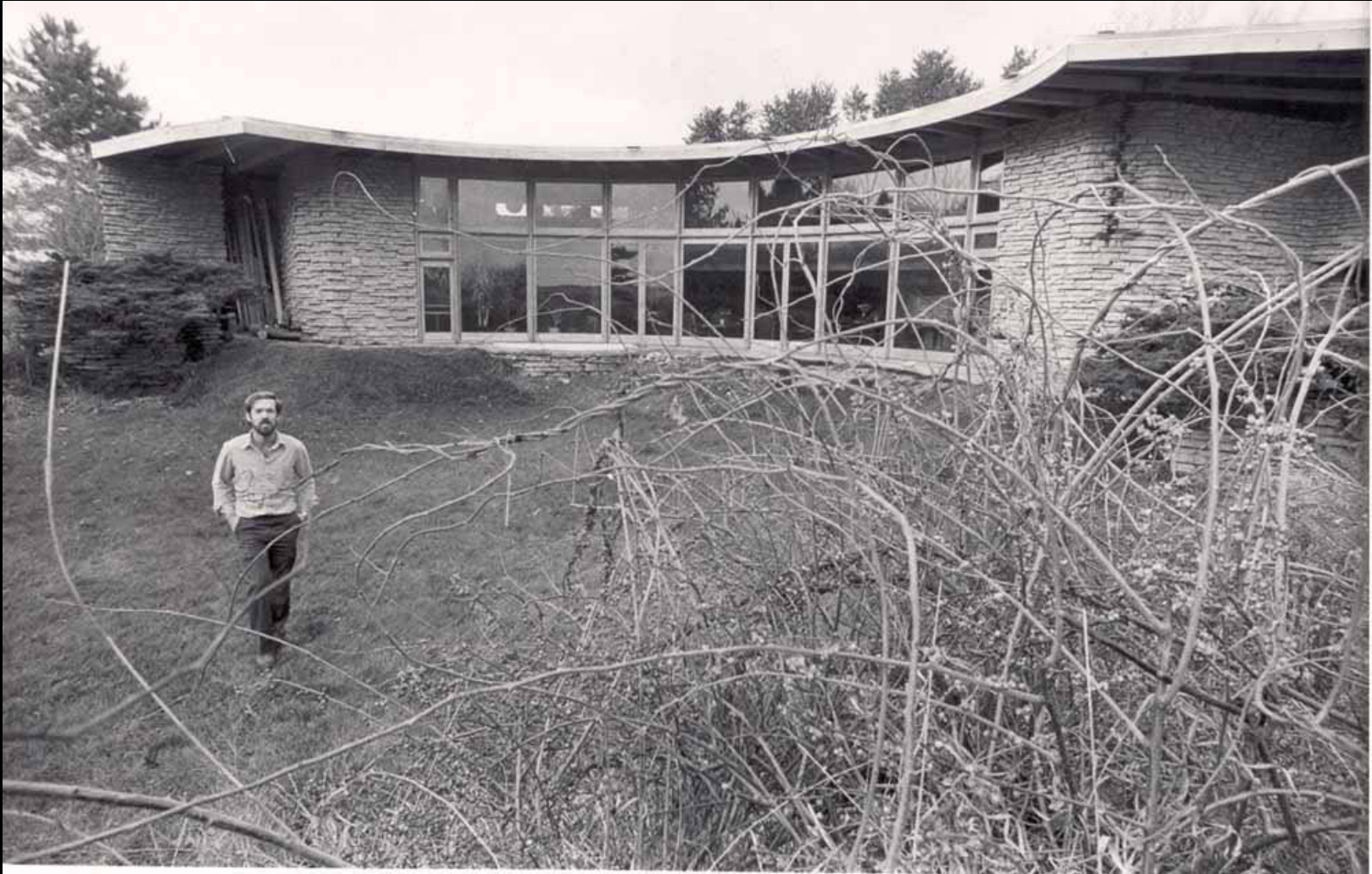
# Summary: Thermal Mass

- ❑ If the outside diurnal temperature swing frequently oscillates around a desired (balance point) temperature, adding thermal mass may increase the hours of comfort in a given time interval.
- ❑ Thermal mass may act as a liability to keep a space comfortable e.g. when it is only used intermittently.
- ❑ Thermal mass has really no effect if the direction of heat flow through the building envelope stays constant for extended periods of time.



# Applications

# Sunspaces with Thermal Mass



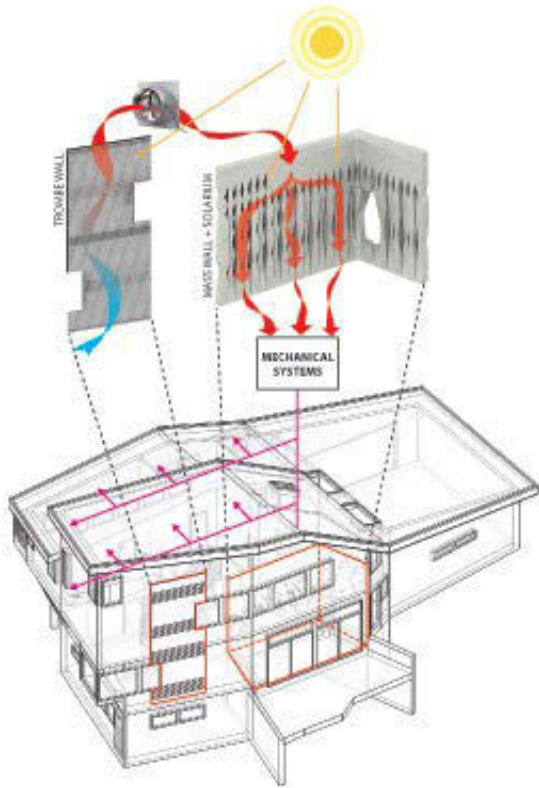
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# Sunspace with Thermal Mass



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# Solarium with Thermal Mass



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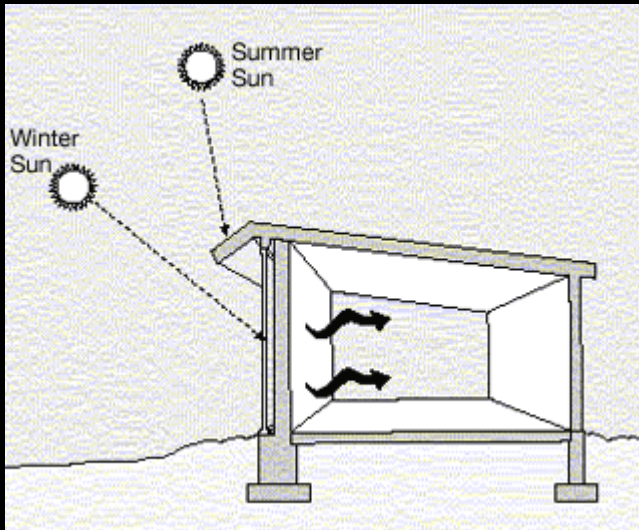
# Phase Change Material (PCM)

Image removed due to copyright restrictions.

<https://www.architectureanddesign.com.au/features/features-articles/the-state-of-phase-change-materials-in-australian>

- ❑ A 1.5-cm-thick PCM panel can have the equivalent thermal heat capacity of a 14-cm-thick concrete wall allowing for lightweight construction with high thermal mass.
- ❑ A key challenge when combined with nighttime flushing is hysteresis.

# Trombe Wall Example



Public domain image courtesy of Leonard P. on Wikipedia.



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Solar radiation incident on an opaque element. Heat is released into the space with a time delay. Most effective with shading.

# Questions?

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