



CPHD Exam:

Building Science Calculations Resource Handbook



Module 1:	Passive House Introduction	Page 3
Module 2:	Insulated Envelope	Page 6
Module 3:	Airtightness	Page 13
Module 4:	Thermal Bridging	Page 20
Module 5:	Windows	Page 24
Module 6:	Mechanical Ventilation	Page 31
Module 7:	Heating and DHW	Page 36
Module 8:	Economics	Page 38
	Key Criteria & Calculations	Page 44

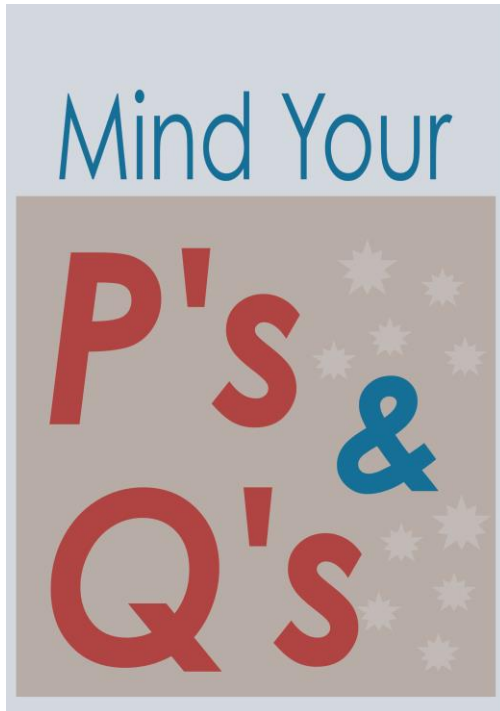
Introduction

- This resource booklet focuses mostly on the kinds of **calculation questions** that most frequently appear on the exam
- Don't forget there will also be lots of **'true-false' questions** to be answered – you can practice these on our online learning platform
- In addition, there will be a **Passive House design exercise** which you'll practice well in advance of the exam

Module 1: Passive House Introduction

Key Pointers for Module 1: Introduction

- Make sure you understand clearly the difference between (1) space heating demand and (2) heat load
- Learners often confuse these two concepts and answer the ‘wrong’ question



The letter **Q** (and *q*) are used for

YEARLY DEMAND

(both heating and cooling)

The letter **P** (and *p*) are used for

PEAK LOAD

(both heating and cooling)

*Capital Q and P are for whole building
Lower case q and p are used per square foot*

SPECIFIC DEMAND

'q'

Heating / Cooling Demand per ft²

This is the total amount of energy the building needs for the whole year for heating and cooling

The units are kBtu/(ft².yr)

Passive House's maximum for specific heating demand is 4.75 kBtu/(ft².yr)

4.75 kBtu/ft².yr X 1,000 ft² project = 4,750 kBtu/year or 4,750,000 Btu/year

There's 100,000 Btu in one therm of gas, so this equates to approximately **47.5** Therms of gas = **\$48** per year

Gas prices per Therm November 2014 for NYC = \$1.00

'p'

Heating / Cooling Load per ft²

This is the peak output needed for the heating / cooling system to achieve indoor temperatures in winter of 68°F and in summer of 77°F

The units are Btu/(hr.ft²)

Passive House's maximum for specific heating load = 3.17 Btu/(hr.ft²)

$$1,000 \text{ ft}^2 = 3,170 \text{ Btu/hr furnace}$$

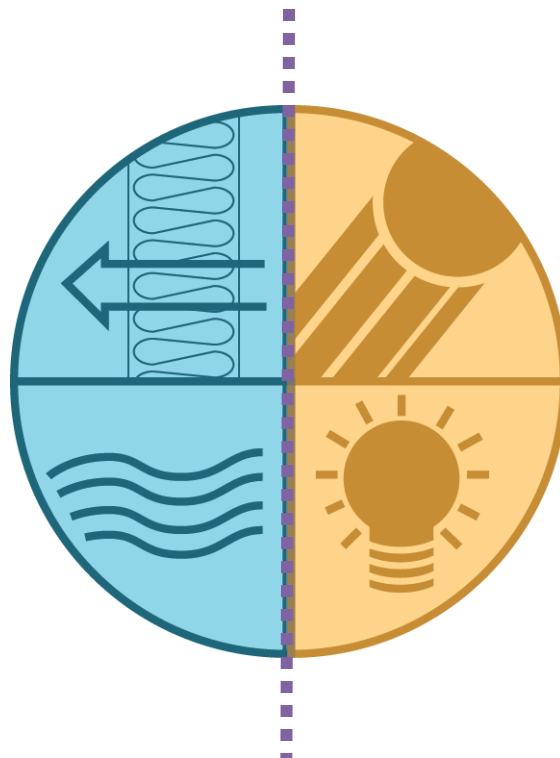
$$= 0.26 \text{ tons of cooling}$$

ANNUAL BUILDING HEATING AND COOLING 'ENERGY BALANCE'

Heat Losses

Transmission Losses ('T')
Insulation, window quality & thermal bridging

Ventilation Losses ('V')
Infiltration & heat recovery efficiency



Heat Gains

Solar Gains ('S')
Orientation, glazing spec and shading

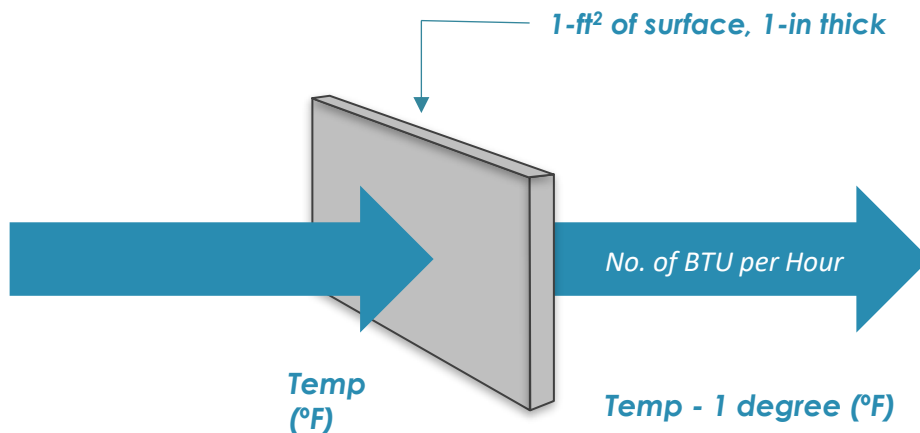
Internal Gains ('I')
Occupational uses & pattern

Module 2: Insulated Envelope

Key Pointers for Module 2: Insulated Envelope

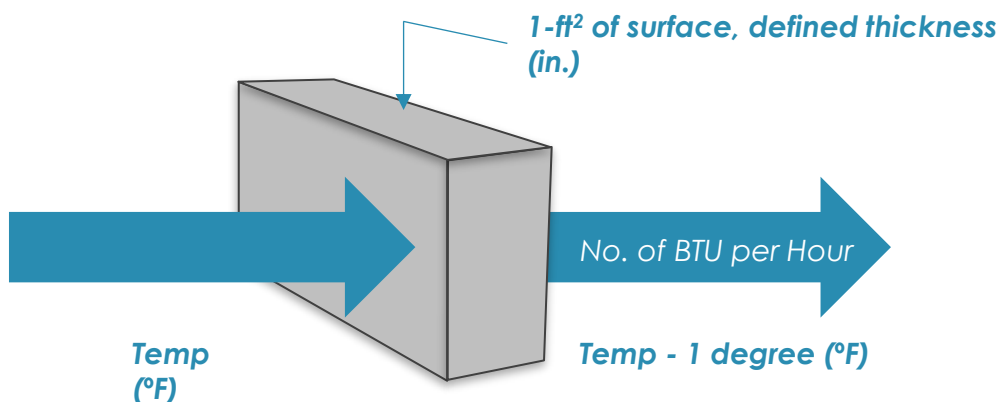
- Most common questions from Module 2 are (1) **R-value** calculations and (2) **transmission heat loss** calculations.
- Regarding R-value calculations, most common mistake is people forget to include the **surface film resistances**
- Regarding transmission loss calculation, people often confuse **'heating demand' versus 'heat load'**.
- **Tip:** for heating demand, use $k \cdot ^\circ\text{F} \cdot \text{hr}/\text{yr}$, for heat load, use temperature difference between inside and out

Thermal Conductivity (k) is a property of all materials. It is the rate of heat transfer through the material, measured in **Btu.in/(hr.ft². °F)**

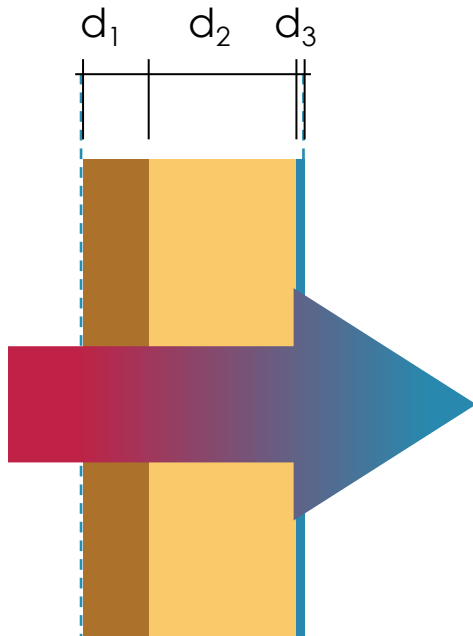


Thermal Resistivity (r) is the reciprocal of the conductivity
It is the ability of a material to resist heat transfer
(hr.ft². °F)/Btu.in (aka “R per inch”)

Thermal Conductance (C) is a property of an actual layer with a certain thickness. It is the rate of heat transfer through a specific thickness of a material, measured in **Btu/(hr.ft².°F)**



Thermal Resistance (R) is the reciprocal of the conductance.
It is the ability of a specific thickness of a material to resist heat transfer.
In construction we call this an **R-VALUE** which is measured in
(hr.ft². °F)/Btu.



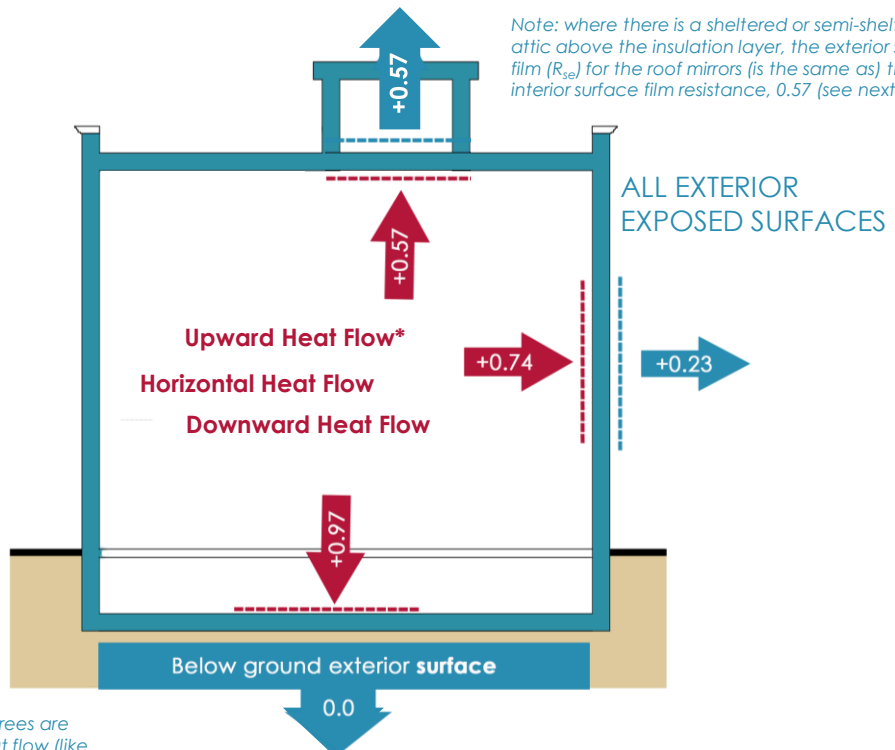
$$\begin{aligned}
 R_{\text{Total}} = & R_{\text{si}} \\
 & + (d_1 \times R_1) \\
 & + (d_2 \times R_2) \\
 & + (d_3 \times R_3) \\
 & + R_{\text{se}}
 \end{aligned}$$

R_{si} = interior surface film resistance
 R_{se} = exterior surface film resistance

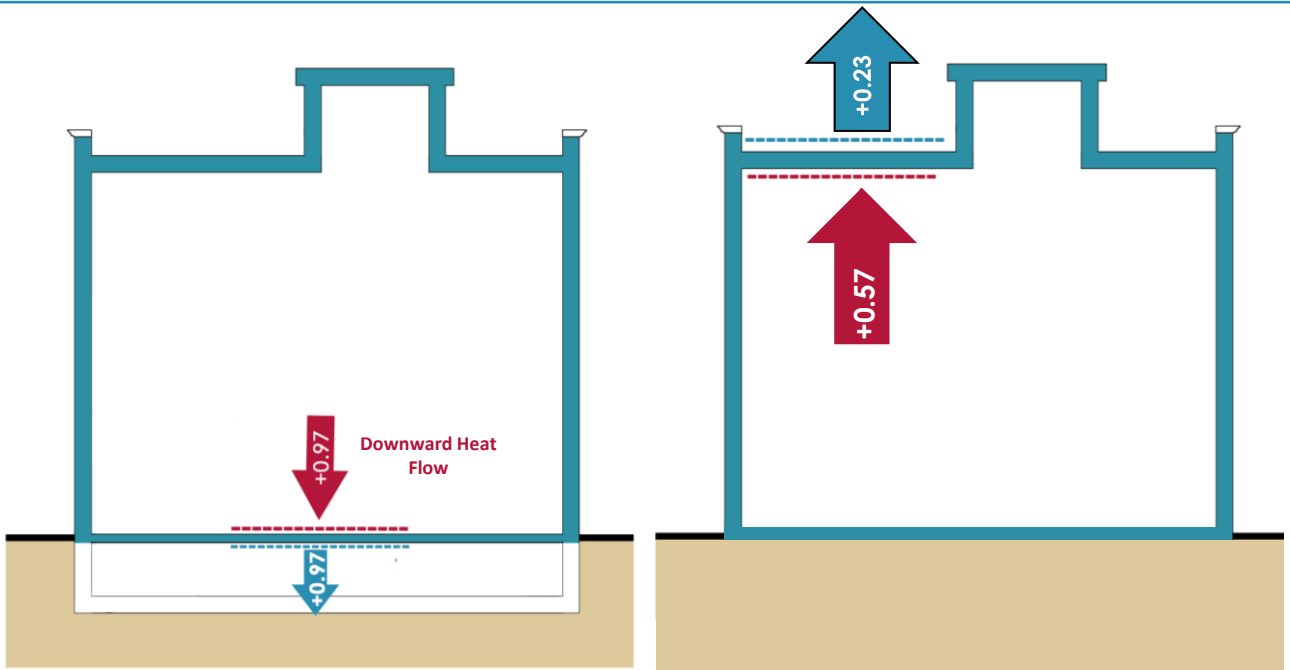
SURFACE FILM RESISTANCES: R_{SI} AND R_{SE}

Units:

hr.ft². °F/Btu



*Note: Ceilings over 60 degrees are considered 'horizontal' heat flow (like walls)



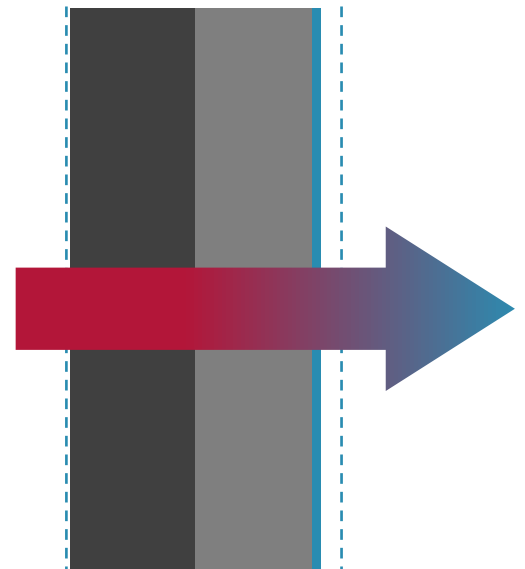
Un-Insulated basements
or crawlspaces.

Where there is no attic space, the
exterior surface film resistance is 0.57
(hr.ft².F)/Btu

R VALUE CALCULATION: EXAMPLE

Exercise: Calculate the **R-value** of the following wall construction.

- R_{si} (Thermal resistance of inner surface)
 - 0.74 (hr.ft².°F)/Btu
- Concrete Structure
 - 10 in thick
 - $r = 0.08$ (hr.ft².°F)/Btu.in
- Insulation
 - 12 in thick
 - $r = 4$ (hr.ft².°F)/Btu.in
- Plaster Finish
 - 0.5 in thick
 - $r = 0.2$ (hr.ft².°F)/Btu.in
- R_{se} (Thermal resistance of outer surface)
 - 0.23 (hr.ft². °F)/Btu



R_T = Total thermal resistance (hr.ft².°F)/Btu

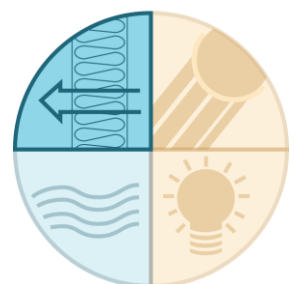
	Thickness (inches)	r per Inch (hr.ft ² .°F)/Btu.in	Total Resistance (hr.ft ² .°F)/Btu
R _{si} (Interior Horizontal Flow)	na	0.74 =	0.74
Layer 1 - Concrete Structure	10.00	× 0.08 =	0.80
Layer 2 - Insulation	12.00	× 4.00 =	48.00
Layer 3 - Plaster	0.50	× 0.20 =	0.10
R _{se} (Exterior)	na	0.23 =	0.23
			= 49.87

Total Resistance, (R-value): 49.87 (hr.ft².°F)/Btu

CALCULATING TRANSMISSION LOSSES

Transmission losses can occur through the following:

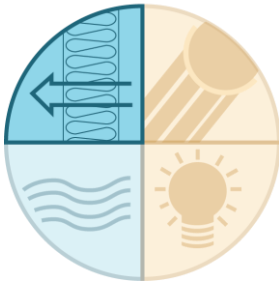
1. Opaque planar elements (R-value: area based) such as walls, floor and roof and window frames
2. Transparent planar elements (U-value: also area based, ie. glazing)
3. Linear thermal bridges (Psi-value: junctions between assemblies).
4. Point thermal bridges (Chi-value: point penetrations, façade clips...)



$$Q_T = A \times (1/R) \times f_t \times G_t$$

$$\text{kBtu/yr} = \cancel{\text{ft}^2} \times \frac{\text{Btu}}{\cancel{\text{hr}} \times \cancel{\text{ft}^2} \times \cancel{\text{°F}}} \times \cancel{\text{unitless}} \times \frac{(\cancel{\text{k}} \cdot \cancel{\text{F}} \cdot \cancel{\text{hr}})}{\text{yr}}$$

Q_T (Transmission Loss) = Area of the thermal envelope (ft²)
 ×
 1/R-Value (*U-Value*: Btu/hr.ft².°F)
 ×
 Temp. Correction Factor (if needed)
 ×
 Yearly Heating Degree Hours (k.°F.hr/yr)
 =kBtu/yr



$$Q_T = A \times (1/R) \times f_t \times G_t$$

For a wall in NYC ($G_t = 116 \text{ kF} \cdot \text{hr/yr}$) which is 10' x 40', with an R-Value of 40, what are the total yearly transmission losses?

$$Q_{T\text{-Wall}} = (10' \times 40') \times \frac{1}{40 \text{ hr.ft}^2 \cdot \text{°F/Btu}} \times 1 \times 116 \text{ k.°F.hr/yr}$$

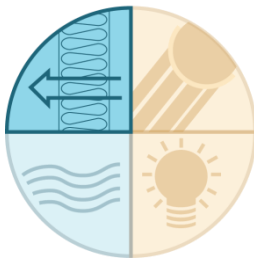
$$Q_{T\text{-Wall}} = 400 \text{ ft}^2 \times 0.025 \text{ Btu/hr.ft}^2 \cdot \text{°F} \times 1 \times 116 \text{ k.°F.hr/yr}$$

$$Q_{T\text{-Wall}} = 1,160 \text{ kBtu/yr}$$

For Peak Load, we use the peak daily average temperature difference (°F Inside-to-Outside)

$$P_T = A \times (1/R) \times f_t \times \Delta T_{1,2}$$

$\text{Btu/hr} = \cancel{\text{ft}^2} \times \frac{\text{Btu}}{(\text{hr } \cancel{\text{ft}^2} \cdot \cancel{\text{F}})} \times \text{unitless} \times \cancel{\text{F}}$



P_T (Transmission Loss) = Area of the thermal envelope
 ×
 1/R-Value (*U-Value*: Btu/hr.ft².°F)
 ×
 Temp. Correction Factor (1.0)*
 ×
 Temp Difference
 =Btu/hr

$$P_T = A \times (1/R) \times f_t \times \Delta T_{1,2}$$

For a wall in NYC which is 10' x 40', with an R-Value of 40, what is the heat load transmission losses for an external design temperature of 24°F (weather condition 2 – 'mild and cloudy')?

$$P_{T\text{-Wall}} = (10' \times 40') \times \frac{1}{40 \text{ hr.ft}^2 \cdot \text{°F/Btu}} \times 1 \times (68\text{°F} - 24\text{°F})$$

$$P_{T\text{-Wall}} = 400 \text{ ft}^2 \times 0.025 \text{ Btu/hr.ft}^2 \cdot \text{°F} \times 1 \times 44\text{°F}$$

$$P_{T\text{-Wall}} = 440 \text{ Btu/hr}$$

Module 3: Airtightness

Key Pointers for Module 3: Airtightness

- There's normally **a few calculation-type questions** and lots of true-false questions on the topic of airtightness
- These questions can be relatively 'easy', such as working out the '**n₅₀**' (air changes per hour), or more complex, such as the **infiltration losses**
- Might be presented with **airtightness test results form** for review. Usually, there will be some key data missing from the sheet and the n50 number will be incorrectly calculated

n_{50} (air-change rate)

= Air changes / hr

 w_{50} (specific leakage rate)= Cubic feet / hr.ft² of floor area **q_{50}** (air-permeability)= Cubic feet / hr.ft² of external surface area **V_{n50} , V_{50} and V_v** **V_{n50} : Tested (Internal) Volume**

In the EN13829 standard, the internal air volume is given as follows:

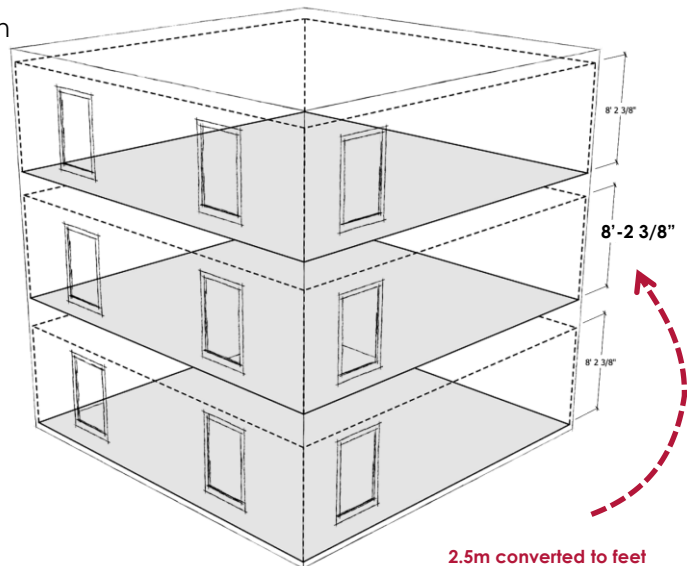
The internal volume, V_{n50} , is the volume of air inside the measured building or part of building. The internal volume is calculated by multiplying the net floor area with the actual net ceiling height. The volume of furniture is not subtracted.

 V_{50} : Tested Air Flow Rate at 50 Pa:

This is the air flow rate (CFM) which passes through the blower door at a pressure difference of 50 Pa between inside and outside.

 V_v : Ventilated Volume

For residential buildings, in order to better compare the different air exchange rates in dwellings, multiply the TFA by a standard 8.2ft to calculate the Ventilated Volume. For Non-residential buildings, use the actual ceiling height.



(EN13289:2001)

BlowerDoor-Test Result														
According to EN 13829, Method A [ISO 9972]														
Minneapolis BlowerDoor Modell 4 - Tectite Express 3.6.7.0														
Object:						Technician:								
Date:						Date:								
Climate data														
Interior Temperature: 57 F			wind force: 1			Test points referential pressure: 1			Site category: B					
Exterior Temperature: 63 F			Additional measuring uncertainty due to wind: 0%			Barometric pressure: 100149 Pa			Additional measuring uncertainty due to wind: 0%					
Underpressure						Overpressure								
Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}	Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}	Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,2 Pa	-0,1 Pa	0,3 Pa	-0,7 Pa	1,1 Pa	0,7 Pa	-	-	1,1 Pa	-	0,7 Pa	-	-	1,1 Pa	-
Series of measurement														
Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation	Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation	Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation
o ABCDE	[Pa]	[Pa]	[CFM]	[%]	o ABCDE	[Pa]	[Pa]	[CFM]	[%]	o ABCDE	[Pa]	[Pa]	[CFM]	[%]
Δp_{01}					Δp_{01}					Δp_{01}				
A	-69	55	1174	0.34	A	71	62	1236	-0.99	A	71	62	1236	-0.99
A	-66	52	1138	-0.40	A	65	56	1180	-0.41	A	65	56	1180	-0.41
A	-62	47	1086	-0.61	A	60	52	1134	-0.45	A	60	52	1134	-0.45
A	-55	42	1020	-0.93	A	56	49	1099	1.87	A	56	49	1099	1.87
A	-49	37	965	0.39	A	50	41	1009	0.26	A	50	41	1009	0.26
A	-44	34	918	0.93	A	46	36	950	-0.61	A	46	36	950	-0.61
A	-40	29	850	-0.51	A	41	31	884	-0.54	A	41	31	884	-0.54
Results														
V = 8900 l/s				A ₁ = 9740 l/s				A ₂ = 23840 l/s						
V ₅₀	Uncertainty	R ₅₀	Uncertainty	W ₅₀	Uncertainty	Q ₅₀	Uncertainty							
977	± 9%	0.65	± 6%	6.0	0.75	2.5	± 6%							
Underpressure														
Overpressure														
Average	996	± 5%	0.66	± 6%	6.1	0.75	2.5	± 6%						
Requirement according to project specific: 0.6 l/s, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0														
The requirements are not met.														
Note: The result does not guarantee the absence of (hidden) faults in the building envelope.														
contractor:														
Date, Signature: Stamp														

Climate data

Interior Temperature: 57 F	Test points referential pressure: 1
Exterior Temperature: 63 F	wind force: 1
Barometric pressure: 100149 Pa	Site category: B
	Additional measuring uncertainty due to wind: 0%

Underpressure

Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,2 Pa	-0,1 Pa	0,3 Pa	-0,7 Pa	1,1 Pa

Overpressure

Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,7 Pa	-	-	1,1 Pa	-

- Weather data at the time of the test must be recorded
- Differential pressure between the interior and exterior **without** fan operation must be recorded before and after (total of 4 baseline pressure readings)
- Minimum 30 second positive and 30 second negative values
- Average values **> 5 Pa** do **not conform to the standard**

AIRTIGHTNESS TEST REPORT: MULTIPLE POSITIVE AND NEGATIVE MEASUREMENTS

BlowerDoor-Test Result														
According to EN 13829, Method A [ISO 9972]														
Minneapolis BlowerDoor Modell 4 - Tectite Express 3.6.7.0														
Object:						Technician:								
Date:						Date:								
Climate data														
Interior Temperature: 57 F			wind force: 1			Test points referential pressure: 1			Site category: B					
Exterior Temperature: 63 F			Additional measuring uncertainty due to wind: 0%			Barometric pressure: 100149 Pa			Additional measuring uncertainty due to wind: 0%					
Underpressure						Overpressure								
Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}	Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}	Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,2 Pa	-0,1 Pa	0,3 Pa	-0,7 Pa	1,1 Pa	0,7 Pa	-	-	1,1 Pa	-	0,7 Pa	-	-	1,1 Pa	-
Series of measurement														
Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation	Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation	Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation
o ABCDE	[Pa]	[Pa]	[CFM]	[%]	o ABCDE	[Pa]	[Pa]	[CFM]	[%]	o ABCDE	[Pa]	[Pa]	[CFM]	[%]
Δp_{01}					Δp_{01}					Δp_{01}				
A	-69	55	1174	0.34	A	71	62	1236	-0.99	A	71	62	1236	-0.99
A	-66	52	1138	-0.40	A	65	56	1180	-0.41	A	65	56	1180	-0.41
A	-62	47	1086	-0.61	A	60	52	1134	-0.45	A	60	52	1134	-0.45
A	-55	42	1020	-0.93	A	56	49	1099	1.87	A	56	49	1099	1.87
A	-49	37	965	0.39	A	50	41	1009	0.26	A	50	41	1009	0.26
A	-44	34	918	0.93	A	46	36	950	-0.61	A	46	36	950	-0.61
A	-40	29	850	-0.51	A	41	31	884	-0.54	A	41	31	884	-0.54
Results														
V = 8900 l/s				A ₁ = 9740 l/s				A ₂ = 23840 l/s						
V ₅₀	Uncertainty	R ₅₀	Uncertainty	W ₅₀	Uncertainty	Q ₅₀	Uncertainty							
977	± 9%	0.65	± 6%	6.0	0.75	2.5	± 6%							
Underpressure														
Overpressure														
Average	996	± 5%	0.66	± 6%	6.1	0.75	2.5	± 6%						
Requirement according to project specific: 0.6 l/s, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 1.0														
The requirements are not met.														
Note: The result does not guarantee the absence of (hidden) faults in the building envelope.														
contractor:														
Date, Signature: Stamp														

Underpressure

Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,2 Pa	-0,1 Pa	0,3 Pa	-0,7 Pa	1,1 Pa

Overpressure

Natural Pressure	Δp_{01+}	Δp_{01-}	Δp_{02+}	Δp_{02-}
0,7 Pa	-	-	1,1 Pa	-

Series of measurement

Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation	Flow ring	Building pressure	Fan pressure	Flow V _r	Deviation
o ABCDE	[Pa]	[Pa]	[CFM]	[%]	o ABCDE	[Pa]	[Pa]	[CFM]	[%]
Δp_{01}					Δp_{01}				
A	-69	55	1174	0.34	A	71	62	1236	-0.99
A	-66	52	1138	-0.40	A	65	56	1180	-0.41
A	-62	47	1086	-0.61	A	60	52	1134	-0.45
A	-55	42	1020	-0.93	A	56	49	1099	1.87
A	-49	37	965	0.39	A	50	41	1009	0.26
A	-44	34	918	0.93	A	46	36	950	-0.61
A	-40	29	850	-0.51	A	41	31	884	-0.54
Δp_{02}					Δp_{02}				

- Underpressure and Overpressure tests are required (positive and negative)
- At least 5 measurements points required for both tests
- Even spacing of reading points - approximately 10 Pa
- Analyze under- and overpressure results and normalize for 50 Pa pressure difference

BlowerDoor-Test Result									
According to EN 13829, Method A [ISO 9972]									
Minneapolis BlowerDoor Modell 4 - Tecitile Express 3.6.7.0									
Object:					Technician:				
Date:					Date:				
Climate data									
Interior Temperature: 57 F		Exterior Temperature: 63 F		Wind force: 1		Test points reference pressure: 1		Site category: B	
Barometric pressure: 1007.9 Pa		Additional measuring uncertainty due to wind: 0%							
Underpressure					Overpressure				
Natural	ΔP ₅₀	ΔP ₁₀	ΔP ₅	ΔP ₂	Natural	ΔP ₅₀	ΔP ₁₀	ΔP ₅	ΔP ₂
Pressure	0.2 Pa	-0.1 Pa	-0.3 Pa	-0.7 Pa	Pressure	0.7 Pa	1.1 Pa	1.1 Pa	-
Series of measurement									
Flow ring	Building pressure	Fan pressure	Flow V ₅₀	Deviation	Flow ring	Building pressure	Fan pressure	Flow V ₅₀	Deviation
direction	Pa	Pa	m³/h	%	direction	Pa	Pa	m³/h	%
ΔP ₅₀					ΔP ₅₀				
A	49	55	1174	0.34	A	71	62	1293	-0.99
A	66	52	1138	0.40	A	65	56	1180	-0.41
A	62	47	1086	-0.61	A	60	52	1134	0.46
A	55	42	1000	-0.93	A	56	49	1059	-1.87
A	49	37	965	-0.39	A	50	41	1009	0.26
A	44	34	918	-0.93	A	46	36	950	-0.61
A	40	29	850	-0.51	A	41	31	884	-0.54
ΔP ₁₀					ΔP ₁₀				
operator coeff. r:	0.088	confidence interval (95%):			operator coeff. r:	0.097	confidence interval (95%):		
C ₅₀ [(l/min Pa²)]	108	max. 113	min. 103		C ₅₀ [(l/min Pa²)]	95	max. 100	min. 90	
C ₁₀ [(l/min Pa²)]	108	max. 113	min. 103		C ₁₀ [(l/min Pa²)]	95	max. 100	min. 90	
B	11	max. 0.60	min. 0.53		B	11	max. 1	min. 0.95	
Results									
	V ₅₀	Uncertainty	n ₅₀	Uncertainty	W ₅₀	Uncertainty	q ₅₀	Uncertainty	
Underpressure	977	+/- 5%	0.65	+/- 6%	6.0	0.75	2.5	+/- 6%	
Overpressure	1015	+/- 5%	0.69	+/- 6%	6.3	0.78	2.6	+/- 6%	
Average	996	+/- 5%	0.66	+/- 6%	6.1	0.76	2.5	+/- 6%	
Requirement according to project specific	0.6		1/h		***		***		
The requirements are not met.									
Note: The result does not guarantee the absence of (hidden) faults in the building envelope.									
contractor									
Date, Signature									
Stamp									

Results								
	V =	89900 ft³	A _F =	9740 ft²	A _E =	23840 ft²		
	V ₅₀	Uncertainty	n ₅₀	Uncertainty	W ₅₀	Uncertainty	q ₅₀	Uncertainty
	CFM	%	h ⁻¹	%	ft³/h	%	ft³/h	%
Underpressure	977	+/- 5%	0.65	+/- 6%	6.0	0.75	2.5	+/- 6%
Overpressure	1015	+/- 5%	0.69	+/- 6%	6.3	0.78	2.6	+/- 6%
Average	996	+/- 5%	0.66	+/- 6%	6.1	0.76	2.5	+/- 6%
Requirement according to project specific	0.6		1/h		***		***	

$$n_{50} = (V_{50} \times 60 \text{ minutes/hour}) \div V_{n50}$$

$$n_{50} = (996 \text{ CFM} \times 60 \text{ minutes/hour}) \div 89,000 \text{ ft}^3$$

$$n_{50} = 0.66 \text{ 1/h}$$

Uncertainty of measurement ("accuracy"):

Includes uncertainties arising from pressure gauges, influence of wind and volume determination

Total uncertainty of measurement is **not** allocated to results

Calm weather: **less than ± 15 %**

Windy weather: **> 40 %**

EXAMPLE: CALCULATE N₅₀

In a Passive House with a net air volume (V_{n50}) of **17,658 ft³**, an air flow rate of **247 CFM** was determined with a differential pressure measurement at 50 Pa.

Was the requirement for Passive Houses of **n₅₀ < 0.6 ACH** met?

$$n_{50} = \frac{V_{50} \times 60 \text{ min/hr}}{V_{n50}}$$

Unit Conversion Factor

$$n_{50} = \frac{247 \text{ CFM} \times 60 \text{ min/hr}}{17,658 \text{ ft}^3} = 0.84 \text{ ACH50}$$

0.84 ACH50 > 0.6 ACH50 = NO!

Please calculate:

You are working on a Passive House project with a TFA of 1,100ft². Prior to considering infiltration losses, the space heating demand is 4.2 kBtu/ft².year. Will it be possible to certify the project based on the following airtightness result: $V_{n50} = 10,500\text{ft}^3$, resting pressure losses, $e = 0.07$, $n_{50} = 0.6 \text{ 1/h}$ & heating degree hours 116 kFh/year

Solution:

$Q_{V\text{-rest}} = 10,500\text{ft}^3 \times 0.07 \times 0.6 \text{ 1/h} \times 0.018 \text{ Btu/ft}^3\cdot\text{F} \times 116 \text{ kFh/year} = 921.8 \text{ kBtu/year} \div \text{TFA } 1,100\text{ft}^2 = 0.84 \text{ kBtu/ft}^2\cdot\text{year}.$

Existing heating demand of 4.2 kBtu/year + resting infiltration losses of 0.84 kBtu/ft².year = 5.04 kBtu/year. Cannot be certified!

$$P_{V\text{-Infil}} = V_{n50} \times e \times 2.5 \times n_{50} \times C_{\text{air}} \times \Delta T_{1,2}$$

- V_{n50} = airtightness test volume: ft³
- e = fraction of air changes per hour at resting atmospheric pressure (value of 0.07 (=7%) commonly used): unitless
- 2.5 = safety factor used for heat load to ensure building can be heated in windy weather: unitless
- n_{50} = airtightness test result @ 50 Pascal: 1/h or h⁻¹
- C_{air} = Heat carrying capacity of air: a constant: 0.018 Btu/ft³ °F
- $\Delta T_{1,2}$ = Temperature difference between inside (always 68°F) and outside in Weather Condition 1 (cold and sunny) and 2 (mild and cloudy): °F

Module 4: Thermal Bridging

Key Pointers for Module 4: Thermal Bridging

- There's normally **a few calculation-type questions** and true-false questions on the topic of thermal bridging
- You might be asked about the impact of either **linear** thermal bridges or **point** thermal bridges
- Normally the question will seek to find out what is the **impact of improving thermal bridge coefficients** (on either heating demand or heat load)

Linear thermal bridges

- Found at connections between different planes of the envelope (example, wall to roof)
- The magnitude of a linear thermal bridge is determined by its 'Psi Value', denoted by Ψ_e , measured in Btu/hr.ft.°F

Point thermal bridges

- Found at point penetrations of the envelope (example, wall ties through insulation layer)
- The magnitude of a point thermal bridge is determined by its 'Chi Value', denoted by χ , typically reported in Btu/hr.°F

CALCULATING LOSSES VIA LINEAR THERMAL BRIDGES

$$Q_{T-tb} = L \times \Psi \times f_t \times G_t$$

$\text{kBtu/yr} = \cancel{\text{ft}} \times \frac{\text{Btu}}{\cancel{\text{hr}} \times \cancel{\text{ft}} \times \cancel{\text{°F}}} \times \cancel{\text{unitless}} \times \frac{\text{(k.} \cancel{\text{°F}} \cdot \cancel{\text{hr}})}{\text{yr}}$

Transmission Losses due to linear thermal bridges =

Length of the Thermal Bridge
 ×
 PSI-Value (Ψ)
 ×
 Temp. Correction Factor (if needed)
 ×
 Yearly Heating Degree Hours (G_t)

=kBtu/yr

$$Q_{T-tb} = L \times \Psi \times f_t \times G_t$$

EXAMPLE: A proposed balcony connection detail on a NYC building ($G_t = 117$ kFh/yr) has been simulated to have a Psi value of 0.06 Btu/hr·ft·°F. For a 7-story building with 23 feet of balcony per floor, what is the yearly heat loss due to this Linear Thermal Bridge?

$$Q_{T-tb} = (7 \times 23') \times 0.06 \text{ Btu/hr.ft.}^\circ\text{F} \times 1.0 \times 117 \text{ kFh/yr}$$

$$Q_{T-tb} = 161 \text{ ft} \times 0.06 \text{ Btu/hr.ft.}^\circ\text{F} \times 1.0 \times 117 \text{ kFh/yr}$$

$$Q_{T-tb} = 1,130.22 \text{ kBtu/yr}$$

$$Q_{T-tb} = n \times \chi \times f_t \times G_t$$

$$\text{kBtu/yr} = \frac{\text{Btu}}{\text{hr} \cdot ^\circ\text{F}} \times \text{unitless} \times \frac{\text{k} \cdot ^\circ\text{F} \cdot \text{hr}}{\text{yr}}$$

Transmission Losses due to thermal bridge

$$Q_{T-tb} = \begin{aligned} &\text{Number of point thermal bridges} \\ &\times \\ &\text{CHI-Value (Btu/hr.}^\circ\text{F)} \\ &\times \\ &\text{Temp. Correction Factor (if needed)} \\ &\times \\ &\text{Yearly Heating Degree Hours (k.}^\circ\text{F.hr/yr)} \\ &= \text{kBtu/yr} \end{aligned}$$

$$Q_{T-tb} = n \times \chi \times f_t \times G_t$$

EXAMPLE: A proposed structural column detail on a NYC building ($G_t = 117$ kFh/yr) has been simulated to have a CHI value of 0.18 Btu/hr.°F. For a building with 17 columns at its base, what is the yearly heat loss due to this Point Thermal Bridge?

$$Q_{T-tb} = 17 \text{ columns} \times 0.18 \text{ Btu/hr.}^\circ\text{F} \times 1.0 \times 117 \text{ kFh/yr}$$

$$Q_{T-tb} = 358.02 \text{ kBtu/yr}$$

Module 5: Windows

Key Pointers for Module 5: Windows

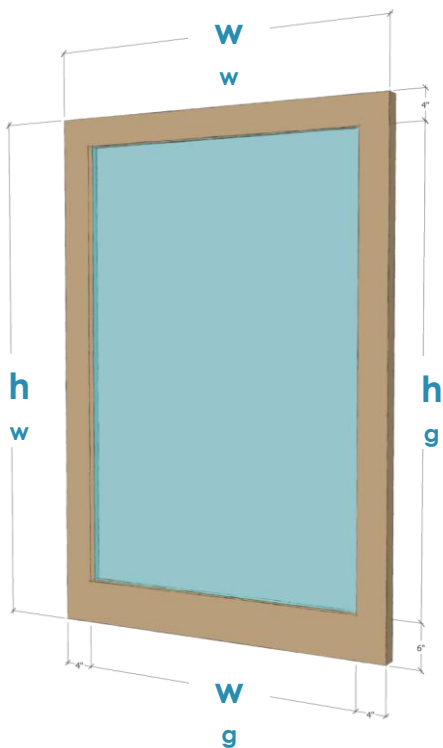
- Normally **a few calculation-type questions** and true-false questions on the topic of windows
- Often asked to calculate **overall window U-value** – key pitfall is measuring areas & lengths (*make sure to draw a sketch of the window and frame thicknesses on your rough-work*)
- Might have to calculate **energy balance of a window** (differences between losses & gains)
- Sometimes presented with **‘spurious’ solar gains data** but not asked to calculate solar gains – don’t waste time answering wrong question!

$$U_w = \frac{(U_g \times A_{glass}) + (U_f \times A_{frame}) + (\Psi_{spacer} \times L_{spacer})}{A_{window}}$$

$$U_{w-installed} = \frac{(U_g \times A_{glass}) + (U_f \times A_{frame}) + (\Psi_{spacer} \times L_{spacer}) + (\Psi_{install} \times L_{install})}{A_{window}}$$

The addition of the Psi-Install (calculated separately) is used to calculate the $U_{W-INSTALLED}$

CALCULATE $U_{W-INSTALLED}$



Window Measurements:

Width (to outside of frame): 4'-0"

Height (to outside of frame): 6'-0"

Frame Width (top, 2 sides): 4"

Frame Width (bottom): 6"

$U_g = 0.08 \text{ Btu/hr-ft}^2\text{-F}$

$U_f = 0.11 \text{ Btu/hr-ft}^2\text{-F}$

$\Psi_{spacer} = 0.06 \text{ Btu/hr-ft-F}$

$\Psi_{install} = -0.01 \text{ Btu/hr-ft-F}$

Tip on calculation of areas and lengths:

1. Draw a small sketch of window with all its dimensions
2. First calculate A_w , then A_g . Then subtract A_g from A_w to calculate A_f

$$U_{w\text{-installed}} = \frac{(U_g \times A_{\text{glass}}) + (U_f \times A_{\text{frame}}) + (\Psi_{\text{spacer}} \times L_{\text{spacer}}) + (\Psi_{\text{install}} \times L_{\text{install}})}{A_{\text{window}}}$$

$$A_{\text{win}} = w_w \times h_w = 4'-0'' \times 6'-0'' = 24 \text{ ft}^2$$

$$A_{\text{glass}} = w_g \times h_g = 3'-4'' \times 5'-2'' = 17.2 \text{ ft}^2$$

$$A_{\text{frame}} = A_{\text{win}} - A_{\text{glass}} = 24 \text{ ft}^2 - 17.2 \text{ ft}^2 = 6.8 \text{ ft}^2$$

$$L_{\text{spacer}} = 2 w_g + 2 h_g = 2 \times 3'-4'' + (2 \times 5'-2'') = 17'-0''$$

$$L_{\text{installation}} = 2 w_w + 2 h_w = 2 \times 4'-0'' + (2 \times 6'-0'') = 20'-0''$$

CALCULATING $U_{W\text{-INSTALLED}}$

$$U_{w\text{-installed}} = \frac{(U_g \times A_{\text{glass}}) + (U_f \times A_{\text{frame}}) + (\Psi_{\text{spacer}} \times L_{\text{spacer}}) + (\Psi_{\text{installed}} \times L_{\text{installed}})}{A_{\text{window}}}$$

$$U_{w\text{-installed}} = \frac{0.08 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}) \times 17.2 \text{ ft}^2 + 0.11 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}) \times 6.8 \text{ ft}^2 + 0.06 \text{ Btu}/(\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}) \times 17'-0'' + -0.01 \text{ Btu}/(\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}) \times 20'-0''}{24 \text{ ft}^2}$$

$$U_{w\text{-installed}} = 0.123 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F})$$

$$Q_s = r \times SHGC \times A_w \times G_{N,E,S,W}$$

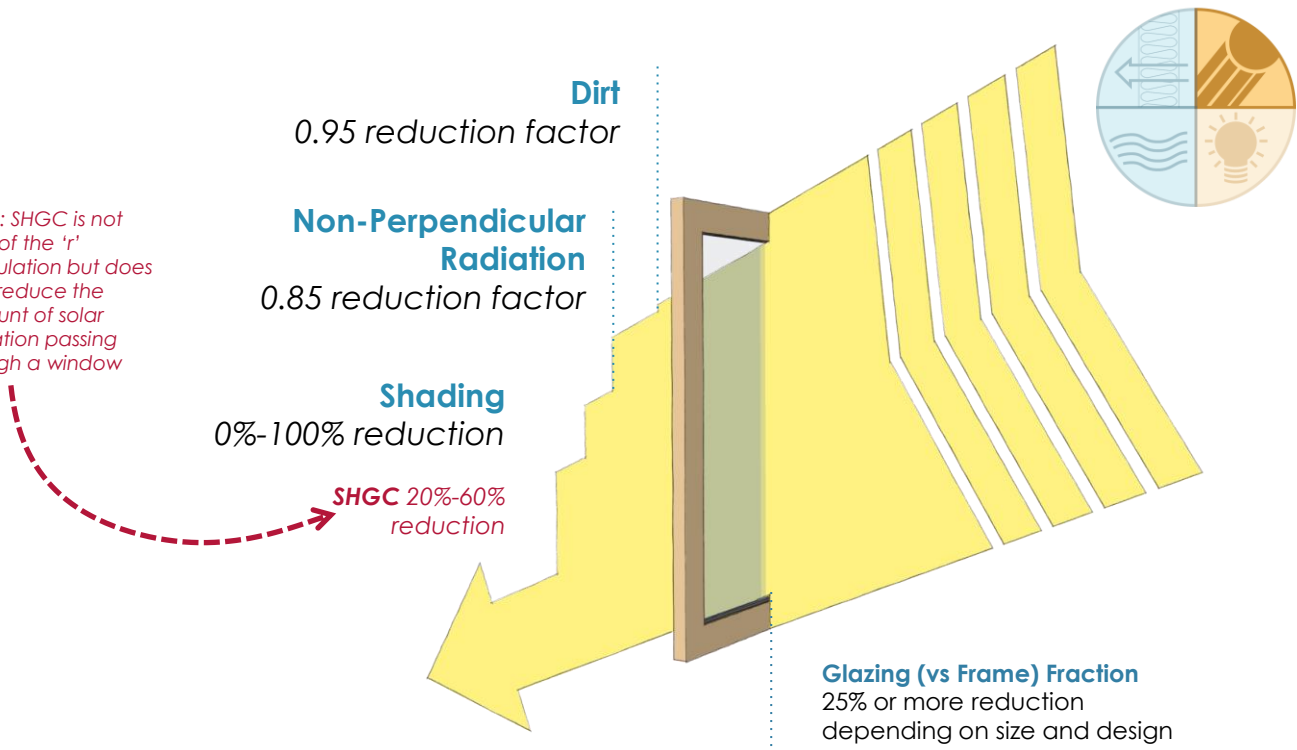
r = Shading Factor × Dirt Factor × Non-Perp. Rad. Factor × Glazing Factor

Q_s (Solar Heat Gains) = Reduction Factor (unitless)
 × Solar Heat Gain Coefficient (unitless)
 × Gross area of the window (ft²)
 × Global Radiation (kBtu/ft².yr)
 =kBtu/yr



HEAT GAIN: 4 REDUCTION FACTORS + SHGC

Note: SHGC is not part of the 'r' calculation but does also reduce the amount of solar radiation passing through a window



$$r = \text{Dirt} \times \text{Non-Perp. Radiation} \times \text{Shading} \times \text{Glazing-fraction}$$

$$Q_S = r \times SHGC \times A_w \times G_{N,E,S,W}$$

$$Q_T = A \times (1/R) \times f_t \times G_t$$

EXAMPLE:

Calculate the overall yearly net energy balance for a south-facing window with the following characteristics:

NYC G_t	117 kWh/yr	SHGC	0.6
Width	3'-6"	R_{Glass}	9.0
Height	6'-0"	R_{Frame}	6.5
Frame Width (Bottom)	5-1/2"	G_{south}	177 kBtu/ft ² .yr
Frame Width (Side +Top)	3"	Spacer Length	16.583'
Shading Factor	0.67	Ψ_{spacer}	0.06 Btu/hr.ft.°F
Glazing Factor	0.76	$\Psi_{install}$	-0.04 Btu/hr.ft.°F

$$Q_S = r \times SHGC \times A_w \times G_{N,E,S,W}$$



Reminder: these two reduction factors are constants and pertain to dirt and non-perpendicular radiation respectively

$$Q_S = (0.67 \times 0.95 \times 0.85 \times 0.76) \times 0.6 \times 21 \text{ ft}^2 \times 177 \text{ kBtu/ft}^2.\text{yr}$$

$$Q_S = 0.41 \times 0.6 \times 21 \text{ ft}^2 \times 177 \text{ kBtu/ft}^2.\text{yr}$$

$$Q_S = 917.0 \text{ kBtu/yr}$$

$$U_{w\text{-installed}} =$$

$$\frac{(U_g \times A_{\text{glass}}) + (U_f \times A_{\text{frame}}) + (\Psi_{\text{spacer}} \times L_{\text{spacer}}) + (\Psi_{\text{installed}} \times L_{\text{installed}})}{A_{\text{window}}}$$

$$U_{w\text{-installed}} = \frac{0.11 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}) \times 15.875 \text{ ft}^2 + 0.154 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}) \times 5.125 \text{ ft}^2 + 0.06 \text{ Btu}/(\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}) \times 16.583' + -0.04 \text{ Btu}/(\text{hr} \cdot \text{ft} \cdot ^\circ\text{F}) \times 19'}{21 \text{ ft}^2}$$

$$U_{w\text{-installed}} = 0.132 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F})$$

CALCULATING ENERGY BALANCE

$$Q_T = A \times (1/R) \times f_t \times G_t$$

$$\text{Transmission Loss } (Q_T) = 21 \text{ ft}^2 \times 0.132 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F}) \times 1.0 \times 117 \text{ k}^\circ\text{F} \cdot \text{hr}/\text{yr}$$

$$\text{Transmission Loss } (Q_T) = 324.3 \text{ kBtu}/\text{yr}$$

CALCULATING ENERGY BALANCE

Note: in the PHPP tool, a 'utilization factor' is applied which reduces the amount of solar gains we can assume in our energy model. This utilization factor is going to be ignored for the purposes of simplification here.

$$Q_H = \text{Solar Gain } (Q_S) - \text{Transmission Loss } (Q_T)$$

$$\begin{aligned} \text{Solar Gain } (Q_S) &= 917.0 \text{ kBtu/yr} \\ \text{Transmission Loss } (Q_T) &= 324.3 \text{ kBtu/yr} \end{aligned}$$

$$\begin{aligned} Q_H &= 917.0 \text{ kBtu/yr} - 324.3 \text{ kBtu/yr} \\ Q_H &= 592.7 \text{ kBtu/yr} \end{aligned}$$

This results in a net solar gain over the heating season. A NEGATIVE value for Q_H would mean there is a net loss (expected for north-facing windows in northern hemisphere, for example)

Module 6

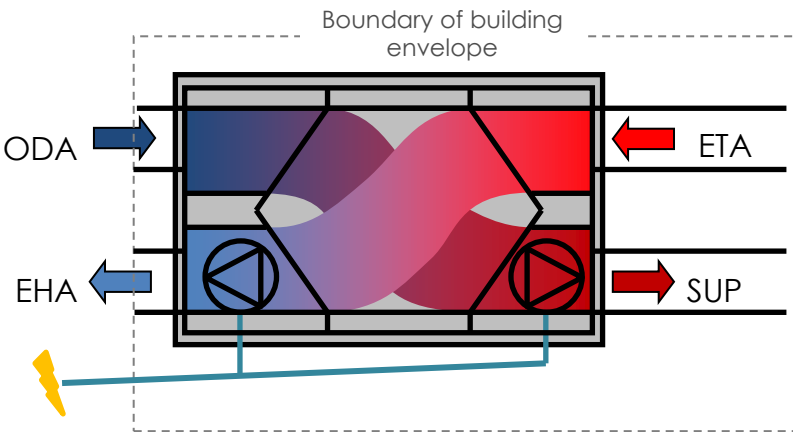
Mechanical Ventilation

Key Pointers for Module 6: Ventilation

- There's normally **one or two calculation-type questions** and true-false questions on the topic of ventilation
- Most common calculation question to be asked is to determine the **heat losses through the H/ERV** (usually called an 'MVHR' on the exam paper). This can be tricky – be sure to practice it.

$$\eta_{HR} = \frac{\left\{ T_{ETA} - T_{EHA} \right\} + \frac{P_{ELEC} \times 3.413 \text{ Btu/h}}{V \times c_{air} \times 60 \text{ Min/h}}}{T_{ETA} - T_{ODA}}$$

Measures 'efficiency' gain from heat of fans in the H/ERV box



Units:

- η_{HR} = heat recovery efficiency in %
- Air temperatures in °F
- P_{ELEC} = electrical energy for the extract fan in Watts
- 3.413 converts Watts to Btu/h
- V = Ventilation Rate (CFM)
- c_{air} = 0.018 Btu/ft³·F, a constant for heat carrying capacity of air
- 60 converts hours to minutes.

PRACTICE THERMAL EFFICIENCY CALCULATION

An independent lab has carried out tests on the ERV that you are considering using for your Passive House project. Please calculate the efficiency of this ERV based on the data provided by the lab:

$V = 70 \text{ cfm}, T_{ETA} = 68 \text{ F}, T_{ODA} = 32 \text{ F}, T_{EHA} = 39 \text{ F}, P_{el} = 37 \text{ W}$

$$\eta_{HR} = \frac{\left\{ T_{ETA} - T_{EHA} \right\} + \frac{P_{ELEC} \times 3.413 \text{ Btu/h}}{V \times c_{air} \times 60 \text{ Min/h}}}{T_{ETA} - T_{ODA}}$$

$$\eta_{HR} = \frac{\left\{ 68 \text{ F} - 39 \text{ F} \right\} + \frac{37 \text{ W} \times 3.413}{70 \text{ CFM} \times 0.018 \times 60}}{68 \text{ F} - 32 \text{ F}}$$

$\eta_{HR} = 0.85, \text{ or } \mathbf{85\%}$

$$\begin{aligned}
 Q_{V-ERV} &= \text{Ventilation volume} \times \text{Number of ventilation air changes per hour at 'normal'} \times \text{1 minus heat recovery efficiency of ERV} \times \text{Heat carrying capacity of air} \times \text{Heating Degree Hours} \\
 Q_{V-ERV} &= V_v \times n_{V, \text{system}} \times (1 - \eta_{ERV}) \times C_{\text{air}} \times G_t \\
 &\text{ft}^3 \times \frac{1}{\text{h}} \times \text{Unitless} \times \frac{\text{Btu}}{(\text{ft}^3 \cdot \text{F})} \times \frac{(\text{k} \cdot \text{F} \cdot \text{h})}{\text{year}} \\
 &= \text{kBtu/year}
 \end{aligned}$$

Example: What are ERV ventilation losses for project with $V_v = 7,750\text{ft}^3$, air change rate at normal ventilation setting of $0.5 \text{ } 1/\text{h}$, ERV efficiency of 88% and heating degree hours 116 kFh/year.

$$Q_v = 7,750\text{ft}^3 \times 0.5 \text{ } 1/\text{h} \times (1-0.88) \times 0.018 \text{ Btu}/\text{ft}^3 \cdot \text{F} \times 116 \text{ kFh}/\text{year} = 970.92 \text{ kBtu}/\text{year}$$

$$Q_{V-ERV} = V_v \times n_{V, \text{system}} \times (1 - \eta_{ERV}) \times C_{\text{air}} \times G_t$$

Please calculate:

You are working on a Passive House project with a TFA of 900ft^2 . Prior to considering ERV losses, the space heating demand is $3.45 \text{ kBtu}/\text{ft}^2 \cdot \text{year}$. Will it be possible to certify the project below based on the following ventilation rate and ERV efficiency: $V_v = 7,950\text{ft}^3$, air change rate @ normal = $0.4 \text{ } 1/\text{h}$, ERV efficiency of 85% and heating degree hours $126 \text{ kFh}/\text{year}$?

Solution:

$$Q_v = 7,950\text{m}^3 \times 0.4 \text{ } 1/\text{h} \times (1-0.85) \times 0.018 \text{ Btu}/\text{ft}^3 \cdot \text{F} \times 126 \text{ kFh}/\text{year} = 1,081.83 \text{ kBtu}/\text{year} \div \text{TFA } 900\text{ft}^2 = 1.20 \text{ kBtu}/\text{ft}^2 \cdot \text{year}.$$

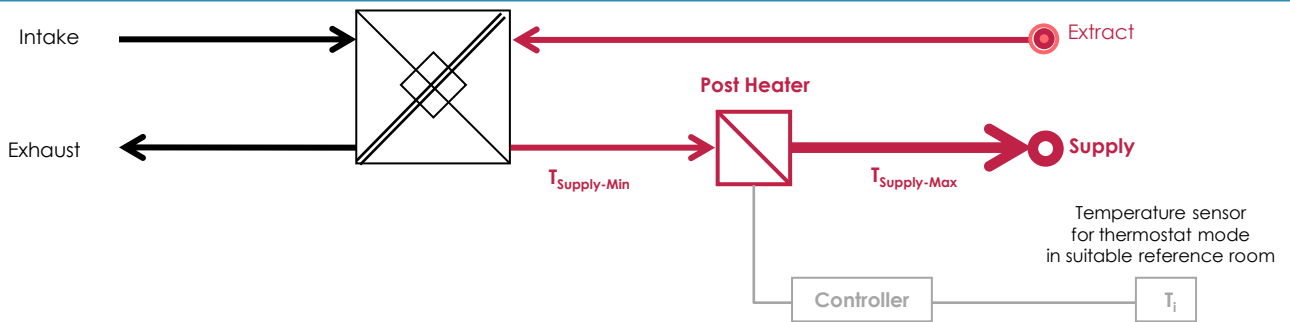
Existing heating demand of $3.45 \text{ kBtu}/\text{ft}^2 \cdot \text{year}$ + ERV losses of $1.20 \text{ kBtu}/\text{ft}^2 \cdot \text{year}$ = $4.65 \text{ kBtu}/\text{ft}^2 \cdot \text{year}$. Can be certified!

Module 7: Heating and DHW

Key Pointers for Module 7: Heat and Hot Water

- There's **occasionally** a question on heating systems in the exam (not as common as the other topics presented earlier)
- The most common type of question is to work out heat losses from **hot water storage tanks**

SIZING POST HEATER FOR HEATING VIA AIR



$$P_{\text{air heating}} = C_{\text{air}} \times V_{\text{SYSTEM}} \times \Delta T \times 60 \text{ min/hr}$$

The system flow rate (cfm) comes from the vent. design (supply, extract and min ACH)

Here the ΔT is the temp difference from before and after the post heater ($T_{\text{SUPPLY-MAX}} - T_{\text{SUPPLY-MIN}}$)

C_{air} (heat capacity of air @ 68 °F) = 0.018 Btu/ft³.°F

MAX 3.17 BTU/HR.FT² PEAK HEAT LOAD?

- Fresh air flow rate at boost is at least 18 CFM/person
- At 68°F and standard pressure, air has a heat carrying capacity of 0.018 Btu/ft³F

$$P_{\text{air heating}} = C_{\text{air}} \times V_{\text{airflow}} \times (T_{\text{SUPPLY-MAX}} - T_{\text{SUPPLY-MIN}}) \times 60 \text{ min/h}$$

(125° - 68° = 57°)

Just a unit correction factor because we want Btu/Hour

$$P_{\text{air heating per Person}} = 0.018 \text{ Btu/ft}^3 \cdot \text{°F} \times 18 \text{ cfm/person} \times 57 \text{ °F} \times 60 \text{ min/h} = 1,108 \text{ Btu/person}$$

So... at a typical 350 ft²/person occupancy

$$\frac{1,108 \text{ Btu/person-max}}{350 \text{ ft}^2/\text{person}} = \text{Max Load of } 3.17 \text{ Btu/ft}^2$$

Note: this math is all a lot cleaner in Metric...

Module 8: Economics

Key Pointers for Module 8: Economics

- There's **always a few questions on Economics**
- It tends to be the **least-liked** question in the exam 😞
- We get the sense that **many people don't even attempt** the economic questions
- We urge you to '**give it a go**' – the questions might not be as difficult as you think
- You might gather a few **valuable points** from the economics questions

To calculate the Present Value (PV) of annual energy savings (C)

For Passive House, this method is used when you know the annual energy savings (C) and you want to know what size of additional mortgage this would fund (PV)

$$PV = C \times \frac{1 - (1 + i)^{-n}}{i}$$

Present Value Factor (PVF)

PV = Present value

C = Annual energy saving in Year 1

i = Mortgage interest rate (written as decimal)

n = Term of the mortgage in number of years

PRESENT VALUE METHOD: EXAMPLE CALCULATION

How much extra can you afford to invest in a Passive House project so that the repayments on the additional mortgage do not exceed the annual savings on your heating bill?

- Imagine you can save \$1,500 each year on heating and hot water costs.
- Interest rate of 3%
- 25 year mortgage term

$$PV = C \times \frac{1 - (1+i)^{-n}}{i}$$

$$PV = \$1,500 \times \frac{1 - (1+0.03)^{-25}}{0.03}$$

Present Value (PV) = \$26,119

You could borrow an additional \$26,119 and pay for the extra mortgage from the future savings you make on heating bills

To calculate the Annuity (A) of the Principal borrowed (P)

For Passive House, this method is used when you know the amount that you are borrowing (*the principal, P*) and you want to know the annual repayments (A)

$$A = P \times \frac{i}{1 - (1 + i)^{-n}}$$

Annuity Factor (AF)

- A = Annual (not monthly!) mortgage repayments
- P = Principal that you are borrowing
- i = Mortgage interest rate (written as decimal)
- n = Term of the mortgage in number of years

ANNUITY: EXAMPLE

A client needs an amount of \$250,000 for the construction of their house.
 Interest rate (i): 4.5%
 Repayment period (n): 30 years

What is the annual (and monthly) **Annuity** for interest and repayment?

$$AF = \frac{i}{1 - (1 + i)^{-n}} = \frac{0.045}{1 - (1 + 0.045)^{-30}} = 0.0614$$

$$A = P \times AF = \$250,000 \times 0.0614 = \$15,347.89$$

\$15,347.89 per year / 12 months = \$1,278.99 monthly payment

NOTE: Total repaid over life of loan = $A \times n = \$15,347.89 \times 30 \text{ years} = \$460,436.70$

$$\frac{1 - (1 + i)^{-n}}{i}$$

Present Value Factor (PVF)

$$\frac{i}{1 - (1 + i)^{-n}}$$

Annuity Factor (AF)

- Have you noticed that the Present Value Factor is simply the inverse of the Annuity Factor!
- This is important for the exam – if you're given the annuity factor, you can easily convert this to a present value factor.

NOMINAL VERSUS REAL INTEREST RATES

The nominal interest rate is 7.5%.

How high is the real interest rate at an inflation rate of 4% ?

$$i_{\text{real}} = \left[\frac{1 + i_{\text{nominal}}}{1 + r} \right] - 1$$

$$i_{\text{real}} = \left[\frac{1 + 0.075}{1 + 0.04} \right] - 1 = 0.034$$

$i_{\text{real}} = 3.4\%$

FORMULA TO DETERMINE COST OF A 'SAVED KBTU'

$$P_{\text{SAVED}} = \frac{AF_{\text{loan term}} \times (I_{\text{additional}} - R) + Z}{E_{\text{SAVED}}}$$



The measure is profitable if $P_{\text{SAVED}} < P_{\text{ENERGY COST}}$

- P_{SAVED} = cost to save 1 kBtu of energy (\$/kBtu)
- $P_{\text{ENERGY COST}}$ = cost to purchase 1 kBtu of energy (\$/kBtu)
- $AF_{\text{loan term}}$ = annuity factor for the length of the loan (annuity per year)
- $I_{\text{additional}}$ = additional investment required specifically to meet Passive House standard, over and above what 'normal' retrofit works might have been required anyway to maintain the project (\$)
- R = Residual value of the component after the end of the loan term (\$)
- Z = Annual maintenance cost resulting from the introduction of the Passive House measure (for example, changing filters) (\$)
- E_{SAVED} = Amount of energy saved as a result of the Passive House measure (kBtu/year)

Example:

If it costs \$0.06 to 'save' a kBtu (P_{SAVED}) but it costs just \$0.08 to 'buy' a kBtu ($P_{\text{ENERGY COST}}$) then the measure should be undertaken.

RESIDUAL VALUE FORMULA

Annuity Factor
(over product life)

Present Value Factor
(over loan term)

$$\text{Residual value} = (1 - (AF_{\text{product life}} \times PVF_{\text{loan term}})) \times I_{\text{add}}$$

Investment Cost

- Use this formula when you want to know the economic value of a Passive House measure (for example, insulation) after the loan for that measure has been paid off.

Exercise:

What is the residual value of external insulation (with a product life of 50 years) costing \$15,000 borrowed over 20 year period at a real interest rate of 3% (i_{real})?

$$R = (1 - AF_{50} \times PVF_{20}) \times I_{add}$$

$$AF_{50} = \frac{0.03}{1 - (1 + 0.03)^{-50}} = 0.0388$$

$$PVF_{20} = \frac{1 - (1 + 0.03)^{-20}}{0.03} = 14.877$$

$$R = (1 - (0.0388 \times 14.877)) \times \$15,000 = \$6,341.58$$

NOTE that the Annuity Factor (AF) is calculated over the **life of the product**, while the Present Value Factor (PVF) is calculated over the **loan term**.

There will be a similar calculation for you to complete at the end of this video

The insulation (after the loan is repaid) has a **Residual Value of \$6,341.58**

Summary of Key Criteria & Calculations

Passive House Certification Criteria

- Heating: Demand $\leq 4.75 \text{ kBtu}/(\text{ft}^2 \cdot \text{yr})$
- **or** Load $\leq 3.17 \text{ Btu}/\text{hr} \cdot \text{ft}^2$
- Cooling Demand $\leq 4.75 \text{ kBtu}/(\text{ft}^2 \cdot \text{year})$ * additional allowance for dehumidification (PHPP determined)
- Excess temperature (77°F) frequency $\leq 10\%$
- Building Air-tightness $\leq 0.6 \text{ }^1/\text{h}$ or h^{-1}
- Primary Energy Demand **PE**: $\leq 38 \text{ kBtu}/(\text{ft}^2 \cdot \text{year})$
- Primary Energy Demand **PER**: Classic = $\leq 19 \text{ kBtu}_{\text{per}}/(\text{ft}^2 \cdot \text{year})$,
Plus = ≤ 14.25 , Premium = ≤ 9.50
- Energy Generation PER: Classic = $0 \text{ kBtu}_{\text{per}}/(\text{ft}^2_{\text{footprint}} \cdot \text{year})$,
Plus = ≥ 19.0 , Premium = ≥ 38.0

Heating Demand (kBtu/yr):

$$Q_H = Q_T + (Q_{V\text{-rest}} + Q_{V\text{-ERV}}) - [\eta \times (Q_S + Q_I)]$$

$$\text{Transmission losses } Q_T = A \times U \times f_t \times G_t$$

Area of thermal envelope × U-value × Temperature correction factor × Heating degree hours

$$\text{Infiltration losses } Q_{V\text{-rest}} = V_{n50} \times e \times n_{50} \times C_{\text{air}} \times G_t$$

n_{50} test volume × fraction of air changes per hour at 'resting' atmospheric pressure (normally 7% or 0.07) × airtightness test result at 50 Pascal × Heat carrying capacity of air (a constant, 0.018 Btu/(ft³.°F)) × Heating degree hours

$$\text{ERV Ventilation losses } Q_{V\text{-ERV}} = V_v \times n_{V,\text{system}} \times (1 - \eta_{\text{ERV}}) \times C_{\text{air}} \times G_t$$

Ventilation volume (= TFA X 8.2 feet) × air exchange rate of the ventilation system at average or 'normal' speed (minimum 0.3 1/h) × (1 - heat recovery efficiency of ERV) × Heat carrying capacity of air (a constant, 0.018 Btu/(ft³.°F)) × Heating degree hours

η = utilization factor, defined as 'the fraction of 'free heat' that can be used for space heating'. Surplus heat, for example excess solar gains, is only partially usable.

$$\text{Solar gains } Q_S = r \times \text{SHGC} \times A_w \times G$$

reduction factor × SHGC × gross window area × solar irradiation. Reduction factor 'r' has four components: Dirt (0.95) × Non-Perp. Radiation (0.85) × Shading × Glazing-fraction

$$\text{Internal heat gains } Q_I = t_{\text{Heat}} \times q_i \times A_{\text{TFA}}$$

Length heating period (no. of heating days × 0.024h) × Internal Heat Gains (=0.67 Btu/(hr-ft²)) × Treated Floor Area

Heating Load (Btu/hr):

$$P_H = P_T + (P_{V\text{-rest}} + P_{V\text{-ERV}}) - (P_S + P_I)$$

$$\text{Transmission losses } P_T = A \times U \times f_t \times \Delta T$$

Area of thermal envelope × U-value × Temperature correction factor (typ.=1) × temperature difference between inside & out

$$\text{Infiltration losses } P_{V\text{-rest}} = V_{n50} \times (e \times 2.5) \times n_{50} \times C_{\text{air}} \times \Delta T$$

n_{50} test volume × (fraction of air changes per hour at 'resting' atmospheric pressure (normally 7% or 0.07 × safety factor of 2.5 allowing for losses on windy days)) × airtightness test result at 50 Pascal × Heat carrying capacity of air (a constant, 0.018 Btu/(ft³.°F)) × temperature difference between inside & out

$$\text{ERV Ventilation losses } P_{V\text{-ERV}} = V_v \times n_{V,\text{system}} \times (1 - \eta_{\text{ERV}}) \times C_{\text{air}} \times \Delta T$$

Ventilation volume (= TFA X 8.2 feet) × air exchange rate of the ventilation system at average or 'normal' speed (minimum 0.3 1/h) × (1 - heat recovery efficiency of ERV) × Heat carrying capacity of air (a constant, 0.018 Btu/(ft³.°F)) × temperature difference between inside & out

$$\text{Solar gains } P_S = r \times \text{SHGC} \times A_w \times G_1 \text{ or } G_2$$

reduction factor × SHGC × gross window area × solar irradiation (for 2 weather conditions)

$$\text{Internal heat gains } P_I = q_i \times A_{\text{TFA}}$$

Internal Heat Gains (=0.51 Btu/(hr-ft²), unoccupied status) × Treated Floor Area

Airtightness: $n_{50} < 0.649 \text{ }^1/\text{h}$ or h^{-1}

$$n_{50} = \frac{V_{50} \times 60 \text{ min/hr}}{V_{n50}} \quad \begin{array}{l} V_{50} = \text{air flow rate in CFM at 50 Pa} \\ V_{n50} = \text{net airtightness volume in ft}^3 \end{array}$$

For 'large' buildings ($V_{n50} \geq 53,000\text{ft}^3$), $q_{50} \leq 0.034 \text{ CFM/ft}^2$

$$q_{50} = \frac{V_{50} \times 60 \text{ min/hr}}{EA_{n50}} \quad \begin{array}{l} V_{50} = \text{air flow rate in CFM at 50 Pa} \\ EA_{n50} = \text{external surface area in ft}^2 \end{array}$$

Thermal Bridging

Thermal bridge "free" = $\Psi_{(\text{exterior dimensions})} < 0.006 \text{ Btu/hr} \cdot \text{ft} \cdot \text{F}$

Point thermal bridges = $\Delta U_{\text{TB}} = \sum \chi / A < 0.0018 \text{ Btu}/(\text{hr} \cdot \text{ft}^2 \cdot \text{F})$

Q_{TB} (kBtu/year) = Linear: $\Psi \times L \times f_t \times G_t$ Point: $\chi \times \text{number} \times f_t \times G_t$

P_{TB} (Btu/hr) = Linear: $\Psi \times L \times f_t \times \Delta T$ Point: $\chi \times \text{number} \times f_t \times \Delta T$

Heating Degree Hours

G_t = Sum of temp. differences between inside & out over time

Example calculation for January in location where the average exterior temperature is 30 °F

$$G_{t,\text{Jan}} = (T_i - T_e) \times k \cdot h_{\text{Jan}}$$

$$G_{t,\text{Jan}} = (68^\circ\text{F} - 30^\circ\text{F}) \text{ F} \times 31 \text{ days} \times 0.024 \text{ kh/d} = 27.3 \text{ kFh/Jan}$$

R-Value Calculation ($\text{hr} \cdot \text{ft}^2 \cdot \text{F}/\text{Btu}$)

$$R_T = R_{si} + d_1 \times r_1 + d_2 \times r_2 + d_3 \times r_3 + (d_n \times r_n) + R_{se}$$

Where d = thickness of each layer (in inches), and r is the resistivity (R per inch) of materials (in $\text{hr} \cdot \text{ft}^2 \cdot \text{F}/\text{Btu} \cdot \text{in}$), for each of n number of layers.

R_{si} : Roof = 0.57 $\text{hr} \cdot \text{ft}^2 \cdot \text{F}/\text{Btu}$, Walls = 0.74, Floors = 0.97

R_{se} : Roof = 0.23 $\text{hr} \cdot \text{ft}^2 \cdot \text{F}/\text{Btu}$, Walls = 0.23, Ground = 0.0

Window U-value

$U_{w, \text{ installed}} \text{ (Btu/(hr} \cdot \text{ft}^2 \cdot \text{F))} =$

$$\frac{(U_g \times A_{\text{glass}}) + (U_f \times A_{\text{frame}}) + (\Psi_{\text{spacer}} \times L_{\text{glass}}) + (\Psi_{\text{install}} \times L_{\text{installed}})}{A_{\text{window}}}$$

Solar reduction factor, r (unitless) = shading × dirt × non-perp. radiation × glazing fraction

If not otherwise given, dirt = 0.95, (non-perp. radiation) = 0.85

Window Energy Balance (kBtu/year):

$$Q_T - Q_S = (A_w \times U_{w\text{-inst}} \times G_t) - [\eta \times (A_w \times r \times \text{SHGC} \times G)]$$

Where A_w = gross window area, $U_{w\text{-inst}}$ = overall installed U-value, G_t = Heating degree hours, r = reduction factors, SHGC = solar heat gain coefficient, G = annual solar Irradiation, η = Utilization Factor. A 'negative' energy balance is when gains are higher than losses.

Window Heat Load Energy Balance (Btu/hr):

$$P_T - P_S = (A_w \times U_{w\text{-inst}} \times \Delta T_{1 \text{ or } 2}) - (A_w \times r \times \text{SHGC} \times G_{1 \text{ or } 2})$$

Where A_w = gross window area, $U_{w\text{-inst}}$ = overall installed U-value, $\Delta T_{1 \text{ or } 2}$ = temperature difference in 2 weather conditions, r = reduction factors, SHGC = solar heat gain coefficient, A_w = gross window area, $G_{1 \text{ or } 2}$ = solar energy in 2 weather conditions

Surface Temperature of Component Calculation:

$$T_{si} = T_i - (U \times R_{si} \times \Delta T)$$

T_{si} = surface temperature inside, T_i = inside air temperature (68°F), U = U-value of the window (or any component), R_{si} = surface film resistance inside (for a window (or wall) = 0.74 (hr·ft²·F)/Btu), ΔT = Temperature difference inside & outside ($T_i - T_e$) for given location

Ventilation

Supply boost: 18 CFM/person. Extract boost: Kitchens 36 CFM + Bathrooms 24 + WCs 12.
Minimum whole building = $0.39 \text{ ach} \times V_v / 60$

Recommended sound limits: mech room = 35 dB(A), functional rooms = 30, habitable rooms = 25.

Maximum intake & exhaust imbalance = 10%. Ventilation with $\geq 75\%$ heat recovery & $\leq 0.765 \text{ W/CFM}$ elec use

H/ERV heat recovery efficiency

H/ERV efficiency

$$= \frac{(T_{\text{ETA}} - T_{\text{EHA}}) + \left(\frac{P_{\text{elec}} \times 3.413}{V \times C_{\text{air}} \times 60} \right)}{T_{\text{ETA}} - T_{\text{ODA}}}$$

Where T_{ETA} = temperature of extract air ($^{\circ}\text{F}$), T_{EHA} = temp. of exhaust air and T_{ODA} = temp. of outdoor air. P_{elec} = electric power of the fans + controls in Watts, 3.413 is a conversion factor (constant), V = ventilation flow rate in CFM, C_{air} = heat carrying capacity of air (a constant, $0.018 \text{ Btu}/(\text{ft}^3 \cdot ^{\circ}\text{F})$) and 60 is a conversion factor

H/ERV Electrical efficiency (W/CFM) = Power of the fans & controls (in Watts) / volumetric flow rate (CFM)

Duct diameter (inches) = $24 \times \sqrt{V_{\text{flow(cfm)}} / (\text{Air speed}_{(\text{ft}/\text{min})} \times \pi)}$

Where V_{flow} = air flow rate in CFM at normal speed, Air speed = target 400 ft/min but may be 300 to 600 ft/min, and π (Pi) = 3.14

Max heat load deliverable by supply air (Btu/hr):

$$P_{\text{supply max}} = C_{\text{air}} \times V_{\text{system}} \times (T_{\text{supply max}} - T_{\text{supply min}}) \times 60 \text{ min/h}$$

Where C_{air} = heat capacity of air (a constant, $0.018 \text{ Btu}/(\text{ft}^3 \cdot ^{\circ}\text{F})$), V_{system} = volumetric air flow rate in CFM, $T_{\text{supply max}}$ = temperature of supply air after post-heater (max. $125 \text{ }^{\circ}\text{F}$, but can be lower), $T_{\text{supply min}}$ = temperature of supply air before post-heater (min. $62 \text{ }^{\circ}\text{F}$)

Economics

$$PV = C \times \frac{1 - (1 + i)^{-n}}{i}$$

Present Value calculation (\$):

Where PV = present value of savings, C = annual savings, i = interest rate (written in decimal form, eg. 5% written as 0.05) and n = years over which present value is calculated

$$AF = \frac{i}{1 - (1 + i)^{-n}}$$

Annuity factor calculation (unitless):

Where a = factor used to multiply mortgage loan amount to determine annual repayments, i = interest rate (written in decimal form, eg. 5% written as 0.05) and n = years over which mortgage is repaid

$$i_{\text{real}} = \frac{1 + i_{\text{nominal}}}{1 + r} - 1$$

Interest Rate calculation (unitless):

Where i_{real} is the 'real' interest rate on deposits which takes into account inflation, i_{nominal} = rate quoted by bank and r = inflation rate (all rates written in decimal form as above)

$$P_{\text{saved}} = \frac{AF_{\text{loan term}} \times (I_{\text{add}} - R) + Z}{E_{\text{saved}}}$$

Price of saved kWh/kBtu (\$):

Where AF = annuity factor (reciprocal of present value factor), I_{add} = additional costs of investment for saving measures (\$), R = residual value of components (\$), Z = possible annual additional maintenance costs (\$), E_{SAVED} = annual site energy savings (kBtu/year)

Residual Value calc.(\$):

$$R = (1 - AF_{\text{product life}} \times PVF_{\text{loan term}}) \times I_{\text{add}}$$

Where $AF_{\text{product life}}$ = annuity factor calculated for the life of the component, $PVF_{\text{loan term}}$ = present value factor calculated for the duration of the mortgage) and I_{add} = additional costs of investment for energy saving measures (\$)