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Heat Load for the ABC House

Jonathan Odim , '23

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Senior Engineering Design Project
(continued from E84 Heat Transfer Project)
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Abstract

Following the protocol set forth in the ASHRAE 2021 Fundamentals Handbook, this project modeled the heating load of the house for a design season (winter). This project reports the heating load calculation for a 1960 residential dwelling used as student housing in Swarthmore, PA. The infiltration, window, door, attic, 1st-3rd floor, and basement loads were found to be 5641 kW, 3239 kW, 273 kW, 262 kW, 4073 kW, and 514 kW respectively: resulting in a total design season heat load of 14001 kW. The three biggest contributors to the seasonal heat load were Infiltration, Window, and Wall load (40.3%, 29.1%, and 23.1% of total heat load respectively). Window and insulation replacement were the two most feasible reduction methods, with estimated installation costs of $16800 and ~$2,000 respectively. The following sections of this report include details on the methods used as well as a discussion of the load calculation and suggestion for heat load reduction.

Introduction

In the 1950s and 60s (when the ABC House was erected) construction options were extremely limited and technicians had to calculate the Joule heating and cooling loads of the house manually. The general elements of consideration included looking at walls' surface area, insulation type, # of residents, outer temperature, and have remained unchanged over the years. The only complication is the abundance of choice (making it a hassle to manually keep track of things).

Understanding the heat load of an enclosure is essential for maintaining thermal homeostasis. Houses are designed to maintain stable temperatures despite fluctuations in environmental temperatures. In the summer, when it's hot, the aim is to prevent heat energy from coming in. In the winter, when it's cold, the aim is to prevent heat energy from leaving. This is thought through during the house design process where each material and its thermal resistance/absorptivity is carefully considered.

A well-constructed house can result in hundreds of dollars of monthly savings for residents by reducing their heating bills. Over time (generally 6-12 years) energy savings can completely amortize the extra fixed costs of using more energy efficient materials.

This year, I am serving as a residential assistant to the ABC Strath Haven house. The ABC program aims to "increase substantially the number of well-educated young people of color who are capable of assuming positions of responsibility and leadership in American society." As a non-profit organization, the ABC Strath Haven branch relies on donations and the charity of the Swarthmore Borough Residents to sustain its students.

"The ABC Strath Haven House is a Victorian-era home tucked in the heart of Swarthmore. The home is owned by the Swarthmore Presbyterian Church, which provides the home and contributes to its capital improvements and upkeep for a nominal rent … The house is designed to accommodate two resident directors, two resident tutors, and eight students. In 2013 and 2014, extensive renovations were done to the first and second floors of the house. " (ABC Strath Haven)

This project aims to:

1) Evaluate the heating load required for a typical winter season.
2) Identify areas of improvement that will result in load reduction.
3) Provide a cost/benefit breakdown of potential house improvements.
4) Estimate the heat load reduction of said improvements based on the model.

If adopted, these changes will lead to financial savings that can be redirected to more productive goals of the ABC program.

History of Thermal Analysis in Residential Buildings

Early residential construction practices (pre-1950's) dictated, little attention should be paid to thermal performance. Buildings were typically poorly insulated and had high rates of air infiltration, leading to discomfort and energy waste.

High fuel costs due to the oil embargos during the 1970's placed an increased importance on energy efficiency in order to reduce building maintenance costs. This prompted the development of thermal analysis tools, like the Building Energy Analysis Program (BEAP).

In the 1980s and 1990s, this kind of computer simulation software became more widely available, and allowed more accurate thermal analysis of buildings. EnergyPlus is one such tool that is still widely used today. Additionally, there has been increased attention on the importance of sustainable design to reducing buildings' carbon footprint.

Methods

Theory

Conduction and convection were the two modes of heat transfer considered for this calculation. Radiative gain was ignored because it would lessen the calculated winter heat load and this model aimed to determine the conservative heat load of the house during a typical January design day.

Conductive Heat Transfer

Conduction involves the transfer of thermal energy due to random, translational motion of the molecules in a material or surface. The energy is diffusing across the surface can be quantified by the rate equation (Fourier's law):

$$q = k\frac{A}{L}\triangledown T$$ **(Equation 1)**

Convective Heat Transfer

Convection involves both diffusive heat transfer, as well as heat transfer due to bulk motion of the fluid/medium. In this case free (not driven by an external means) convection occurs between the air (outside and inside the house) the house's exposed surfaces. The convective heat transfer rate equation is expressed as follows:

$$q = hA\triangledown T$$ **(Equation 2)**

Thermal Resistivity and the U Factor

The thermal resistivity of a material measures its ability to resist heat transfer. The U-Factor is a measure of a material/object's ability to transmit heat: its thermal conductance. It follows that this measurement is the reciprocal of the thermal resistance of said material. We can relate the two using the following equality:

$$R_t = \sum R_{total} = \sum R_{conduction} + \sum R_{convection} = \frac{\Delta T}{q} = \frac{1}{UA} \quad \textbf{(Equation 3)}$$

The incorporation of thermal resistivity produces the following generalized heat transfer equation utilized during heat load calculation:

$$q = UA\Delta T = \frac{\Delta T}{R_t} \quad \textbf{(Equation 4)}$$

This equation shows how the heat transferred through a medium is directly proportional the temperature gradient and surface area of said medium.

Building Design Details

The ABC house currently has 8 bedrooms and 4 bathrooms. The water boiler located in the basement is responsible for heating during the winter. Below are pictures of the floor plans for each floor of the house.

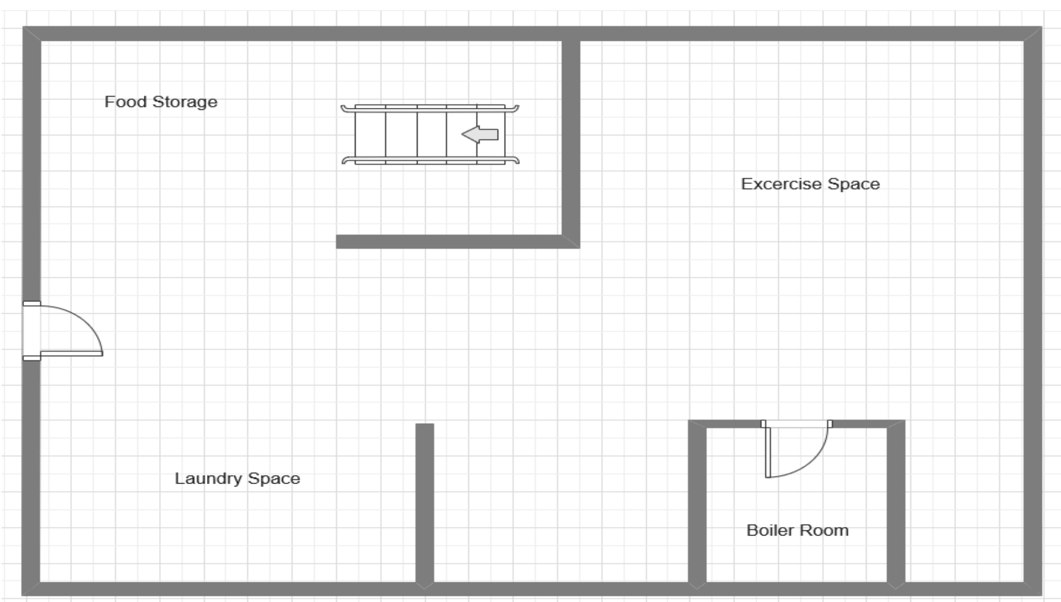

Figure 1: Basement Floor Plan

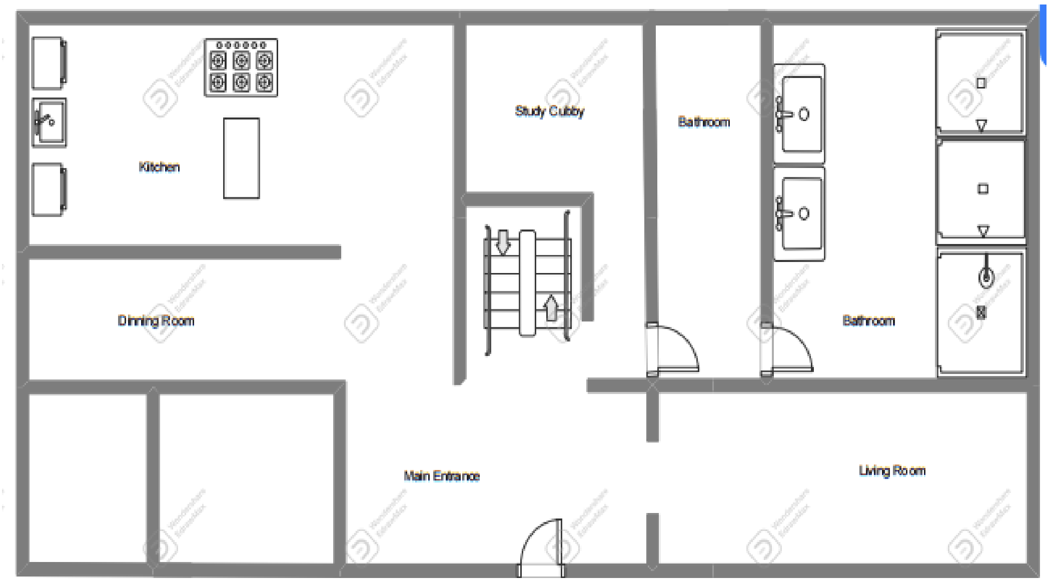

Figure 2: Main Floor Plan

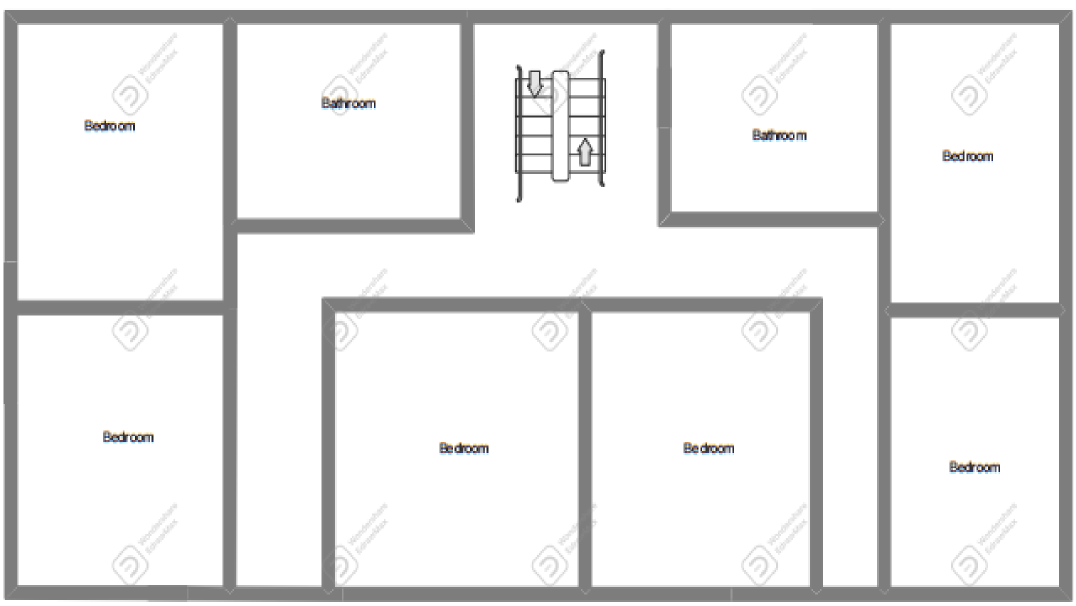

Figure 3: 2nd Floor Plan

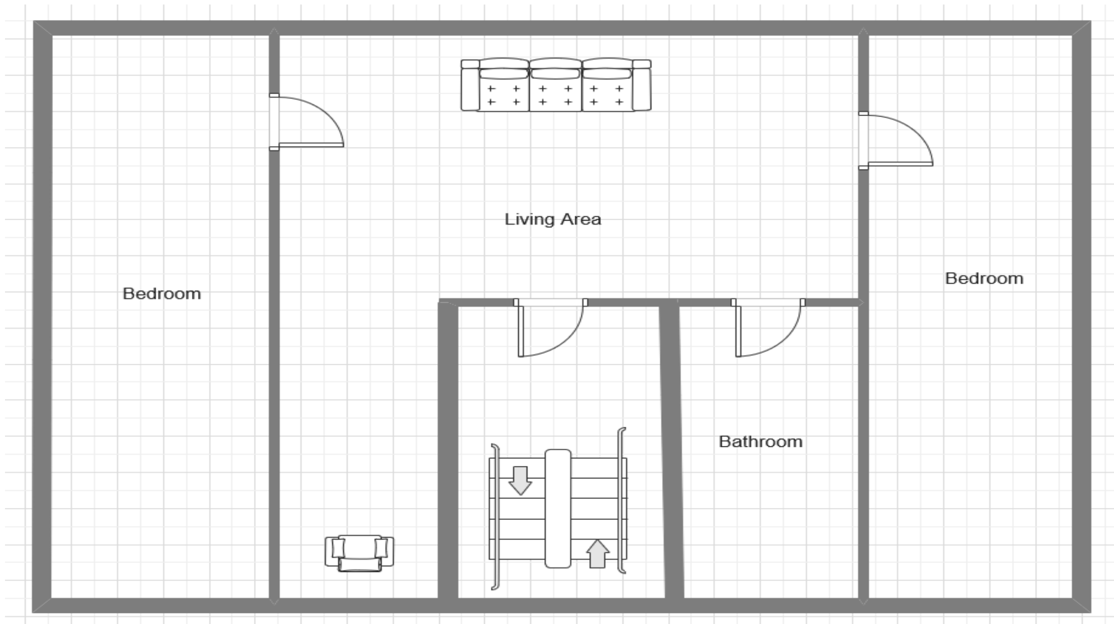

Figure 4: Attic Floor Plan

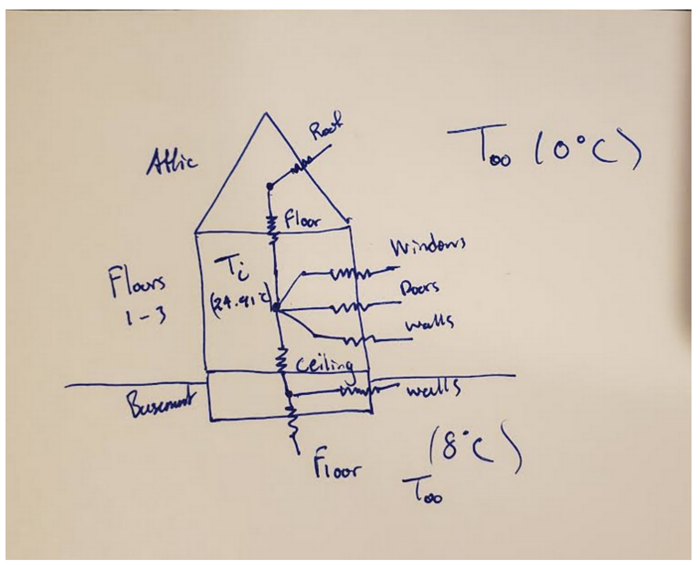

Figure 5: Heat Load Model

This figure shows the model used to calculate the total heat load of the house. The house was divided into 3 sections: the attic, floors 1-3, and the basement. The attic and basement were treated as adjacent, unheated buffer spaces. The attic roof, attic floor, walls, windows, doors, basement ceiling, basement walls, and basement floor were all elements of this calculation.

Approach

1) Inventory and measure the house
2) Determine design conditions
3) Propose a model for heat transfer
4) Calculate the heat load during a design season (based on ASHRAE guidelines)
5) Compare load estimate against energy/heat bill data
6) Identify three areas with greatest potential to improve heat retention
7) Propose an array of house modifications and project their amortization window
8) Propose upgraded heating system with a prediction of its new heating load

ABET Design Parameters

Constraints

The project budget was the primary constraint impacting this project. Limited funding meant that I couldn't conduct a blower door test to quantify the air-tightness of the house (pertains to the infiltration load calculation). Additionally, thermal cameras could have been used to get more precise heat loss data (wouldn't have to rely on an instantaneous heat loss assumption).

Requirements

This project's requirements included:

ASHRAE Residential Heat Load Calculation formalisms found in Appendix Item A.

and

Estimated heat load of housing components to determine low hanging fruit of weatherization options

Evaluation

This project satisfied my initial aims. I was able to use the guidelines provided by the ASHRAE Fundamentals Handbook to determine a reasonable, worst-case scenario, winter heat load of the ABC house and provide insight into the cost-efficiency of heat retention modifications for the house.

Professional Standards and Codes

- Heat Loss Calculation Guide [HYDI H-22]
- Peak Cooling and Heating Load Calculation in Buildings Except Low-Rise Residential Buildings [ANSI/ASHRAE/ACCA 183-2007 (RA14)]
- Residential Load Calculations [ANSI/ACCA 2 Manual J-2016]

- Thermal Energy Storage [ACCA 2005]

A comprehensive list of ASHRAE Standards that were applicable to my project are listed in Appendix Item C.

Seasonal Design Conditions

Table 1: Component Areas, U-Factors, and Temperature Gradients

	Element	Areas (m^2)	U Factor (W/m^2*K)	Temp 1 (C)	Temp 2 (C)	Construction
Basement	Ceiling	167.3	0.210	24.91	-	Hardwood + Plastic Blanket Insulation
	Walls	114.144	1.020	-	8.50	Concrete Slab
	Floor	203.5	1.020	-	8.50	Concrete Slab
Floors 1-3	Walls	107.42	560.00	24.91	0.00	Plaster + Wooden Studs + Plastic Blanket Insulation + Wooden Shingles
Attic	Attic Roof	125.4	0.091	-	0.00	R-11 Rated Insulation + Wooden joists (66.67% grade) [33.69 degree pitch angle]
	Attic Floor	122	1.020	-	25.03	Hardwood + Plastic Blanket Insulation
Doors	Door Style 1 (x2)	1.86	2.300	24.91	0.00	Wood Internal and External
	Door Style 2 (x1)	1.86	2.300	22.50	8.50	Wood Internal and External
Windows	Basement	0.743	2.870	-	0.00	Single Pane, Single Glaze, Clear, Operable
	1st Fl Standard (x6)	0.910	2.870	24.91	0.00	Single Pane, Single Glaze, Clear, Operable
	1st Fl Large (x5)	0.910	2.870	24.91	0.00	Single Pane, Single Glaze, Clear, Operable
	1st Fl Bath (x1)	0.910	2.840	24.91	0.00	Single Pane, Single Glaze, Clear
	1 Fl Small (x2)	0.910	2.840	24.91	0.00	Single Pane, Single Glaze, Clear
	2nd Fl Bath (x2)	0.910	2.870	25.03	0.00	Single Pane, Single Glaze, Clear, Operable
	2nd Fl Bedroom (x6)	0.910	2.870	25.03	0.00	Single Pane, Single Glaze, Clear, Operable
	3rd Fl Bath (x2)	0.910	2.870	25.21	0.00	Single Pane, Single Glaze,

						Clear, Operable
	3rd Fl Standard (x7)	0.910	2.870	25.21	0.00	Single Pane, Single Glaze, Clear, Operable

Table 1, describes each element of the ABC pertinent to the heat load calculation: surface area, U-Factor, temperature gradient, and construction. The Internal temperatures of adjacent buffer spaces (basement and attic) were not measured. This is denoted by a ‘ -’ .

Table 2: Design Month Parameters

Design Season Parameters	
Location	Swarthmore, PA
Month	Oct-March
Indoor Temp (C)	24
Elevation (m)	40
Wind Speed (mph)	14.4
Design delta T (C)	24
Degree Days for Each Month	
2022-03-01	**462.2**
2022-04-01	352.9
2022-05-01	163.7
2022-06-01	53.2
2022-07-01	7.6
2022-08-01	11.9
2022-09-01	85.7
2022-10-01	**308.3**
2022-11-01	**405.8**
2022-12-01	**637.8**
2023-01-01	**548.7**
2023-02-01	**502.1**
Total	**2864.9**

Table 2 describes the parameters of the design season that were taken into consideration for the heat load calculation. DegTemperatures and wind speed were averaged from last January's meteorological data (Appendix C).

Results

Table 3: Load (W) Breakdown for each Element of the House

Heat Load Components	ACH	IDF	**Average**	Average Load as % of Total
Infiltration Load	7967	3315	**5641**	**0.40**
Window Load	3239	3239	**3239**	**0.23**
Door Load	273	273	273	0.02
Attic Load	262	262	262	0.02
Fl 1-3 Load	4073	4073	**4073**	**0.29**
Basement Load	514	514	514	0.04
[Air Changes] Total (W)	16327	11675	**14001**	1.00

Table 3: Breakdowns of the heat load generated by the design temperature gradient across each house element is described above. The calculation was conducted according to Equation 4. The basement and attic calculations were slightly more complicated.

The basement heat load was calculated as follows:

$$(Eq. 6)\ q = UA\Delta T = \frac{\Delta T}{R_t} \Rightarrow \frac{24.91 - 0\ (°C)}{R_{Ceiling}A_{Ceiling} + (1/R_{Walls}A_{Walls} + 1/R_{Floor}A_{Floor})^{-1}} = \frac{24.91 - 0\ (°C)}{(U_{Ceiling}A_{Ceiling})^{-1} + (U_{Walls}A_{Walls} + U_{Floor}A_{Floor})^{-1}}$$

$$\frac{24.91 - 8\ (°C)}{(.210*167.30)^{-1} + (1.020*114.14 + 1.020*167.30)^{-1}\ (°C/W)} = 513.6\ W$$

The attic load was calculated similarly:

$$(Eq. 6)\ q = UA\Delta T = \frac{\Delta T}{R_t} \Rightarrow \frac{24.91 - 0\ (°C)}{R_{Roof}A_{Roof} + R_{Floor}A_{Floor}} = \frac{24.91 - 0\ (°C)}{(U_{Roof}A_{Roof})^{-1} + (U_{Floor}A_{Floor})^{-1}}$$

$$\frac{24.91 - 8\ (°C)}{(0.091*122.00)^{-1} + (1.020*125.44)^{-1}\ (°C/W)} = 261.7\ W$$

Table 4: Heat Load Conversion to kWh

	Seasonal Heat Load kWh
ACH	46775
IDF	33447
Aver age	40111

Heat Loads were converted to kWh by multiplying by the total seasonal HDD value shown in Table 2.

Table 5: Infiltrative Driving Force (IDF) Method for Calculating Infiltration Load

Infiltration Load (IDF Method)				
Aul (cm^2/m^2)	Aes (m^2)	**AL (cm^2)**	**IDF (L*s)/cm^2**	**Qi (L/s)**
2.800	560.0	1568.00	0.069	108.19
Unit Leakage Area (Table 3 'Leaky')	Exposed Surface Area	Aul * Aes	Table 5	AL * IDF
Cs (W/L*s*K)	**Qvi,s,h (W)**			
1.230	3314.93			
Air Sensible Heat Factor (17.3)	*Cs*Qvi*deltaT*			
(elevation negligible 40m<300m)				

Table 5 details the process for calculating the Infiltration Heating Load via the IDF method described in the ASHRAE 2021 Fundamentals Handbook. The calculation was conducted as follows: $A_{ul} = 2.800\, cm^2/m^2 (Appendix\ B), A_{es} = 2 * 11.2 * (12 + 13) = 560\, m^2\ (Table\ 1)$

$Al = A_{ul} * A_{es} = 1568\, cm^2$ & $IDF = .069\, L/s * cm^2 (Appendix\ B);\ Q_i = Al * IDF = 108.19\, L/s$

$Q_{vi,s,h} = C_s * Q_{vi} * \Delta T = 1.230\, (W * s/L * °C) * 108.19 (L/s) * (24.91 - 8)\, (°C)\ (Table\ 1\ \&\ Appendix\ B)$
$= 3314.93\, W$

Table 6: Air Change (ACH) Method for Calculating Infiltration Load

Infiltration Load (Air Change Method)			
ACH (Air Changes/h)	V (m^3)	**Qi (L/s)**	Qi (m^3/h)
1.0	936	260.0277778	936
Avergae # for Residences	2*2.3* 203.5	1000/3600 * Qi(m^3/h)	ACH*V

Cs (W/L*s*K)	**Qvi,s,h (W)**		
1.230	7967.07		
Air Sensible Heat Factor (17.3)	*Cs*Qvi*deltaT*		
(elevation negligible at 40m			

Table 6 details the process for calculating the Infiltration Heating Load via the Air Changes Method. The calculation is conducted as follows:

$ACH = 1.5\ Air\ Changes/h\ (Average\ Air\ Changes\ in\ a\ Residential\ Building\ -\ Engineering\ Toolbox)$

$V = 3 * 2.4 * 203.5\, m^3\ (Table\ 1);\ Q_i = ACH * V = 1539\, m^3/h = 2198 * \frac{1000L}{m^3} * \frac{1h}{3600s} = 610.5\ L/s$

$Q_{vi,s,h} = C_s * Q_{vi} * \Delta T = 1.230\ (W * s/L * ℃) * 610.5(L/s) * 24.91\ (℃)\ (Table\ 1\ \&\ Appendix\ B)$
$= 18705.29\ W$

*The large value of Qvi,s,h indicates that the ACH used is likely an order of magnitude larger than it should be (since the other independent measurements: house volume, temperature gradient, and air sensible heat factor are likely accurate)

(Include Cost/Benefit and HL reduction table) as well as 3D mock-up of House w. Heat pump)

Table 7: Annual Energy Savings Based on State Residential Data

	Cost	Yearly Savings	Amortization Window
Insulation	1.5-6.5k	1k	1-3 years
2 Glaze, 2 Pane Windows	10-17k	3k	3-6 years
Heat Pump (Air)	3.5-7.5k	1k	5-7 years
Heat Pump (Ground)	10-30k	1-2k	10-15 years

Table 7 details housing modification options to combat the high Infiltrative/Window/Wall heat loads of the house.

Discussion

Table 3, shows a breakdown of the heat load by element. The heat loads determined by the two infiltration estimation methods were:

1) Total + ACH Infiltration: 46775 kW
2) Total + IDF Infiltration: 33447 kW

These heat loads were averaged to 40111 kW, which agrees closely with the check figure of 41909 kW determined by extracting heating fuel usage data from prior heating bills. A blower door test could be used to provide a more accurate measurement of the air-leakage of the buildings which would reduce the uncertainty inherent in the infiltration estimation methods used.

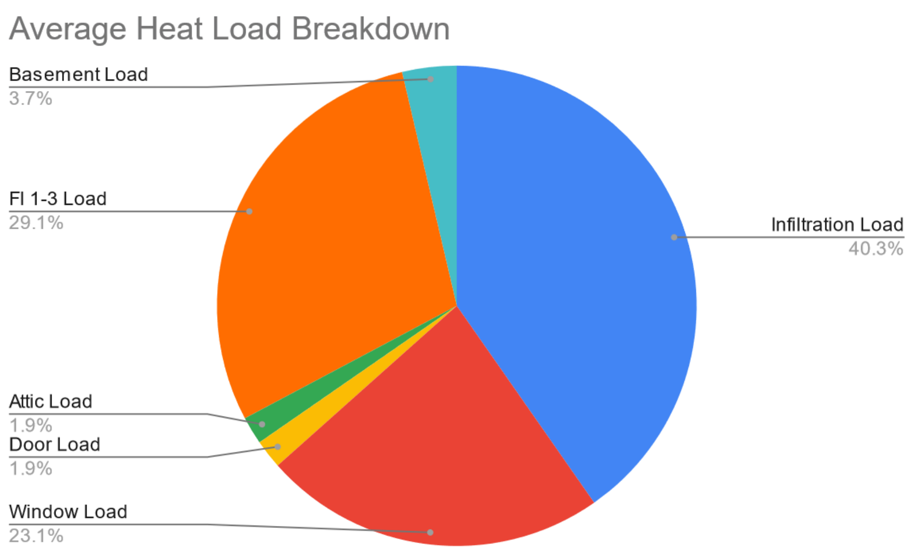

Figure 5: *Each house component's percent contribution to the total house heat load is detailed above*

Figure 5 shows that the floor 1-3, infiltration, and window loads were the three biggest contributors to the total heating load of the house (responsible for 40.3%, 29.1%, and 23.1% of the total heat load respectively). This information suggests that increasing the thermal resistance of the walls or windows will significantly reduce the overall heating load of the house. Since wall renovation is likely expensive, it stands to reason that window or insulation replacement may be the most cost effective renovation option. Table 7 gives a succinct breakdown of the cost-effectiveness of various energy saving modifications. According to wall insulation quotes from Forbes Home, wall insulation replacement will cost between $2.35 and $3.25/sq. ft. ($0.35 - $0.50 material cost, $1.50/sq. ft. to remove pre existing insulation, and $0.50 - $1.25 to install). Therefore, it would cost approximately between $1527 - $2112 (650 sq. ft. * $2.35 & $3.25) to replace the insulation of the ABC House.

On the other hand, the average cost of replacing a mid-range double-hung window is $600, per window replacement quotes on Forbes Homes. Thus, it would cost ~$16800 (28 windows) to replace all the windows on the ABC House.

Appendix

A) Heat Load Calculation Sheet, https://docs.google.com/spreadsheets/d/199SMrYJNdYGzXxqG0Ubq4cxq275jWvUOFdBP5xeER20/edit?usp=sharing

B) ASHRAE Fundamentals 2021 Handbook (tables included below)

Table 6 Typical Duct Loss/Gain Factors

		1 Story						2 or More Stories					
	Supply/Return Leakage	11%/11%			5%/5%			11%/11%			5%/5%		
Duct Location	Insulation (m²·K)/W	R-0	R-0.7	R-1.4	R-0	R-0.7	R-1.4	R-0	R-0.7	R-1.4	R-0	R-0.7	R-1.4
Conditioned space		No loss (F_{dl} = 0)											
Attic	C	1.26	0.71	0.63	0.68	0.33	0.27	1.02	0.66	0.60	0.53	0.29	0.25
	H/F	0.49	0.29	0.25	0.34	0.16	0.13	0.41	0.26	0.24	0.27	0.14	0.12
	H/HP	0.56	0.37	0.34	0.34	0.19	0.16	0.49	0.35	0.33	0.28	0.17	0.15
Basement	C	0.12	0.09	0.09	0.07	0.05	0.04	0.11	0.09	0.09	0.06	0.04	0.04
	H/F	0.28	0.18	0.16	0.19	0.10	0.08	0.24	0.17	0.15	0.16	0.09	0.08
	H/HP	0.23	0.17	0.16	0.14	0.09	0.08	0.20	0.16	0.15	0.12	0.08	0.07
Crawlspace	C	0.16	0.12	0.11	0.10	0.06	0.05	0.14	0.12	0.11	0.08	0.06	0.05
	H/F	0.49	0.29	0.25	0.34	0.16	0.13	0.41	0.26	0.24	0.27	0.14	0.12
	H/HP	0.56	0.37	0.34	0.34	0.19	0.16	0.49	0.35	0.33	0.28	0.17	0.15

Values calculated for ASHRAE *Standard* 152 default duct system surface area using model of Francisco and Palmiter (1999). Values are provided as guidance only; losses can differ substantially for other conditions and configurations. Assumed surrounding temperatures:

Cooling (C): t_o = 35°C, t_{attic} = 49°C, t_b = 20°C, t_{crawl} = 22°C Heating/furnace (H/F) and heating/heating pump (H/HP): t_o = 0°C, t_{attic} = 0°C, t_b = 18°C, t_{crawl} = 0°C

$$\text{IDF} = \frac{I_0 + H|\Delta t|[I_1 + I_2(A_{L,flue}/A_L)]}{1000} \quad (10)$$

where

I_0, I_1, I_2 = coefficients, as follows:

	Cooling 3.4 m/s	Heating 6.7 m/s
I_0	25	51
I_1	0.38	0.35
I_2	0.12	0.23

H = building average stack height, m (typically 2.5 m per story)

Table 3 Unit Leakage Areas

Construction	Description	A_{ul}, cm²/m²
Tight	Construction supervised by air-sealing specialist	0.7
Good	Carefully sealed construction by knowledgeable builder	1.4
Average	Typical current production housing	2.8
Leaky	Typical pre-1970 houses	5.6
Very leaky	Old houses in original condition	10.4

Table 4 Evaluation of Exposed Surface Area

Situation	Include	Exclude
Ceiling/roof combination (e.g., cathedral ceiling without attic)	Gross surface area	
Ceiling or wall adjacent to attic	Ceiling or wall area	Roof area
Wall exposed to ambient	Gross wall area (including fenestration area)	
Wall adjacent to unconditioned buffer space (e.g., garage or porch)	Common wall area	Exterior wall area
Floor over open or vented crawlspace	Floor area	Crawlspace wall area
Floor over sealed crawlspace	Crawlspace wall area	Floor area
Floor over conditioned or semiconditioned basement	Above-grade basement wall area	Floor area
Slab floor		Slab area

Table 6 Design U-Factors of Swinging Doors in W/(m²·K)

Door Type (Rough Opening = 970 × 2080 mm)	No Glazing	Single Glazing	Double Glazing with 12.7 mm Air Space	Double Glazing with e = 0.10, 12.7 mm Argon
Slab Doors				
Wood slab in wood frame[a]	2.61			
6% glazing (560 × 200 lite)	—	2.73	2.61	2.50
25% glazing (560 × 910 lite)	—	3.29	2.61	2.38
45% glazing (560 × 1620 lite)	—	3.92	2.61	2.21
More than 50% glazing		Use Table 4 (operable)		
Insulated steel slab with wood edge in wood frame[b]	0.91			
6% glazing (560 × 200 lite)	—	1.19	1.08	1.02
25% glazing (560 × 910 lite)	—	2.21	1.48	1.31
45% glazing (560 × 1630 lite)	—	3.29	1.99	1.48
More than 50% glazing		Use Table 4 (operable)		
Foam-insulated steel slab with metal edge in steel frame[c]	2.10			
6% glazing (560 × 200 lite)	—	2.50	2.33	2.21
25% glazing (560 × 910 lite)	—	3.12	2.73	2.50
45% glazing (560 × 1630 lite)	—	4.03	3.18	2.73
More than 50% glazing		Use Table 4 (operable)		
Cardboard honeycomb slab with metal edge in steel frame	3.46			
Stile-and-Rail Doors				
Sliding glass doors/French doors		Use Table 4 (operable)		
Site-Assembled Stile-and-Rail Doors				
Aluminum in aluminum frame	—	7.49	5.28	4.49
Aluminum in aluminum frame with thermal break	—	6.42	4.20	3.58

Notes:
[a] Thermally broken sill [add 0.17 W/(m²·K) for non-thermally broken sill]
[b] Non-thermally broken sill
[c] Nominal U-factors are through center of insulated panel before consideration of thermal bridges around edges of door sections and because of frame.

Table 5 Typical IDF Values, L/(s·cm²)

H,	Heating Design Temperature, °C					Cooling Design Temperature, °C			
m	−40	−30	−20	−10	0	10	30	35	40
2.5	0.10	0.095	0.086	0.077	0.069	0.060	0.031	0.035	0.040
3	0.11	0.10	0.093	0.083	0.072	0.061	0.032	0.038	0.043
4	0.14	0.12	0.11	0.093	0.079	0.065	0.034	0.042	0.049
5	0.16	0.14	0.12	0.10	0.086	0.069	0.036	0.046	0.055
6	0.18	0.16	0.14	0.11	0.093	0.072	0.039	0.050	0.061
7	0.20	0.17	0.15	0.12	0.10	0.075	0.041	0.051	0.068
8	0.22	0.19	0.16	0.14	0.11	0.079	0.043	0.058	0.074

Table 2 Typical Fenestration Characteristics[a]

					Frame									
					Operable					Fixed				
Glazing Type	Glazing Layers	ID[b]	Property[c,d]	Center of Glazing	Aluminum	Aluminum with Thermal Break	Reinforced Vinyl/Aluminum Clad Wood	Wood/Vinyl	Insulated Fiberglass/Vinyl	Aluminum	Aluminum with Thermal Break	Reinforced Vinyl/Aluminum Clad Wood	Wood/Vinyl	Insulated Fiberglass/Vinyl
Clear	1	1a	*U*	5.91	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
			SHGC	0.86	0.75	0.75	0.64	0.64	0.64	0.78	0.78	0.75	0.75	0.75
	2	5a	*U*	2.73	4.62	3.42	3.00	2.87	5.83	3.61	3.22	2.86	2.84	2.72
			SHGC	0.76	0.67	0.67	0.57	0.57	0.57	0.69	0.69	0.67	0.67	0.67
	3	29a	*U*	1.76	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
			SHGC	0.68	0.60	0.60	0.51	0.51	0.51	0.62	0.62	0.60	0.60	0.60
Low-e, low-solar	2	25a	*U*	1.70	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90
			SHGC	0.41	0.37	0.37	0.31	0.31	0.31	0.38	0.38	0.36	0.36	0.36
	3	40c	*U*	1.02	3.22	2.07	1.76	1.71	1.45	2.13	1.76	1.44	1.40	1.33
			SHGC	0.27	0.25	0.25	0.21	0.21	0.21	0.25	0.25	0.24	0.24	0.24
Low-e, high-solar	2	17c	U	1.99	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
			SHGC	0.70	0.62	0.62	0.52	0.52	0.52	0.64	0.64	0.61	0.61	0.61
	3	32c	*U*	1.42	3.54	2.36	2.02	1.97	1.70	2.47	2.10	1.77	1.73	1.66
			SHGC	0.62	0.55	0.55	0.46	0.46	0.46	0.56	0.56	0.54	0.54	0.54
Heat-absorbing	1	1c	*U*	5.91	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
			SHGC	0.73	0.64	0.64	0.54	0.54	0.54	0.66	0.66	0.64	0.64	0.64
	2	5c	*U*	2.73	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
			SHGC	0.62	0.55	0.55	0.46	0.46	0.46	0.56	0.56	0.54	0.54	0.54
	3	29c	*U*	1.76	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
			SHGC	0.34	0.31	0.31	0.26	0.26	0.26	0.31	0.31	0.30	0.30	0.30
Reflective	1	1l	*U*	5.91	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
			SHGC	0.31	0.28	0.28	0.24	0.24	0.24	0.29	0.29	0.27	0.27	0.27
	2	5p	*U*	2.73	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
			SHGC	0.29	0.27	0.27	0.22	0.22	0.22	0.27	0.27	0.26	0.26	0.26
	3	29c	*U*	1.76	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
			SHGC	0.34	0.31	0.31	0.26	0.26	0.26	0.31	0.31	0.30	0.30	0.30

[a]Data are from Chapter 15, Tables 4 and 14 for selected combinations. [b]ID = Chapter 15 glazing type identifier. [c]*U* = U-factor, W/(m²·K). [d]SHGC = solar heat gain coefficient.

C) ASHRAE Standards and Codes

Energy	Air-Conditioning and Refrigerating Equipment Nameplate Voltages	AHRI	ANSI/AHRI 110-2012
	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS-1997
	Thermal Energy Storage	ACCA	ACCA 2005
	Measurement of Energy and Demand Savings	ASHRAE	ASHRAE *Guideline* 14-2014
	Energy Standard for Buildings Except Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE/IES 90.1-2016
	Energy-Efficient Design of Low-Rise Residential Buildings	ASHRAE	ANSI/ASHRAE/IES 90.2-2007
	Energy Conservation in Existing Buildings	ASHRAE	ANSI/ASHRAE/IES 100-2015
	Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions	ASHRAE	ANSI/ASHRAE 105-2014
	Method of Test for the Evaluation of Building Energy Analysis Computer Programs	ASHRAE	ANSI/ASHRAE 140-2011
	Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems	ASHRAE	ANSI/ASHRAE 152-2014
	Standard for the Design of High-Performance, Green Buildings Except Low-Rise Residential Buildings	ASHRAE/ USGBC	ANSI/ASHRAE/USGBC/IES 189.1-2014
	National Green Building Standard	ICC/ ASHRAE	ICC/ASHRAE 700-2015
	Fuel Cell Power Systems Performance	ASME	PTC 50-2002 (RA14)
	International Energy Conservation Code® (2015)	ICC	IECC
	International Green Construction Code™ (2012)	ICC	IGCC
	Uniform Solar Energy Code (2012)	IAPMO	IAPMO
	Energy Management Guide for Selection and Use of Fixed Frequency Medium AC Squirrel-Cage Polyphase Induction Motors	NEMA	NEMA MG 10-2013
	Energy Management Guide for Selection and Use of Single-Phase Motors	NEMA	NEMA MG 11-1977 (R2012)
	HVAC Systems—Commissioning Manual, 2nd ed.	SMACNA	SMACNA 2013
	Building Systems Analysis and Retrofit Manual, 2nd ed.	SMACNA	SMACNA 2011
	Energy Systems Analysis and Management, 2nd ed.	SMACNA	SMACNA 2014
	Energy Management Equipment	UL	UL 916-2007

Heating	Commercial Systems Overview	ACCA	ACCA Manual CS-1993
	HVAC Quality Installation Specification	ACCA	ANSI/ACCA 5 QI-2015
	Technician's Guide & Workbook for Quality Installations	ACCA	ACCA 2015
	Residential Load Calculations	ACCA	ANSI/ACCA 2 Manual J-2016
	Comfort, Air Quality, and Efficiency by Design	ACCA	ACCA Manual RS-1997
	Residential Equipment Selection, 2nd ed.	ACCA	ANSI/ACCA 3 Manual S-2014
	Heating, Ventilating and Cooling Greenhouses	ASABE	ANSI/ASAE EP406.4-2003 (R2008)
	Peak Cooling and Heating Load Calculations in Buildings Except Low-Rise Residential Buildings	ASHRAE/ ACCA	ANSI/ASHRAE/ACCA 183-2007 (RA14)
	Heater Elements	CSA	C22.2 No. 72-10 (R2014)
	Determining the Required Capacity of Residential Space Heating and Cooling Appliances	CSA	CAN/CSA-F280-12
	Heat Loss Calculation Guide (2001)	HYDI	HYDI H-22
	Residential Hydronic Heating Installation Design Guide	HYDI	IBR Guide
	Radiant Floor Heating (1995)	HYDI	HYDI 004
	Advanced Installation Guide (Commercial) for Hot Water Heating Systems (2001)	HYDI	HYDI 250
	Environmental Systems Technology, 2nd ed. (1999)	NEBB	NEBB
	Pulverized Fuel Systems	NFPA	NFPA 8503-97
	Aircraft Electrical Heating Systems	SAE	SAE AIR860B-2011
	Heating Value of Fuels	SAE	SAE J1498-2011
	Performance Test for Air-Conditioned, Heated, and Ventilated Off-Road Self-Propelled Work Machines	SAE	SAE J1503-2004
	HVAC Systems Applications, 2nd ed.	SMACNA	SMACNA 2010
	Electric Baseboard Heating Equipment	UL	ANSI/UL 1042-2009
	Electric Duct Heaters	UL	ANSI/UL 1996-2009
	Heating and Cooling Equipment	UL/CSA	ANSI/UL 1995-2011/C22.2 No. 236-11

D) Source for Swarthmore Weather Averages
https://www.worldweatheronline.com/swarthmore-weather-averages/pennsylvania/us.aspx

E) Infiltration/Ventilation Calculation

The sensible and latent heat loss from outdoor air infiltration and ventilation are calculated by determining the volumetric flow, Q, of outdoor air entering the building.

First the Air Leakage Rate is calculated based on the number of air exchanges per hour experienced by the building:

$$Q_i = ACH * V$$

Q_i depends on:

1) The building effective leakage area and its distribution along surfaces and flues
2) The driving pressure caused by buoyancy and wind.

$$Q_i = A_L IDF$$

Additionally,

$$A_L = A_{es} A_{ul}$$

The infiltration driving force can be calculated as follows

$$IDF = \frac{I_0 + H|\Delta t|(I_1 + I_2(A_{L,flue}/A_L))}{1000}$$

where

I_0, I_1, I_2 = coefficients, as follows:

	Cooling 3.4 m/s	Heating 6.7 m/s
I_0	25	51
I_1	0.38	0.35
I_2	0.12	0.23

H = building average stack height, m (typically 2.5 m per story)

Equation 10 (17.6) of the ASHRAE Handbook

However, an IDF value of 0.069 (Under the assumption that $A_{L,flue} = 0$) from Table 5 is used in this model

Table 5 Typical IDF Values, L/(s·cm²)

H, m	Heating Design Temperature, °C					Cooling Design Temperature, °C			
	−40	−30	−20	−10	0	10	30	35	40
2.5	0.10	0.095	0.086	0.077	0.069	0.060	0.031	0.035	0.040
3	0.11	0.10	0.093	0.083	0.072	0.061	0.032	0.038	0.043
4	0.14	0.12	0.11	0.093	0.079	0.065	0.034	0.042	0.049
5	0.16	0.14	0.12	0.10	0.086	0.069	0.036	0.046	0.055
6	0.18	0.16	0.14	0.11	0.093	0.072	0.039	0.050	0.061
7	0.20	0.17	0.15	0.12	0.10	0.075	0.041	0.051	0.068
8	0.22	0.19	0.16	0.14	0.11	0.079	0.043	0.058	0.074

Table 5 (17.6) of the ASHRAE Handbook

Unit Leakage Areas are calculated under the "leaky" construction assumption from Table 3 (since the house was built in the 60's)

Table 3 Unit Leakage Areas

Construction	Description	A_{ul}, cm^2/m^2
Tight	Construction supervised by air-sealing specialist	0.7
Good	Carefully sealed construction by knowledgeable builder	1.4
Average	Typical current production housing	2.8
Leaky	Typical pre-1970 houses	5.6
Very leaky	Old houses in original condition	10.4

Table 3 (17.6) of the ASHRAE Handbook (Appendix B)

The ASHRAE *Standard* 62.2 specifies that residential buildings must have a required whole-building ventilation rate determined by the following equation

$$Q_v = 0.15A_{cf} + 3.5(N_{br} + 1)$$

Finally, the sensible heating ventilation/infiltration load (15) is calculated per the following ASHRAE guideline (here we assume that $Q_{bal,hr}$, $Q_{bal,oth}$, & $Q_{unbal} = 0$ [based on the prior assumption that the ventilation rate requirement provided above is satisfied]) :

Ventilation/infiltration load. The cooling or heating load from ventilation and infiltration is calculated as follows:

$$q_{vi,s} = C_s[Q_{vi} + (1 - \varepsilon_s)Q_{bal,hr} + Q_{bal,oth}]\Delta t \qquad (15)$$

$$q_{vi,l} = C_l(Q_{vi} + Q_{bal,oth})\Delta W \quad \text{(no HRV/ERV)} \qquad (16)$$

$$q_{vi,t} = C_{t6}[Q_{vi} + (1 - \varepsilon_t)Q_{bal,hr} + Q_{bal,oth}]\Delta h \qquad (17)$$

$$q_{vi,l} = q_{vi,t} - q_{vi,s} \qquad (18)$$

where

$q_{vi,s}$ = sensible ventilation/infiltration load, W
ε_s = HRV/ERV sensible effectiveness
$Q_{bal,hr}$ = balanced ventilation flow rate via HRV/ERV equipment, L/s
$Q_{bal,oth}$ = other balanced ventilation supply airflow rate, L/s
Δt = indoor/outdoor temperature difference, K
ΔW = indoor/outdoor humidity ratio difference
$q_{vi,t}$ = total ventilation/infiltration load, W
ε_t = HRV/ERV total effectiveness
Δh = indoor/outdoor enthalpy difference, kJ/kg
$q_{vi,l}$ = latent ventilation/infiltration load, W

Equations 15 - 18 from the ASHRAE Handbook (Appendix B)

Nomenclature

Symbol	Significance (units)
k	$Proportionality\ Constant\ (W/mK)$
h	$Convection\ Heat\ Transfer\ Coefficient\ (W/m^2K)$
A	$Exposed\ Area\ (m^2)$
L	$Characteristic\ Length\ (m)$
$\bigtriangledown T$	$Temperature\ Gradient\ Across\ Surface\ (K)$
q	$Heat\ Energy\ (W)$
$\sum R_{total},\ R_t$	$Total\ Thermal\ Resistivity\ (m^2K/W)$
U	$Total\ Thermal\ Conductance\ (W/m^2K)$
$\sum R_{conduction}$	$Conductive\ Thermal\ Resistivity\ (m^2K/W)$
$\sum R_{convection}$	$Convective\ Thermal\ Resistivity\ (m^2K/W)$
$\sum R_{convection}$	$Convective\ Thermal\ Resistivity\ (m^2K/W)$
IDF	$Infiltration\ Driving\ Force\ (L * s/cm^2)$
ACH	$Air\ Changes\ per\ Hour\ (\#/h)$
A_{ul}	$Unit\ Leakage\ Area\ (cm^2/m^2)$
A_{es}	$Exposed\ Area\ (m^2)$
Al	$Average\ Leakage\ Per\ Area\ (cm^2)$
Q_i	$Air\ Leakage\ Rate\ (L/s)$

C_s	$Air\ Sensible\ Heat\ Factor\ (W/L * s * K)$ 1.230 for elevation < 300m
$Q_{vi, s, h}$	$Sensible\ Infiltration/Ventilation\ Heat\ Load\ (W)$

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ASHRAE Standard 62.1 ("Ventilation and Acceptable Indoor Air Quality in Residential Buildings") recommends homes receive no less than 0.35 air changes per hour of outdoor air to ensure adequate indoor air.

Ventilation for Indoor Air Quality, ASHRAE Standard 62-89, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

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