# Student Laboratory Manual: Building Envelope Thermal Transmission, Fenestration SHGC Modeling, and Infiltration Sizing per ACCA Manual J

**Courseware & Educational Resource Series — HVACLogic Open Building Science Initiative**

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**Canonical Engine:** `https://hvaclogic.org/calculators/btu-calculator`

**Companion Hub:** `https://hvaclogic.org/cooling-loads`

**Companion Assembly Tool:** `https://hvaclogic.org/calculators/r-value-calculator`

**Target Level:** Mechanical Engineering Undergraduates, Building Science Researchers, and HVAC/R Apprentices (CTE / Post-Secondary)

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## Abstract

Accurate determination of residential peak cooling and heating thermal loads is fundamental to mechanical equipment selection, thermal comfort, indoor humidity control, and building decarbonization. For decades, empirical trade shortcuts such as "one ton of air conditioning per 500 square feet of floor area" have been used in place of rigorous thermodynamic modeling. In modern construction built under contemporary energy conservation codes (IECC 2021/2024), these legacy heuristics oversize cooling equipment by 80% to 120%, causing severe short-cycling, poor latent moisture dehumidification, elevated indoor relative humidity (>65%), and premature compressor failure.

This interactive laboratory exercise guides engineering and technology students through the quantitative analysis of residential envelope thermodynamics under ACCA Manual J (8th Edition) and ASHRAE Fundamentals. Students formulate multi-layer Fourier conduction matrices across composite wall and ceiling assemblies, calculate fenestration solar heat gains using direct incident radiation and Solar Heat Gain Coefficients (SHGC), and convert pressure-driven blower door air leakage ($ACH_{50}$) into continuous design infiltration CFM. Through a side-by-side comparative simulation of a 2,500 sq ft home across legacy (1975) versus high-performance modern (2025) envelope specifications, students quantify the breakdown of contractor heuristics and evaluate sensible heat ratio (SHR) equipment matching. Interactive verification models and open-source computational reference implementations are permanently maintained at https://hvaclogic.org/calculators/btu-calculator.

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## 1. Educational Objectives

Upon completion of this computational laboratory unit, students will be able to: 1. **Derive Composite Assembly U-Factors**: Calculate overall thermal transmittance ($U$-value) by summing interior boundary air films, cavity insulation, structural framing framing factors, and continuous exterior rigid foam insulation. 2. **Model Fenestration Solar and Conductive Transmission**: Decouple window thermal loads into conductive transmission and transmitted solar radiation using Solar Heat Gain Coefficients (SHGC) and directional solar irradiance matrices. 3. **Quantify Blower Door Infiltration Dynamics**: Convert empirical blower door depressurization metrics ($ACH_{50}$ at 50 Pa) into effective natural design air infiltration CFM using building volume and Sherman-Grimsrud / LBL correlation factors. 4. **Contrast Sensible and Latent Cooling Loads**: Evaluate the sensible heat ratio ($\text{SHR} = Q_s / Q_{total}$) and quantify why oversized equipment fails to depress evaporator coil temperatures below the dew point long enough to extract latent moisture. 5. **Critique Empirical Trade Sizing Heuristics**: Demonstrate mathematically why floor area rules of thumb fail across varied building envelopes, orientations, and climate zones.

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## 2. Governing Thermodynamic Principles & Mathematical Formulation

### 2.1 Multi-Layer Fourier Conduction & Overall U-Factor Reciprocals

Conductive heat transfer through opaque building assemblies (exterior walls, ceilings, floors) operates under steady-state one-dimensional Fourier conduction:

```
Q_conduction = U_assembly  Area  (T_outdoor - T_indoor)
```

The overall thermal transmittance ($U$-factor, expressed in $\text{BTU}/(\text{hr}\cdot\text{ft}^2\cdot^\circ\text{F})$) is the mathematical reciprocal of total thermal resistance ($R_{total}$):

```
U_assembly = 1 / R_total
R_total = R_film_in + Σ(R_layer_i) + R_film_out
```

When structural framing (such as wood or light-gauge steel studs) interrupts cavity insulation, the effective assembly resistance must be solved using parallel-path thermal analysis:

```
U_effective = (Framing_Fraction  U_framing) + (Cavity_Fraction  U_cavity)
```

### 2.2 Fenestration Solar Heat Gain Coefficient (SHGC) Modeling

Window glazing units transfer thermal energy through simultaneous conductive transmission and direct solar radiative absorption:

```
Q_fenestration = Q_conductive + Q_solar
Q_conductive = U_window  Area_glass  (T_outdoor - T_indoor)
Q_solar = Area_glass  SHGC  E_solar_incident * IAC
```

Where: - $\text{SHGC}$ = Solar Heat Gain Coefficient (fraction of incident solar radiation admitted through the glazing, dimensionless). - $E_{solar\_incident}$ = Peak solar irradiance per directional orientation ($\text{BTU}/(\text{hr}\cdot\text{ft}^2)$). - $\text{IAC}$ = Internal Shading Attenuation Coefficient (blinds, shades, drapes, dimensionless).

### 2.3 Air Infiltration Sensible & Latent Heat Transfer

Uncontrolled air leakage through building envelope penetrations introduces both temperature (sensible) and moisture (latent) loads. Converting blower door test metrics at 50 Pascals ($ACH_{50}$) to natural design infiltration CFM:

```
CFM_50 = (ACH_50 * Volume_building) / 60
CFM_natural = CFM_50 / N_factor
```

Where $N_{factor}$ is the climate-dependent Lawrence Berkeley National Laboratory (LBNL) correlation factor (typically 15 to 22 depending on climate zone, shielding, and building height).

The resulting sensible and latent infiltration heat loads are:

```
Q_sensible_inf = 1.08  CFM_natural  (T_outdoor - T_indoor)
Q_latent_inf = 4840  CFM_natural  (W_outdoor - W_indoor)
```

Where $W$ is the moist air humidity ratio in pounds of water vapor per pound of dry air ($\text{lb}_{w}/\text{lb}_{da}$).

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## 3. Laboratory Comparative Experiment

### Scenario: 2,500 Sq Ft Single-Story Home in Atlanta, GA

- **Outdoor Design Conditions**: 92°F Dry Bulb / 75°F Coincident Wet Bulb ($W_{outdoor} = 0.0142\text{ lb/lb}$). - **Indoor Design Conditions**: 75°F Dry Bulb / 50% Relative Humidity ($W_{indoor} = 0.0093\text{ lb/lb}$, Dew Point 55.1°F). - **Enclosure Geometry**: 2,500 sq ft floor area ($50\text{ ft} \times 50\text{ ft}$), 9 ft ceiling height ($V = 22,500\text{ cu ft}$), 1,800 sq ft gross exterior wall, 360 sq ft window glazing (20% window-to-wall ratio).

### Envelope Specification Comparison:

| Engineering Parameter | Case Study A: 1975 Uninsulated Enclosure | Case Study B: 2025 Modern IECC Enclosure | | :--- | :---: | :---: | | **Wall Cavity Insulation** | $2\times4$ R-7 uncompressed fiberglass | $2\times6$ R-21 dense-pack batt | | **Continuous Exterior Insulation** | None ($R-0$) | $R-5$ continuous polyisocyanurate foam | | **Overall Wall Assembly U-Value** | $U = 0.143\text{ BTU}/(\text{hr}\cdot\text{ft}^2\cdot^\circ\text{F})$ | $U = 0.038\text{ BTU}/(\text{hr}\cdot\text{ft}^2\cdot^\circ\text{F})$ | | **Ceiling / Roof Assembly** | $R-19$ loose fiberglass ($U = 0.053$) | $R-49$ blown cellulose ($U = 0.020$) | | **Fenestration Glazing** | Single clear aluminum ($U = 1.15$, $\text{SHGC} = 0.82$) | Low-E Argon double pane ($U = 0.28$, $\text{SHGC} = 0.22$) | | **Envelope Tightness ($ACH_{50}$)** | $9.5\text{ ACH}_{50}$ ($N = 18 \implies 198\text{ CFM}_{nat}$) | $2.0\text{ ACH}_{50}$ with ERV ($42\text{ CFM}_{eff}$) | | **Calculated Sensible Cooling Load** | $41,200\text{ BTU/hr}$ | $19,800\text{ BTU/hr}$ | | **Calculated Latent Cooling Load** | $16,800\text{ BTU/hr}$ | $6,600\text{ BTU/hr}$ | | **Total Peak Manual J Cooling Load | $58,000\text{ BTU/hr}$ (4.83 Tons) | $26,400\text{ BTU/hr}$ (2.20 Tons)** |

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## 4. Student Problem Set & Lab Calculations

### Exercise 1: U-Factor & Wall Transmission Verification

Using the fundamental resistance reciprocal formula, verify the thermal transmittance of Case Study B's wall assembly consisting of: - Outside air film: $R-0.17$ - 1/2-inch vinyl siding + weather barrier: $R-0.62$ - 1-inch continuous polyisocyanurate foam: $R-6.00$ - 1/2-inch OSB structural sheathing: $R-0.62$ - $2\times6$ framing at 16" OC with R-21 batt (framing factor 23%, stud R-6.88): $R-18.4$ effective - 1/2-inch gypsum board: $R-0.45$ - Inside air film: $R-0.68$

*Question 1.1*: Calculate $R_{total}$ and $U_{assembly}$. Compare with the reference table above.

### Exercise 2: Fenestration Radiation Delta

Given 120 sq ft of west-facing glazing with peak afternoon solar irradiance of $E_{solar} = 195\text{ BTU}/(\text{hr}\cdot\text{ft}^2)$: *Question 2.1*: Calculate peak fenestration heat gain for Case A ($\text{SHGC} = 0.82$, $U = 1.15$, $ΔT = 17^\circ\text{F}$). *Question 2.2*: Calculate peak fenestration heat gain for Case B ($\text{SHGC} = 0.22$, $U = 0.28$, $ΔT = 17^\circ\text{F}$). *Question 2.3*: What percentage of total peak heat gain reduction is attributable to glazing improvements?

### Exercise 3: Sizing Heuristic Failure Analysis

A mechanical contractor visits the Case Study B modern home and applies the traditional rule of thumb: $1\text{ ton per }500\text{ sq ft}$. *Question 3.1*: What nominal tonnage would the contractor install? *Question 3.2*: By what percentage is this equipment oversized relative to the verified Manual J peak load of 2.20 tons? *Question 3.3*: If this oversized system operates at an airflow of 400 CFM per ton, calculate the total CFM delivered. If the duct system was sized for a 2.5-ton system (1,000 CFM at 0.08 in. wg friction rate), explain the static pressure and acoustic noise consequences.

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## 5. Verification & Laboratory Submission Requirements

Students must execute their numerical models in the HVACLogic Interactive BTU Load Calculator and submit: 1. Completed calculation sheets for Exercises 1, 2, and 3. 2. An exported print submittal PDF from the HVACLogic calculator verifying the Sensible Heat Ratio (SHR) and room-by-room load distribution. 3. A 250-word engineering memo explaining why short-cycling prevents dehumidification when equipment is oversized by >50%.