Building Science Education for Solar Decathlon

First Law of Thermodynamics

First Law of Thermodynamics

“Thermo-” comes from the Greek word *thermos* meaning “hot” or “warm”

“Dynamics” comes from the Greek word *dynamis* meaning “force” or “power”

Law of Conservation of Energy:
“Energy cannot be created nor destroyed”

The first step of any thermodynamic problem is to define a system boundary.
Measuring Energy Flows Across a Boundary

Work (W):
The transfer of mechanical or electrical energy across the boundary

Heat (Q):
The transfer of thermal energy across the boundary due to a temperature difference at the boundary.

Energy associated with mass crossing the boundary is described as "heat equivalent" (e.g., natural gas)

$W + Q = \Delta E$

Theoretical energy boundary of a system
Direction of Energy Flow is Important

\[ W_1 + W_2 + Q_{\text{In}} = \Delta U \]
Direction of Energy Flow is Important

\[ W_1 + W_2 + Q_{\text{in}} + (-Q_{\text{Lost}}) = \Delta E \]

Caution: Units of Work (W) and Heat (Q) must be the same in order to add them together!
Direction of Energy Flow is Important

\[ W_1 + W_2 + Q_{\text{in}} - Q_{\text{Lost}} = \Delta E \]

Over time, \( \Delta E = 0 \)

Therefore, \( \text{Energy}_{\text{in}} = \text{Energy}_{\text{out}} \)

Caution: Units of Work (W) and Heat (Q) must be the same in order to add them together!
Energy_{in} = Energy_{out}
Energy_{in} = Energy_{out}

- Roof
- Walls
- Windows
- Chimney
- Floors

W_{elec}
Q_{fuel}
Coming up in the Building Envelope module…

Look at the concept of Energy_{in} = Energy_{out}

Study how energy flows through the building envelope (e.g., walls, windows, doors)

Use that information to determine how much energy a building needs
Questions or comments?

Please email SolarDecathlon@nrel.gov
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

Holly Carr
U.S. Department of Energy

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Building Science Education for Solar Decathlon

*Fourier’s Law of Heat Transfer*

*(Part 1)*

Source: Marjorie Schott, NREL
Heat always flows from hot to cold

\[ Q = \text{thermal energy transferred (i.e., heat)} \]

Units: Btu, J, Wh

\[ \dot{Q} = \text{rate of thermal energy transfer (i.e., heat transfer rate)} \]

Units: Btu/hr, J/s = W
Modes of Heat Transfer

Conduction

Convection

Radiation

Source: Marjorie Schott, NREL
Modes of Heat Transfer

Conduction

• Exchange of kinetic energy between molecules, without any macroscopic movement of the molecules

Convection

Radiation

Source: Marjorie Schott, NREL


Modes of Heat Transfer

Conduction

Convection

• Motion of molecules in a fluid (i.e., liquid or gas) resulting from density gradient

Radiation

Source: Marjorie Schott, NREL
Modes of Heat Transfer

Conduction

Convection

Radiation

• Transfer of thermal energy through electromagnetic waves. No physical contact is required.

Source: Marjorie Schott, NREL
Coming up in Part 2…

Application of heat transfer law to building science

Definition of each term of the heat transfer equation

\[ \dot{Q} = U \cdot A \cdot \Delta T \]
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Fourier’s Law of Heat Transfer

(Part 2)

Source: Marjorie Schott, NREL
Modes of Heat Transfer

How does this apply to building science?

Source: Marjorie Schott, NREL
The building envelope isolates the indoor environment from the outdoor environment.

Source: secondnature.org/solutions-center/building-envelope/
Heat transfer through the building envelope is actually very complex…

Solar radiation is considered “shortwave” radiation (higher frequency/higher energy).

Longwave radiation is the lower frequency/lower energy portion of the electromagnetic spectrum (i.e., infrared).

Source: Marjorie Schott, NREL
Heat transfer through the building envelope is actually very complex…
Heat Transfer Through the Building Envelope

Heat Transfer \propto \text{Area (A)} \cdot \text{Difference in Temp. (}\Delta T\text{)}

Proportionality constant = ?
Heat Transfer Through the Building Envelope

Heat transfer is dependent upon:

\[ D \Delta T = U A (T_1 - T_2) \]

- **Difference in Temperature** ($\Delta T$)
- **Cross-sectional area of the wall** ($A$)
- **Thermal transmittance of the materials** in the wall

Greater $\Delta T$ results in a higher rate of heat transfer.
Heat Transfer Through the Building Envelope

Inside (Warm)  >  Outside (Cold)

Heat transfer is dependent upon:

- Difference in temperature from inside to outside ($\Delta T$). Larger $\Delta T$ results in a higher rate of heat transfer.
- Cross-sectional area of the wall ($A$). Larger $A$ results in a higher rate of heat transfer.

Area ($A$)
Heat Transfer Through the Building Envelope

- Difference in temperature from inside to outside ($\Delta T$). Larger $\Delta T$ results in a higher rate of heat transfer.
- Cross-sectional area of the wall ($A$). Larger $A$ results in a higher rate of heat transfer.
- Thermal transmittance of the materials in the wall. Larger U-factor results in a higher rate of heat transfer.

In a homogeneous material:

$$U = \frac{\text{Thermal Conductivity of the Material} (k)}{\text{Thickness of the Material} (x)}$$
Heat Transfer Through the Building Envelope

\[ U = \frac{\Delta T}{T_{inside} - T_{outside}} \cdot \text{Area (A)} \]
Heat Transfer Through the Building Envelope

Heat Transfer \propto Area (A) \cdot Difference in Temp (\Delta T)

Proportionality constant = U

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

\[ \frac{\text{Btu}}{\text{hr}} = U \cdot \text{ft}^2 \cdot \circF \]

\[ \dot{Q} = \frac{\text{Btu}}{\text{hr} \cdot \text{ft}^2 \cdot \circF} \cdot \text{ft}^2 \cdot \circF \]
# U-Factor vs. R-Value

**Thermal Transmittance**

**Thermal Resistance**

## U – Factor

<table>
<thead>
<tr>
<th>English System</th>
<th>( \frac{Btu}{hr \cdot ft^2 \cdot ^\circ F} )</th>
</tr>
</thead>
</table>
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National Renewable Energy Laboratory
References

   a. Chapter 26: Material Properties
   b. Chapter 27: Calculate U-Factor
Commonly Used Units for the Heat Transfer Law

**English System**

\[ \dot{Q} \propto \frac{Btu}{hr} \]

\[ T \propto °F \]

\[ A \propto ft^2 \]

\[ U \propto \frac{Btu}{ft^2 \cdot hr \cdot °F} \]

\[ R \propto \frac{1}{U} \propto \frac{ft^2 \cdot hr \cdot °F}{Btu} \]

**Metric System**

\[ \dot{Q} \propto W \]

\[ T \propto °C \]

\[ A \propto m^2 \]

\[ U \propto \frac{W}{m^2 \cdot °C} \]

\[ R_{SI} \propto \frac{1}{U} \propto \frac{m^2 \cdot °C}{W} \]
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Building Science Education for Solar Decathlon

*R-values and Insulation*

Photo by Paul Norton, NREL
**U-Factor vs. R-Value**

### English System

\[ U \propto \frac{Btu}{hr \cdot ft^2 \cdot ^\circ F} \]

\[ R \propto \frac{1}{U} \propto \frac{hr \cdot ft^2 \cdot ^\circ F}{Btu} \]

### Metric System

\[ U \propto \frac{W}{m^2 \cdot ^\circ C} \]

\[ R_{SI} \propto \frac{1}{U} \propto \frac{m^2 \cdot ^\circ C}{W} \]
R-Value is Printed on Insulation Product Labels

Higher R-Value = Higher Resistance to Heat Flow
Dr. Bianchi is a senior research engineer with NREL’s Building Energy Science Group. He is a thermal energy expert and employs his background to conduct research in thermal sciences modeling, analysis, and testing of advanced building envelope components and systems to improve the energy performance of buildings. He conducts business development for the Buildings and Thermal Sciences Center in collaborations and partnerships with external organizations to support their common objectives in energy efficiency and generation.
R-values and Insulation

R-values are used to compare insulation products.

Insulation products are tested under standardized conditions to evaluate R-value (e.g., fixed $\Delta T$, fixed thickness).

It’s important to consider R-value for the entire insulation assembly, not the individual materials.

Insulation behaves differently at different temperatures. As $\Delta T$ increases, thermal resistance decreases; as $\Delta T$ decreases, thermal resistance increases.

R-values incorporate all modes of heat transfer, even though we typically model it as primarily conduction.

Once known for a given insulation assembly, R-values can be used as inputs to building simulation tools to calculate annual heat loss.

It’s important to understand that R-values have units. It is assumed that insulation products in the US display R-values in English Units, while insulation products in other countries display RSI-values in Metric Units.
What does it mean that insulation behaves differently at different temperatures?

- The R-value that is noted on the insulation label has been tabulated through a standardized testing process to indicate performance at typical building temperatures.
- This value works well as a constant value to calculate heat transfer through a wall.

What is the insulation “assembly”? And how is that R-value determined?

- More on this in another episode.
- The wall assembly consists of the various layers of materials in the wall.

Different types of insulation

- More on this in another episode.
- R-value is not the only consideration when selecting a type of insulation.
Questions or comments?

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Building Science Education for Solar Decathlon

Calculating Area
Fourier’s Law of Heat Transfer

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

Cross-Sectional Area
Different components of the building envelope have different U-factors, so we need to consider them separately.

\[
A_{\text{Front Wall}} = (30 \text{ ft} \cdot 8 \text{ ft}) - 2(3 \text{ ft} \cdot 4 \text{ ft}) - (3 \text{ ft} \cdot 7\text{ ft})
\]

\[
A_{\text{Front Wall}} = 240 \text{ ft}^2 - 2(12 \text{ ft}^2) - 21 \text{ ft}^2
\]

\[
A_{\text{Front Wall}} = 195 \text{ ft}^2
\]
Floor Plan

Not to Scale

U.S. DEPARTMENT OF ENERGY
SOLAR DECAHOLON

58
\[ A_{\text{Front Wall}} = 195 \text{ ft}^2 \]

\[ A_{\text{Side Walls}} = 2(20 \text{ ft} \cdot 8 \text{ ft}) \]

\[ A_{\text{Back Wall}} = (30 \text{ ft} \cdot 8 \text{ ft}) \]

\[ A_{\text{Side Walls}} = 320 \text{ ft}^2 \]

\[ A_{\text{Back Wall}} = 240 \text{ ft}^2 \]
\[ A_{\text{Front Wall}} = 195 \text{ ft}^2 \] 
\[ A_{\text{Side Walls}} = 2(20 \text{ ft} \cdot 8 \text{ ft}) = 320 \text{ ft}^2 \] 
\[ A_{\text{Back Wall}} = (30 \text{ ft} \cdot 8 \text{ ft}) = 240 \text{ ft}^2 \] 
\[ A_{\text{Net Wall}} = 755 \text{ ft}^2 \]
\[ A_{Ceiling} = 600 \text{ ft}^2 \]

\[ A_{NetWall} = 755 \text{ ft}^2 \]

\[ A_{Floor} = (30 \text{ ft} \cdot 20 \text{ ft}) \]

\[ A_{Floor} = 600 \text{ ft}^2 \]
Volume = 30 \text{ ft} \cdot 20 \text{ ft} \cdot 8 \text{ ft} = 4800 \text{ ft}^3
Key Consideration

Walls, floors, roof, doors, windows must be considered separately when calculating heat loss.
### Geometry Inputs

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>30 ft</td>
<td>width</td>
<td>20 ft</td>
</tr>
<tr>
<td>height</td>
<td>8 ft</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Volume**: 4,800 ft³
- **Area**: 600 ft²

### Climate Data

<table>
<thead>
<tr>
<th></th>
<th>HDD</th>
<th>CDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>-2</td>
<td>65</td>
</tr>
</tbody>
</table>

### Temperature (F)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside</td>
<td>65</td>
<td></td>
</tr>
</tbody>
</table>

### Window Calculations

<table>
<thead>
<tr>
<th></th>
<th>Length</th>
<th>Height</th>
<th>Area</th>
<th>Window Width</th>
<th>Window Height</th>
<th>Window Number</th>
<th>Window Area</th>
<th>Window Door (ft²)</th>
<th>Net Area (ft²)</th>
<th>Window to Wall Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall1</td>
<td>30</td>
<td>8</td>
<td>240</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>24</td>
<td>21</td>
<td>195</td>
<td>10.00</td>
</tr>
<tr>
<td>wall2</td>
<td>20</td>
<td>8</td>
<td>160</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>160</td>
<td>0.00</td>
</tr>
<tr>
<td>wall3</td>
<td>30</td>
<td>8</td>
<td>240</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>240</td>
<td>0.00</td>
</tr>
<tr>
<td>wall4</td>
<td>20</td>
<td>8</td>
<td>160</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>160</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Total Wall Area**: 755 ft²
Questions or comments?

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National Renewable Energy Laboratory
Building Science Education for Solar Decathlon

Temperature and Weather Data

Photo by Warren Gretz, NREL
Heat Transfer Through the Building Envelope

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

\[ \Delta T = T_{\text{outside}} - T_{\text{inside}} \]
Heat Transfer Through the Building Envelope

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

**Inside**
- Temperature remains at a “comfortable” level

**Outside**
- Temperature varies with the weather

**Change in Temperature**
\( (\Delta T) \)

**Inside Temperature**
\( T_{\text{inside}} \)

**Outside Temperature**
\( T_{\text{outside}} \)

**Thermal Transmittance**
\( U \)

**Area**
\( A \)

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

If \( T_{\text{inside}} = T_{\text{outside}} \)
\[ \Delta T = 0 \]
\[ \dot{Q} = U \cdot A \cdot 0 \]
\[ \dot{Q} = 0 \]
Heat Transfer Through the Building Envelope

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

**Inside**
- Temperature remains at a "comfortable" level

**Outside**
- Temperature varies with the weather

If \( T_{\text{inside}} \gg T_{\text{outside}} \)

\( \Delta T \) increases, so \( \dot{Q} \) also increases

Temperature setback:
- Reduce \( T_{\text{inside}} \) in order to reduce \( \Delta T \)
Sample $\Delta T$ (15-minute intervals)

\[
\dot{Q}_1 = U \cdot A \cdot \Delta T_1 \\
\dot{Q}_2 = U \cdot A \cdot \Delta T_2 \\
\dot{Q}_3 = U \cdot A \cdot \Delta T_3 \\
\dot{Q}_4 = U \cdot A \cdot \Delta T_4 \\
\dot{Q}_n = U \cdot A \cdot \Delta T_n
\]
## Weather Data

<table>
<thead>
<tr>
<th>Time</th>
<th>Outside Temperature (°F)</th>
<th>Inside Temperature (°F)</th>
<th>Delta T (ΔT) (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00 AM – 01:00 AM</td>
<td>35</td>
<td>72</td>
<td>37</td>
</tr>
</tbody>
</table>

**Hourly weather data is collected at many locations and is available from numerous sources.**

This data is called Typical Meteorological Year, or “TMY” data.

**TMY data represents a typical year of weather based on actual data in that location for a 30-year period.**

*This is not the same as the 30-year average.*
\[ \dot{Q} = U \cdot A \cdot \Delta T \]

\[ \Delta T \text{ can be represented as the average inside temperature minus the average outside temperature} \]

Assume \( U \) and \( A \) are constant for a given wall.

\[ \dot{Q} \cdot t = Q \]

\[ \text{The rate of heat transfer (} \dot{Q} \text{), times a period of time (} t \text{) equals the amount of heat transferred during that time (} Q \text{)} \]

\[ Q = U \cdot A \cdot \Delta T \cdot t \]
\[ Q = U U_\Delta T \]

\[ \Delta T = \text{Difference in temperature} \]

\[ I_{eff} = T_{HDD} \times C \times F \]

\[ R = 0.56 \times 10^{0.19} \times T^{0.8} \]

Example:

\[ \Delta T = T_{CPC} - T_{FF} \]

\[ = 651 \text{ F} - (T_{HDD} + T_{UP}) \]

\[ = 651 \text{ F} - 333 \text{ F} + 33 \text{ F} = 185 \text{ F} \]

When the HDD's are added up over a month or a year, this information is used as part of the climate data for a location.
 Cooling Degree Days

If $T_{\text{outside avg}} < 65^\circ F$, it's called a Heating Degree Day (HDD)  

If $T_{\text{outside avg}} > 65^\circ F$, it's called a Cooling Degree Day (CDD)

$$\Delta T \cdot t = \left( 65^\circ F - \frac{T_{\text{high}} + T_{\text{low}}}{2} \right) \cdot t$$

***HDD’s and CDD’s cannot be converted from English Units (°F) to SI Units (°C).

In SI units, the Base Temperature is 18°C, so you must recalculate.
HDD and CDD with Different Base Temperatures

HDD65  CDD65
HDD50  CDD50

GDD50
HDD and CDD work best…

When there are large temperature differences from inside to outside

In buildings that have limited thermal mass

When there is low humidity (CDD only)

Degree Days are a way to model the Temperature term in Fourier’s Law.

Models try to represent the physical phenomenon, but with assumptions that make them approximations.
Example

Total Insulation = R12
HDD = 6100 °F · days

Height = 8 ft.
Length = 40 ft.

\[ Q = U \cdot A \cdot \Delta T \cdot t \]

\[ Q = U \cdot A \cdot HDD \quad \rightarrow A = 40 \text{ ft} \cdot 8 \text{ ft} = 320 \text{ ft}^2 \]

\[ Q = \frac{1}{R} \cdot A \cdot HDD \]

\[ Q = \frac{320 \text{ ft}^2 \cdot 6100 \frac{\text{oF} \cdot \text{days}}{\text{year}}}{12 \frac{\text{ft}^2 \cdot \text{oF} \cdot \text{hr}}{\text{Btu}}} \]
How does this relate to Building Design?

If we want to reduce Q...

\[ Q = U \cdot A \cdot \Delta T \cdot t \]

- Reduce A (i.e., build a smaller building)

\[ Q = \frac{1}{R} \cdot A \cdot \Delta T \cdot t \]

- Increase R (i.e., add more insulation)

\[ Q = \frac{1}{R} \cdot A \cdot HDD \]

- Reduce HDD (i.e., move the building to another location – NOT LIKELY)

\[ Q = \frac{320 \, ft^2 \cdot 6100 \frac{^\circ F \cdot days}{year} \cdot 24 \frac{hr}{day}}{24 \frac{ft^2 \cdot ^\circ F \cdot hr}{Btu}} = 1.95 \frac{MMBtu}{year} \]
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References


4. NREL National Solar Radiation Database, Typical Meteorological Year: https://nsrdb.nrel.gov/about/tmy.html

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Calculating R-Value for a Wall (Part 1)
Heat Transfer Through the Building Envelope

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

- **U-Factor**: Thermal Transmittance
- **R-Value**: Thermal Resistance

\[ \frac{1}{U} = R \]
Example: Concrete Wall with Foam Board Insulation

Photo by Dwight Stone
Example: Concrete Wall with Foam Board Insulation

- We want to determine the total R-value for the wall
- What are all the materials in the wall?
  - 4-inch poured concrete wall
  - 2-inch foam board insulation
  - ½-inch stucco exterior
  - Thin layers of air on the interior and exterior called the *Surface Films*
Example: Concrete Wall with Foam Board Insulation

- We want to determine the total R-value for the wall
- What are all the materials in the wall?
  - 4-inch poured concrete wall
  - 2-inch foam board insulation
  - ½-inch stucco exterior
  - Thin layers of air
    - Warmed up by the wall as heat transfers from inside to outside
    - Creates convection current in the air that creates a thin film of stagnant air
- Exterior film coefficient\(^1\) has an R-value\(^*\) of \(0.17 \frac{ft^2 \cdot \circ F \cdot hr}{Btu}\)

---

\(^1\) Surface film coefficients in ASHRAE Handbook of Fundamentals are specified for an average wind speed of 15mph. Part of the reason for this assumption is so that we underestimate the thermal resistance, as we do not want to undersize the heating and cooling system for the building.
We want to determine the total R-value for the wall.

What are all the materials in the wall?
- 4-inch poured concrete wall
- 2-inch foam board insulation
- ½-inch stucco exterior
- Thin layers of air
- Warmed up by the wall as heat transfers from inside to outside
- Creates convection current in the air that creates a thin film of stagnant air
- Exterior film coefficient\(^1\) has an R-value\(^*\) of \(0.17 \frac{ft^2 \cdot ^0F \cdot hr}{Btu}\)
- Interior film coefficient\(^1\) has an R-value\(^*\) of \(0.68 \frac{ft^2 \cdot ^0F \cdot hr}{Btu}\)

\(^*\) Surface film coefficients in ASHRAE Handbook of Fundamentals are specified for an average wind speed of 15mph. Part of the reason for this assumption is so that we underestimate the thermal resistance, as we do not want to undersize the heating and cooling system for the building.
Example: Concrete Wall with Foam Board Insulation

R-values of wall components:

- 0.17 Exterior film coefficient\(^1\)
- 0.10 Stucco\(^2\)
- 10.00 Foam board\(^1\)
- 0.52 Concrete\(^1\)
- 0.68 Interior film coefficient\(^1\)
Example: Concrete Wall with Foam Board Insulation

R-values of wall components:

0.17 Exterior film coefficient

0.10 Stucco

10.00 Foam board

0.52 Concrete

+ 0.68 Interior film coefficient

\[
11.47 \frac{ft^2 \cdot ^\circ F \cdot hr}{Btu}
\]
Example: Concrete Wall with Foam Board Insulation

R-values of wall components:

- 0.17 Exterior film coefficient
- 0.10 Stucco
- 10.00 Foam board
- 0.52 Concrete
- + 0.68 Interior film coefficient

\[ 11.47 \frac{ft^2 \cdot \circ F \cdot hr}{Btu} \]
Example: Concrete Wall with Foam Board Insulation

R-values of wall components:

- 0.17 Exterior film coefficient\(^1\)
- 0.10 Stucco\(^2\)
- 20.00 Foam board\(^1\)
- 0.52 Concrete\(^1\)
- + 0.68 Interior film coefficient\(^1\)

\[ 21.47 \text{ ft}^2 \cdot ^\circ \text{F} \cdot \text{hr} \]

\[ \text{Btu} \]
Surface Film Coefficients for Horizontal Surfaces

- Previous example focused on vertical wall surfaces and introduced the concept of Interior and Exterior film coefficients.
- Horizontal surfaces, like a flat roof, also have Interior and Exterior film coefficients.
  - Interior (i.e., air at the ceiling)$^3$
    - $R = 0.61 \frac{ft^2 \cdot \circ F \cdot hr}{Btu}$
  - Exterior (i.e., air adjacent to roof surface)$^3$
    - $R = 0.17 \frac{ft^2 \cdot \circ F \cdot hr}{Btu}$
- Exceptions exist, such as unconditioned attics.
Questions or comments?

Please email SolarDecathlon@nrel.gov
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

Holly Carr
U.S. Department of Energy

Stacey Rothgeb, Zachary Peterson, Ron Judkoff, Jes Stershic, Dave Roberts, Michael Deru, Jennifer Daw, Linh Truong, and Kelly MacGregor
National Renewable Energy Laboratory

David Brown
Accenture Federal Services
Authors

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Paul Torcellini, Michael Young, and Marlena Praprost

National Renewable Energy Laboratory
References


U.S. DEPARTMENT OF ENERGY

SOLAR DECA-ThALON

Building the Next Generation
Building Science Education for Solar Decathlon

Calculating R-Value for a Wall (Part 2)

Photo by Paul Norton, NREL
Homogeneous Layers vs. Heterogeneous Layers

- In our concrete wall example, the materials and thickness of each layer are the same everywhere on the wall.
- Thermal resistance is consistent for all heat transfer pathways.
- Not all walls are constructed this way:
  - Some have multiple components within the same layer.
  - Thermal resistance differs depending on the location of the heat transfer pathway.
Example: Stud Frame Wall

View from Top of Wall (Looking Down)

Wooden Studs

Inside

Outside

Photo by Michael Young, NREL
Example: Stud Frame Wall

Photos by Michael Young, NREL
# Example: Stud Frame Wall

<table>
<thead>
<tr>
<th>Naming Convention for Stud Dimensions</th>
<th>Actual Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2” x 4”</td>
<td>1.5” x 3.5”</td>
</tr>
<tr>
<td>2” x 6”</td>
<td>1.5” x 5.5”</td>
</tr>
<tr>
<td>2” x 8”</td>
<td>1.5” x 7.25”</td>
</tr>
<tr>
<td>2” x 10”</td>
<td>1.5” x 9.25”</td>
</tr>
<tr>
<td>2” x 12”</td>
<td>1.5” x 11.25”</td>
</tr>
</tbody>
</table>

Source: [https://www.fpl.fs.fed.us/documents/misc/miscpub_6409.pdf](https://www.fpl.fs.fed.us/documents/misc/miscpub_6409.pdf)
Example: Stud Frame Wall with Fiberglass Insulation

View from Top of Wall (Looking Down)

2x4 Wooden Studs

Inside

Fiberglass Batt Insulation

Outside

16" On-Center

Drywall

Plywood

16" On-Center

Photo by Michael Young, NREL
Example: Stud Frame Wall with Fiberglass Insulation

• Before the 1970’s, wall cavities were often empty
• As interest in energy efficiency and indoor environmental comfort grew…
  • Wall cavities were filled with insulation
  • 2”x6” studs were used to increase thickness of the cavity and allow for more insulation
Example: Stud Frame Wall with Fiberglass Insulation

Heat transfer rates are additive

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

\[ \dot{Q}_{\text{total}} = \dot{Q}_{\text{stud}} + \dot{Q}_{\text{insulation}} \]

\[ U_t A_t \Delta T = U_s A_s \Delta T_s + U_i A_i \Delta T_i \]

\[ U_t = \frac{U_s A_s + U_i A_i}{A_t} \]

\[ U_t = U_s \frac{A_s}{A_t} + U_i \frac{A_i}{A_t} \]
Example: Stud Frame Wall with Fiberglass Insulation

Heat transfer rates are additive

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

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\[ U_t A_t \Delta T = U_s A_s \Delta T_s + U_i A_i \Delta T_i \]

\[ U_t = \frac{U_s A_s + U_i A_i}{A_t} = \frac{U_s A_s + U_i A_i}{A_s + A_i} \]

\[ U_t = U_s \frac{A_s}{A_t} + U_i \frac{A_i}{A_t} \]

\[ \frac{A_s}{A_t} = \text{"Framing Factor"} \]
Example: Stud Frame Wall with Fiberglass Insulation

\[ \frac{A_s}{A_t} = "\text{Framing Factor}" \]

- Amount of frame compared to total area of insulated wall
- Not uncommon to assume 15%

\[ A = w \cdot h \]

\[ \frac{A_s}{A_t} = \frac{w_s \cdot h_s}{w_t \cdot h_t} = \frac{w_s}{w_s + w_i} \]

\[ \frac{A_s}{A_t} = \frac{w_s}{w_s + w_i} \]

\[ A = w \cdot h \]

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\[ \frac{A_s}{A_t} = \frac{w_s}{w_s + w_i} \]

View from Top of Wall (Looking Down)

16" o.c. In: 14.5"

2x4 Wooden Studs

Fiberglass Batt Insulation

Drywall

 Plywood

1.5”

1.5”

1.5”

14.5”

9.4%
Example: Stud Frame Wall with Fiberglass Insulation

Assume wall is constructed with 2x4 studs, spaced 16” o.c. (on-center)
  • Studs are 3.5” wide
  • Fiberglass insulation fills wall cavity 14.5” wide

From inside to outside:
  • 0.5” Drywall
  • 3.5” Stud / 3.5” Fiberglass Batt Insulation
  • 0.5” Plywood
### Example: Stud Frame Wall with Fiberglass Insulation

#### View from Top of Wall (Looking Down)

<table>
<thead>
<tr>
<th>Material</th>
<th>R-value/inch</th>
<th>R-value: Path 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior film coefficient</td>
<td></td>
<td>0.68</td>
</tr>
<tr>
<td>Drywall (0.5”)</td>
<td>1.10</td>
<td>0.55</td>
</tr>
<tr>
<td>Stud (3.5”)</td>
<td>0.94</td>
<td>3.29</td>
</tr>
<tr>
<td>Insulation (3.5”)</td>
<td>3.14</td>
<td></td>
</tr>
<tr>
<td>Plywood (0.5”)</td>
<td>1.56</td>
<td>0.78</td>
</tr>
<tr>
<td>Exterior film coefficient</td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5.47</strong></td>
</tr>
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Example: Stud Frame Wall with Fiberglass Insulation

<table>
<thead>
<tr>
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<th>R-value: Path 2</th>
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<td><strong>13.17</strong></td>
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View from Top of Wall (Looking Down)

- **2x4 Wooden Studs**
- **Fiberglass Batt Insulation**
- **Interior film coefficient**
- **Drywall (0.5”)**
- **Plywood (0.5”)**
- **Exterior film coefficient**

**R-value: Path 1**

- **Drywall (0.5”)**: 0.55
- **Stud (3.5”)**: 3.29
- **Insulation (3.5”)**: 10.99
- **Plywood (0.5”)**: 0.78
- **Exterior film coefficient**: 0.17
- **Total**: 5.47

**R-value: Path 2**

- **Drywall (0.5”)**: 0.55
- **Stud (3.5”)**: 3.29
- **Insulation (3.5”)**: 10.99
- **Plywood (0.5”)**: 0.78
- **Exterior film coefficient**: 0.17
- **Total**: 13.17
# Example: Stud Frame Wall with Fiberglass Insulation

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\[
U_t = U_s \frac{w_s}{w_t} + U_i \frac{w_i}{w_t}
\]

\[
U_t = \frac{1}{5.47} \cdot \frac{1.5}{16} + \frac{1}{13.17} \cdot \frac{14.5}{16}
\]

\[
U_{total\ wall} = 0.086
\]

\[
R_{total\ wall} = \frac{1}{0.086} = 11.63
\]
Questions or comments?

Please email SolarDecathlon@nrel.gov
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National Renewable Energy Laboratory
References


Building Science Education for Solar Decathlon

Insulation Materials

Photo by Paul Torcellini, NREL
Insulation Materials

Mineral wool
Source: Marjorie Schott, NREL

Fiberglass
Source: David Springer, NREL

Cellulose
Source: Paul Norton, NREL

Foams/Thermoplastics
Source: Paul Norton, NREL

Natural Fibers
Source: Marjorie Schott, NREL
Fiberglass

Composition
• Molten glass blown into fibers

Recycled Material Content
• 40-60% recycled glass

Other information
• One of the most common insulation materials

Source: Amanda Kirkeby, NREL
Mineral Wool

Composition

- Rock wool: man-made from natural minerals, such as basalt
- Slag wool: man-made from blast furnace slag, the waste matter that forms on surface of molten metal

Recycled Material Content

- 75% post-industrial material

Other information

- Fire-resistant

Source: Paul Torcellini, NREL
Cellulose

**Composition**
- Recycled paper products, such as newsprint

**Recycled Material Content**
- 82-85% recycled paper product

**Other information**
- Additives such as mineral borate ensure fire and insect resistance
- Requires no moisture barrier

Source: David Springer, NREL
Natural Fibers

Cotton

Sheep wool

Straw

Source: Evelyn Simak
Cotton

Composition

• 85% recycled cotton and 15% plastic fibers treated with borate

Recycled Material Content

• 85% (some use recycled blue jean trim waste)

Other information

• Additives such as mineral borate ensure fire and insect resistance
• Minimal energy to manufacture
Sheep wool

Composition

• Sheep wool

Recycled Material Content

• Natural material

Other information

• Treated with mineral borate to ensure fire, insect, and mold resistance
• Can hold large quantities of water
• 2” x 4” wall (R-13)
• 2” x 6” wall (R-19)
Straw

Composition

• Straw Bales finished with stucco
• Straw boards

Recycled Material Content

• Natural material

Other

• Popular 150 years ago in Great Plains of United States
• Inexpensive
• R-25 walls

Source: Straw Bale House, Philipp, flickr
Polystyrene Insulation Materials

R-Value is dependent on density: Loose-fill/bead has lower R-Value than foam board

**Molded Expanded Polystyrene (MEPS)**
- Foam board
- or Small foam beads

**Expanded Polystyrene (EPS)**
- Small, thermoplastic beads fused together

**Extruded Polystyrene (XPS)**
- Molten thermoplastic pressed into rigid boards
- R-value can drop over time – “Thermal drift”
Polyisocyanurate Insulation Materials

- Low-conductivity
- Hydrochlorofluorocarbon-free
- Subject to Thermal Drift

Liquid, Sprayed Foam
- Molds itself to all surfaces, leading to better performance
- Cheaper than foam board installation

Rigid Foam Board
- Can be laminated with a variety of facings

Source: Paul Norton, NREL
Source: Amanda Kirkeby, NREL
Polyurethane Insulation Materials

Spray-in foam insulation with different density options.

**Open-cell Foam**
- Low density
- Lower R-Value
- Spongy texture that can absorb water
- Little thermal drift

**Close-cell Foam**
- High-density
- Higher R value
- Expand to space around it
- Expensive
- Thermal drift

Source: Rodney Diaz
Cementitious Foam Insulation Materials

Composition
• Cement-based foam minerals such as magnesium silicate and magnesium oxide (found in seawater)

Other
• Pumped into closed cavities
• Fire-resistant
• Non-toxic

Source: Dennis Schroeder, NREL
Autoclaved Concrete

Composition

- Solid, precast autoclaved, lightweight concrete masonry
- Autoclaved Aerated Concrete (AAC) – High-Silica Sand
- Aerated Cellular Concrete (ACC) – Fly ash, a waste product of coal-burning power plants

Other

- 80% air by volume
- 10 times the insulating value of conventional concrete

Source: Tarmo Tamm
Insulation Facings

Common Facing Materials

- Kraft paper
- Vinyl sheeting
- Aluminum foil (radiant barrier)

Other

- Protects insulation surface
- Some facings provide air, radiant, and/or vapor barrier
- Can provide flame and insect resistance

Source: Amanda Kirkeby, NREL

Note: Radiant barriers only work if there is a non-solid/non-liquid space between the radiant barrier and the next space.
Key Points

Many different types of insulation materials

• Each type has its benefits and different applications.

Insulation materials mitigate heat transfer in building envelope

Up next…

• Applications of different insulation materials
Questions or comments?

Please email SolarDecathlon@nrel.gov
Acknowledgements

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Building Science Education for Solar Decathlon

Insulation Types

Photo by Paul Norton / NREL
How to Choose the Right Insulation Type

• **Where** will you install the insulation?
  1. Unfinished attic spaces
  2. Finished attic rooms
  3. All exterior walls
  4. Floors above cold spaces
  5. Band joists
  6. Windows

• **What R-Value** do you want to achieve?

• **Impact** of insulation type on:
  • Indoor air quality
  • Life cycle costs
  • Embodied environmental impact
  • Ease/cost of installation


**Note:** Moisture management and condensation control are critical elements of insulation selection, placement, and design.
Blanket – Batt and Roll Insulation

**Types**

- Fiberglass (most common)
- Mineral wool
- Cotton
- Sheep Wool

**Applications**

- Attic trusses, rafters, walls, and floor joists
- Higher R-values in thicker spaces

Source: US Department of Energy
Fiberglass Batt Insulation Characteristics

<table>
<thead>
<tr>
<th>Thickness (inches)</th>
<th>R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 1/2</td>
<td>11</td>
</tr>
<tr>
<td>3 5/8</td>
<td>13</td>
</tr>
<tr>
<td>3 1/2 (high density)</td>
<td>15</td>
</tr>
<tr>
<td>6 to 6 1/4</td>
<td>19</td>
</tr>
<tr>
<td>5 1/4 (high density)</td>
<td>21</td>
</tr>
<tr>
<td>8 to 8 1/2</td>
<td>25</td>
</tr>
<tr>
<td>8 (high density)</td>
<td>30</td>
</tr>
<tr>
<td>9 1/2 (standard)</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>38</td>
</tr>
</tbody>
</table>

Source: [https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1](https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1)
Foam Board

Types

• Polystyrene
• Polyisocyanurate
• Polyurethane

Applications

• Exterior wall sheathing
• Interior sheathing in basement walls
• Special applications, such as attic hatches

Photo by Amanda Kirkeby, NREL
Loose Fill and Blown-In Insulation

Types

- Cellulose
- Fiberglass
- Rock wool

Applications

- Retrofits
- Small, unusually shaped spaces where other insulation is difficult to install

Recommended Specifications by Loose-Fill Insulation Material

<table>
<thead>
<tr>
<th></th>
<th>Cellulose</th>
<th>Fiberglass</th>
<th>Rock Wool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density in lb/ft³ (kg/m³)</td>
<td>1.5–2.0 (24–36)</td>
<td>0.5–1.0 (10–14)</td>
<td>1.7 (27)</td>
</tr>
<tr>
<td>Weight at R-38 in lb/ft² (kg/m²)</td>
<td>1.25–2.0 (6–10)</td>
<td>0.5–1.2 (3–6)</td>
<td>1.6–1.8 (8–9)</td>
</tr>
</tbody>
</table>

Source: [https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1](https://www.energy.gov/energysaver/weatherize/insulation/types-insulation#271890-tab-1)
Loose Fill and Blown-In Insulation

Loose-Fill

Photo by Robert Hendron

Blown-in

Photo by Dennis Schroeder, NREL
Spray-Foam and Foamed-In-Place Insulation

Types

- Polyisocyanurate
- Polyurethane
- Cementitious Foam

Applications

- Injected into closed wall cavities
- Sprayed or foamed-in-place to fill wall cavities or small spaces
- Conforms to shape of cavity
Spray-Foam and Foamed-In-Place Insulation

Types

• Polyisocyanurate
• Polyurethane
• Cementitious Foam

Applications

• Reduce air leakage
• Injected into closed wall cavities
• Sprayed or foamed-in-place to fill wall cavities or small spaces
• Conforms to shape of cavity

Photo by Paul Norton, NREL

Foamed-in-place

Photo by Dennis Schroeder, NREL

Injected into closed cavity
Radiant Barriers and Reflective Insulation Systems

Types

• Highly-reflective aluminum foil
• Kraft paper
• Plastic film
• Polyethylene bubbles
• Cardboard
• Thermal insulation materials

Applications

• Reduce summer heat gain through a radiant heat transfer barrier

Note: Radiant barriers only work if there is a non-solid / non-liquid space between the radiant barrier and the next space.

Photo by Amanda Kirkeby, NREL
Concrete Block Insulation

Types

• Core filling
• Exterior insulation
• Polystyrene beads incorporated into concrete
• Rigid foam inserts

Applications

• Insulate concrete foundation and wall constructions

Credit: FESC/IBACOS
Concrete Block Insulation (cont.)

Types

- Core filling
- Exterior insulation
- Polystyrene beads incorporated into concrete
- Rigid foam inserts

Applications

- Insulate concrete foundation and wall constructions
Insulating Concrete Forms (ICFs)

**Description**

- Insulated forms for poured concrete walls that remain part of the wall assembly

**Applications**

- Walls
- Look like stick-built construction
Structural Insulated Panels (SIPs)

**Description**

- Pre-fabricated insulated structural elements

**Applications**

- Building walls
- Ceilings
- Floors
- Roofs
- High R-value
- High strength-to-weight ratio

Source: Craig Miller Productions, DOE
Installation: Quality matters

Quality of installation impacts R-value

Source: Craig Miller Productions, DOE

Source: Dane Christensen, NREL
How much and where

1. Unfinished attic spaces
2. Finished attic rooms
3. All exterior walls
4. Floors above cold spaces
5. Band joists
6. Windows

Key Points

Strive to go beyond the minimum requirements of the building code

Make an informed decision

• Know *where* you are going to install the insulation
• Understand impact of insulation type on all aspects of design, including embodied environmental impact, life cycle cost, indoor air quality, and energy use.
Questions or comments?

Please email SolarDecathlon@nrel.gov

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Building Technologies Office. The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

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Intro to Windows and Fenestration
Windows

Outdoor  Indoor

Source: Efficient Windows Collaborative

Photo by Dennis Schroeder, NREL
Key Terms

✔ U-Factor
• Visible Transmittance (VT)
• Solar Heat Gain Coefficient (SHGC)
• Air Leakage (AL)

NFRC labels on window units give ratings for U-factor, SHGC, visible light transmittance (VT), and (optionally) air leakage (AL) and condensation resistance (CR) ratings.

Credit: DOE³
The Electromagnetic Spectrum

Source: NASA's Imagine the Universe²
Visible Transmittance (VT)

the fraction of the *visible* spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.
Key Terms

Visible Transmittance (VT)
the fraction of the visible spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.

Solar heat gain coefficient (SHGC)
the fraction of solar radiation admitted through a window, door, or skylight -- either transmitted directly and/or absorbed, and subsequently released as heat inside a home.
Key Terms

Visible Transmittance (VT)
the fraction of the visible spectrum of sunlight that is transmitted through the glazing of a window, door, or skylight.

Solar heat gain coefficient (SHGC)
the fraction of solar radiation admitted through a window, door, or skylight -- either transmitted directly and/or absorbed, and subsequently released as heat inside a home.

Air Leakage (AL)
the rate of air movement around a window, door, or skylight in the presence of a specific pressure difference across it. (Units - cfm/ft²)

Opaque
0%
No solar energy transmitted

Transparent
100%
All solar energy transmitted

0 cfm/ft² = Airtight
0.30 cfm/ft² is required by most codes and standards

Opaque
Transparent
0% 100%
NFRC labels on window units give ratings for U-factor, SHGC, visible light transmittance (VT), and (optionally) air leakage (AL) and condensation resistance (CR) ratings. Credit: DOE³
Reducing U-Factor

3 Modes of Heat Transfer

Conduction

Convection

Radiation

Photo by Dennis Schroeder, NREL
Single Glazed Window

- Single pane of glass is highly conductive

- Substantial portion of window’s resistance to heat transfer comes from convection layer and radiative exchange
Double Glazed Window

- Conduction is reduced

- Spacing between layers of glazing provide additional thermal resistance
  - Convection can occur in the air gap
  - Spacing is fine-tuned to optimize insulative properties

Illustration adapted from Efficient Windows Collaborative
Other Strategies to Reduce Window U-Factor

- Noble-gases (ex. argon)
  - Less dense than air, so less heat transfer

- Aero-gel
  - Encapsulates tiny pockets of air into a clear structure
  - Inhibits convection by separating the air pockets

- Third glazing
  - Third layer of glass
  - Creates two air gaps

Illustration adapted from Efficient Windows Collaborative
Low-e Coatings to Reduce Radiative Heat Transfer

- Radiative heat transfer caused by
  - Temperature difference between panes of glass
  - Temperature difference between controlled interior environment and outside
- Low-emissivity (Low-e) coating applied to Surfaces 2 and 3
Low-e Coatings to Reduce Radiative Heat Transfer

- Low-e coating on Surface 2 helps to reflect radiant energy before it can enter the indoor space.

- Low-e coating on Surface 3 allows the inner pane of glass to warm up and transfer the sun’s thermal energy to the indoor space via conduction.

Illustration adapted from Efficient Windows Collaborative.
Low-e Coatings to Reduce Radiative Heat Transfer

- Low-e coating on Surface 2 helps to reflect radiant energy before it can enter the indoor space

- Low-e coating on Surface 3 allows the inner pane of glass to warm up and transfer the sun’s thermal energy to the indoor space via conduction
  - Also reduces heat loss from the building at night
  - Ideal for beneficial solar heating on south-facing windows (Northern Hemisphere)
Building Design Example

If you want free heat from the sun during wintertime...

- You need a window with a high Solar Heat Gain Coefficient (SHGC)
- You also need a low U-factor to limit heat loss
- This is typically achieved by using a Low-e coating on Surface 3 for south-facing windows (in the Northern Hemisphere)
Summary

• **U-Factor**
• **Visible Transmittance (VT)**
• **Solar heat gain coefficient (SHGC)**
• **Air Leakage (AL)**

---

**Summary**

NFRC labels on window units give ratings for **U-factor**, **SHGC**, **visible light transmittance (VT)**, and (optionally) **air leakage (AL)** and **condensation resistance (CR)** ratings.

Credit: DOE³
Questions or comments?

Please email SolarDecathlon@nrel.gov
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

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U.S. Department of Energy

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National Renewable Energy Laboratory
References

   https://www.commercialwindows.org/ufactor.php
Building Science Education for Solar Decathlon

The Importance and Opportunity for Advanced Window Technologies
The Importance and Opportunity for Advanced Window Technologies

Presented by Marc LaFrance
Windows Technology Manager

Topics

• General background on windows
  • Opportunity and market perspectives
  • Major energy flows
• Design software and ratings
• ENERGY STAR Criteria
• Technology development goals and targets
• Latest advancements and technologies
  • Highly insulating windows
  • Dynamic solar control
  • Innovative research
Buildings Natural Gas Use: 60% of U.S. total
Buildings Electricity Use: 75% of U.S. total
U.S. Building Energy Bill: $380 billion per year

Data Source: US Energy Information Administration
Heat and Light Transfer through Windows

More detailed information:
Lawrence Berkeley National Laboratory (LBNL)
Windows and Daylighting, Outreach

https://windows.lbl.gov/outreach
Energy Performance Labels

National Fenestration Rating Council (NFRC)

Attachment Energy Rating Council (AERC)
ENERGY STAR® for Windows, Doors, and Skylights

CLIMATE ZONE MAP

- Northern
- North-Central
- South-Central
- Southern

Source: https://www.energystar.gov/products/residential_windows_doors_and_skylights/key_product_criteria
ENERGY STAR Final Version 6.0 Specification

### Windows

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>U-Factor(^1)</th>
<th>SHGC(^2)</th>
<th>Prescriptive</th>
<th>Equivalent Energy Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern(^*)</td>
<td>≤ 0.27</td>
<td>Any</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 0.28</td>
<td>≥ 0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 0.29</td>
<td>≥ 0.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 0.30</td>
<td>≥ 0.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North-Central</td>
<td>≤ 0.30</td>
<td>≤ 0.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South-Central</td>
<td>≤ 0.30</td>
<td>≤ 0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern</td>
<td>≤ 0.40</td>
<td>≤ 0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The effective date for the Northern Zone prescriptive and equivalent energy performance criteria for windows is January 1, 2016.

### Doors

<table>
<thead>
<tr>
<th>Glazing Level</th>
<th>U-Factor(^1)</th>
<th>SHGC(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>≤ 0.17</td>
<td>No Rating</td>
</tr>
<tr>
<td>≤ ½-Lite</td>
<td>≤ 0.25</td>
<td>≤ 0.25</td>
</tr>
</tbody>
</table>
| > ½-Lite           | ≤ 0.30         | Northern North-Central ≤ 0.40  
|                    |                | Southern South-Central ≤ 0.25 |

Air Leakage for Sliding Doors ≤ 0.3 cfm/ft\(^2\)
Air Leakage for Swinging Doors ≤ 0.5 cfm/ft\(^2\)

### Skylights

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>U-Factor(^1)</th>
<th>SHGC(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern</td>
<td>≤ 0.50</td>
<td>Any</td>
</tr>
<tr>
<td>North-Central</td>
<td>≤ 0.53</td>
<td>≤ 0.35</td>
</tr>
<tr>
<td>South-Central</td>
<td>≤ 0.53</td>
<td>≤ 0.28</td>
</tr>
<tr>
<td>Southern</td>
<td>≤ 0.60</td>
<td>≤ 0.28</td>
</tr>
</tbody>
</table>

Air Leakage ≤ 0.3 cfm/ft\(^2\)
Market Snapshot

Source: EPA ENERGYSTAR analysis, Horiz. sliding windows
## Window Metrics and Targets by Technology

<table>
<thead>
<tr>
<th>Building Sector</th>
<th>Performance</th>
<th>Installed Price Premium</th>
<th>Primary Energy Savings (quads)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2030</td>
</tr>
<tr>
<td><strong>Highly Insulating Windows</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>13 R-value</td>
<td>2.9 $/ft² window area</td>
<td>1.28</td>
</tr>
<tr>
<td>Commercial</td>
<td>10</td>
<td>8.5 $/ft² window area</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Dynamic Windows</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential</td>
<td>0.05/0.65 SHGC (active/inactive)</td>
<td>2.9 $/ft² window area</td>
<td>1.35</td>
</tr>
<tr>
<td>Commercial</td>
<td>15</td>
<td></td>
<td>1.56</td>
</tr>
<tr>
<td><strong>Daylighting</strong></td>
<td>40% Lighting energy savings</td>
<td>13 $/ft² window area</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Latest Breakthrough – Thin Triple Pane Glazings

- Thin float glass
  - 0.7 - 1.6 mm
- Multiple suppliers
- 2 Low-E coatings
- Krypton gas fill
- Non-structural center
  - 2 seals, not 4
- Infrastructure exists
- “Affordable”
Field Studies of Thin Triples

Source: Marc LaFrance
Variable Solar Control and Daylighting

Electrochromic Windows

Electrochromic windows can tint to reduce solar gain. They can be controlled manually or automated to respond to a control signal.

Automated (motorized) shading can reduce solar gains and modulate light levels. Exterior shading is particularly effective for reducing cooling.

Source: sageglass.com
Dynamic – Integrated Facades

• Dynamic solar control - automated shades and dynamic glass
• Validated large peak electricity reduction and lighting savings at US Government buildings and other locations
• R&D on core technology and integration (natural daylight, controls, and grid responsive)

Source: https://eta-intranet.lbl.gov/sites/default/files/lightingsystemsintegration_scoping_study_draft_20200714.pdf
Innovative and Exploratory Technologies

Vacuum Glazing

Aerogel

Thermochromic Photovoltaic

High performance windows are critical to save energy and to achieve zero energy buildings.

Triple pane windows with dynamic solar control are market ready, but improvements are still needed to reduce market barriers and to become affordable.

Many new opportunities for windows exist that can become net energy providers in mixed and cold climate - a home with R10 highly insulating dynamic windows, will use less energy than a home without windows.

Extensive tools available for the design of windows and the impact in buildings through whole building modeling – system level benefits allows for lower capacity HVAC system and elimination of ducts near the perimeter.
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

Holly Carr
U.S. Department of Energy

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The following people were authors on this episode:
Paul Torcellini, Mark LaFrance, Michael Young, and Marlena Praprost

National Renewable Energy Laboratory
Links and References

3. LBNL Windows and Daylighting; resources, software, research studies, https://windows.lbl.gov/
Building Science Education for Solar Decathlon

_Infiltration_

Photo by Dennis Schroeder, NREL
Fourier’s Law of Heat Transfer

\[ \dot{Q} = U \cdot A \cdot \Delta T \]

Thermal Transmittance \( (U) \)

Change in Temperature \( (\Delta T) \)

Area \( (A) \)

Heat Transfer via Air Infiltration

“Infiltration” describes air that comes into the building. If air is moving in, then that air must also be leaving or exfiltrating.
Heat Transfer via Air Infiltration

Air that leaves the structure represents energy that is lost from the building and cannot be recovered. Replacement air brought in from the outside must be heated or cooled to maintain a comfortable indoor environment.

Because the mass of the air in the building at any given time does not change, then the amount of air entering the building must equal the amount of air that is escaping the building.
However, mass flow rate is not a common way to measure air movement through the building envelope…

A more common measurement is the Volumetric Flow Rate, measured in cubic feet per minute

\[ \dot{V} \propto \frac{ft^3}{min} \text{ or "cfm"} \]

\[ \dot{V} = \frac{m}{\rho_{\text{air}}} \left[ \frac{lb/\text{min}}{lb/ft^3} \right] \]

\[ \dot{Q} = \dot{V} \cdot \rho_{\text{air}} \cdot c_p \cdot \Delta T \]

\[ \dot{Q} = 0.018 \left[ \frac{Btu}{ft^3 \cdot ^\circ F} \right] \cdot \dot{V} \left[ \frac{ft^3}{min} \right] \cdot \Delta T[^\circ F] \]

At room temperature:
\[ \rho_{\text{air}} = 0.07298 \text{ lb/ft}^3 \]
\[ c_p = 0.4299 \text{ Btu/lb \cdot } ^\circ F \]
Ultimately, we want a simple metric to account for many of these parameters, so infiltration rate is typically expressed in terms of Air Changes per Hour (ACH).

<table>
<thead>
<tr>
<th>Changes based on several parameters…</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T ) (difference in temperature from inside to outside)</td>
</tr>
</tbody>
</table>

ACH indicates how many times the total volume of air in the building is exchanged with the outdoor air each hour.
Infiltration Rate | Air Changes per Hour (ACH)

1 ACH  All of the air inside the building is replaced by fresh outdoor air every hour

Today, it is common for buildings to have an infiltration rate of 0.2 ACH, meaning the air in the building is exchanged with outdoor air once every five hours.
Example

Assume:

- Infiltration Rate = 0.2 ACH
- Outside Temperature = 20°F
- Inside Temperature = 70°F
- Building Volume = 10,000 ft³

Find the heat lost by infiltration.

\[
\dot{Q} = 0.018 \cdot \dot{V} \cdot \Delta T
\]

\[
\dot{V} = 0.2 \, \text{ACH} \cdot 10,000 \, \text{ft}^3 = 2,000 \, \frac{\text{ft}^3}{\text{hr}}
\]

\[
\Delta T = 70°F - 20°F = 50°F
\]

\[
\dot{Q} = 0.018 \left[ \frac{Btu}{\text{ft}^3 \cdot °F} \right] \cdot 2,000 \left[ \frac{\text{ft}^3}{\text{hr}} \right] \cdot 50[°F]
\]

\[
\dot{Q} = 1,800 \left[ \frac{Btu}{\text{hr}} \right]
\]
Example

Assume:
- Building Volume = 10,000 ft$^3$
- Infiltration Rate = 0.2 ACH
- Outside Temperature = 20°F
- Inside Temperature = 70°F
- Annual HDD = 6,000 °F·days

Find the heat lost by infiltration.

\[ \cdot Q = 0.018 \cdot \dot{V} \cdot \Delta T \]

\[ \cdot Q \cdot t = 0.018 \cdot \dot{V} \cdot \Delta T \cdot t \]

\[ Q = 0.018 \cdot \dot{V} \cdot HDD \]

\[
Q = 0.018 \left[ \frac{Btu}{ft^3 \cdot °F} \right] \cdot 2,000 \left[ \frac{ft^3}{hr} \right] \cdot 6,000 \left[ \frac{°F \cdot days}{season} \right] \cdot 24 \left[ \frac{hr}{day} \right]
\]

\[
Q = 5,184,000 \left[ \frac{Btu}{season} \right] = 5.184 \left[ \frac{MMBtu}{season} \right]
\]

Heat lost through infiltration (Does not include heat lost by conduction through the building envelope)
Questions or comments?

Please email SolarDecathlon@nrel.gov
Acknowledgements

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National Renewable Energy Laboratory
Building Science Education for Solar Decathlon

Calculating R-Value for a Wall (Part 3)
### Calculating Overall R-values for Walls with Different Heat Transfer Paths

<table>
<thead>
<tr>
<th>[IP Units]</th>
<th>R-value/Inch</th>
<th>R-value Path 1</th>
<th>R-value Path 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wall Layers (inside to outside)</strong></td>
<td><strong>Thickness (inches)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interior Air Film Coefficient</td>
<td>0.50</td>
<td>1.10</td>
<td>0.68</td>
</tr>
<tr>
<td>Drywall</td>
<td>3.50</td>
<td>0.94</td>
<td>3.29</td>
</tr>
<tr>
<td>Wooden Stud</td>
<td>3.50</td>
<td>3.50</td>
<td>0.00</td>
</tr>
<tr>
<td>&lt;beginning path1&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiberglass Insulation</td>
<td>3.50</td>
<td>3.14</td>
<td>10.99</td>
</tr>
<tr>
<td>&gt;beginning path2&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plywood</td>
<td>0.50</td>
<td>1.56</td>
<td>0.78</td>
</tr>
</tbody>
</table>

**Continuous Layer of Foam Board Insulation**

**R-Value Totals/Path**

<table>
<thead>
<tr>
<th></th>
<th>Path 1</th>
<th>Path 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-Value</td>
<td>5.47</td>
<td>13.17</td>
</tr>
<tr>
<td>Framing Factor</td>
<td>0.0938</td>
<td></td>
</tr>
<tr>
<td>U-factor</td>
<td>0.0860</td>
<td></td>
</tr>
<tr>
<td>Overall R-Value</td>
<td>11.63</td>
<td></td>
</tr>
</tbody>
</table>
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References

Building Science Education for Solar Decathlon

Building Envelope Control Layers

Photo by US Department of Commerce, National Institute of Standards and Technology (NIST)
The Purpose of a Building

- Shelter – a basic human need
- Building envelope – separates the inside of the building from outside elements

Photos by US Department of Commerce, National Institute of Standards and Technology (NIST)
Exterior Cladding

- Outermost layer of a building - often made of brick or siding
  - Other types as well

- Exterior cladding can prevent some water from penetrating, but is not a perfect vapor barrier

- The invention of insulation saved lots of energy in buildings, but also introduced challenges with moisture penetration

https://basc.pnnl.gov/resource-guides/drainage-plane-behind-exterior-wall-cladding#edit-group-training

https://www.nps.gov/places/building-4-at-thomas-edison-s-laboratory-complex.htm
Building Envelope

• Provides structure for the building

• Controls heat flow, air flow, water flow, and vapor flow

Movement of Heat, Liquid Water, Water Vapor, and Air:

- Heat: Hot → Cold
- Liquid Water: Higher Elevation → Lower Elevation
- Water Vapor: Higher Concentration → Lower Concentration
- Air: Higher Pressure → Lower Pressure
Building Envelope Control Layers

1. **Water Control Layer**
   - Leaking water = big problem

2. **Air Control Layer**
   - Can result in drafty buildings

3. **Vapor Control Layer**
   - Can lead to mold growth and/or structural damage

4. **Thermal Control Layer**
   - Reduces energy use and maintains comfortable indoor temperature
Water Vapor

- Warm air holds more moisture than cold air
- **Dew point**: temperature air needs to be cooled to in order for water droplets to condense and form dew
- In cold climates, this phenomenon results in condensation inside the building envelope
  - Need a vapor control layer located *inside* of the insulation (the thermal barrier)

[https://www.energy.gov/energysaver/moisture-control](https://www.energy.gov/energysaver/moisture-control)
Water Vapor

• Warm air holds more moisture than cold air
• **Dew point:** temperature air needs to be cooled to in order for water droplets to condense and form dew
• In cold climates, this phenomenon results in condensation inside the building envelope
  • Need a vapor control layer located **inside** of the insulation (the thermal barrier)
• In warm climates, the opposite is true
  • Vapor control layer can be located on the outside of the insulation

https://www.energy.gov/energysaver/moisture-control
Liquid Water

• Don’t let water enter the building!

• Achieved through a strong water control layer

• Can cause wood rot and mold growth, which have dangerous structural and health consequences


https://www.cdc.gov/niosh/topics/indoorenv/moldtesting.html
Exterior Cladding

• Outermost layer

• Protects the envelope from damage

• Prevents some moisture penetration but we cannot rely on it as the vapor control barrier

• Design feature (It is the part of the building we see!)
Structure

• Provides structure for the building

• Can be compromised by moisture penetration

• WE DO NOT WANT THE STRUCTURE TO GET WET!
Location of Layers

- Blue line = water control layer
  - Outermost control layer

- Green line = thermal control layer
  - Can go anywhere

- Red line = air control layer
  - Can go anywhere

- Purple = vapor control layer
  - The most complicated control layer
Vapor Control Layer – Cold Climates

• In cold climates, this layer needs to be kept warm (above the dew point of the air)

• Typically, this is near the inside of the wall
  • Keeps moist air from leaving the building and condensing
Vapor Control Layer – Hot Humid Climates

- In hot climates, the vapor control layer has to be outside the thermal layer.
Water Penetration is Inevitable

- Some water will inevitably enter the wall assembly
- Must design wall to allow it to dry if it gets wet
  - All layers inside the vapor barrier must be breathable
  - Thermal control layer must be able to get wet
Drainage Plane

- Drainage plane – somewhere for moisture to wick to the bottom of the wall outside the thermal layer.
One Solution

• Some materials can function as all four building envelope control layers
Traditional Wall Systems

- Historically, insulation is placed at the structure (i.e. inside the stud cavity)

- Need to make sure water does not get into the structure either as vapor or as liquid water
Ceilings and Floors

Roof/Ceiling
- Ballast
- Filter Fabric
- Control Layers
- Roof Structure

Floor
- Slab
- Control Layers
- Stones
- Earth

Exterior Cladding
- Control Layers
- Structure

Outside → Inside

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SOLAR DECATHLON
Connecting Walls, Ceilings, and Floors

- Must maintain the barriers
- Continuous around corners, through doors, windows, etc.
Window Example

Photo by Paul Torcellini, NREL

Photo by Thomas Kelsey, US Department of Energy Solar Decathlon

Top View of Window Frame

Window Frame

Spacer

Window Glass

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SOLAR DECATHLON
Maintain the Barrier

• **Do your homework on barriers**

• If a barrier fails, make sure the wall will dry both to the inside and to the outside

• Want a durable, long-lasting structure that will not rot or decay with moisture – but still have good thermal integrity.
Questions or comments?

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References

Building Science Education for Solar Decathlon

Commissioning

Source: CMTA, Inc.
What is Commissioning?

• Process of ensuring that a building is operating as designed through verification and validation

• Often abbreviated as "Cx"

• Many commissioning procedures focus on the building envelope
  • Major cause of energy (and money) losses
What is Commissioning?

• Process of ensuring that a building is operating as designed through verification and validation

• Often abbreviated as "Cx"

• Many commissioning procedures focus on the building envelope
  • **Major** cause of energy (and money) losses
  • Leaky buildings create occupant comfort and safety issues
    • Temperature
    • Humidity
    • Condensation
    • Mold
    • Mildew
Why is Commissioning Important?

- Verify that the building is operating at the level of energy efficiency to which it was designed
  - Informs HVAC sizing
Why is Commissioning Important?

• Verify that the building is operating at the level of energy efficiency to which it was designed
  • Informs HVAC sizing

• In existing buildings: identify problematic areas/systems; establish baseline to compare to after improvements are made

• Applying the commissioning process to existing buildings is called “retro-commissioning”
Why is Commissioning Important?

- New buildings: verify that the building is operating at the high performance standard to which it was designed
  - Informs HVAC sizing
- Existing buildings: identify problematic areas/systems; establish baseline to compare to after improvements are made
  - Called “retrocommissioning”

A building can be considered code compliant on paper, but there is no guarantee of high performance without commissioning procedures.
Why do Building Envelopes Leak?

- Vintage
  - Gaps and cracks form over time

Why do Building Envelopes Leak?

• Vintage
  • Gaps and cracks form over time

• Non-continuous envelope
  • Windows and doors break up the envelope and introduce more places for leaking
Why do Building Envelopes Leak?

• Vintage
  • Gaps and cracks form over time

• Non-continuous envelope
  • Windows and doors break up the envelope and introduce more places for leaking

• Bad insulation
**Blower Door Testing**

- Blower door fans create positive or negative pressure differential between inside and outside of building

- Used to evaluate air tightness and identify air leakage sites

- Methods outlined in ASTM Standards E1827 and E779
Blower Door Testing

Source: CMTA, Inc.
Blower Door Testing

• Positive pressure test: evaluates exfiltration
• Negative pressure test: evaluates infiltration

Blower Fans Suck Air out of Building, Creating Negative Pressure Differential

50 Pascals

Infiltration Site

Exfiltration: air leaking out

Infiltration: air leaking in
Blower Door Testing

- Positive pressure test: evaluates exfiltration
- Negative pressure test: evaluates infiltration

Exfiltration: air leaking out
Infiltration: air leaking in
Ventilation: controlled air flow

Blower Fans Suck Air out of Building, Creating Negative Pressure Differential

50 Pascals

Infiltration Site
Blower Door Testing

• Positive pressure test: evaluates exfiltration
• Negative pressure test: evaluates infiltration
• Leakage measured in cubic feet per minute (cfm) per square foot of **thermal boundary area**

The thermal boundary area is the entire area between the inside and outside.

It includes walls, floors, ceilings, windows, doors.
Blower Door Testing

- **0.06 cfm/ft²** - best testing results CMTA has tested
- **0.25 cfm/ft²** - Standard for Government/UFC Projects
- **>1.00 cfm/ft²** - worst testing results CMTA has tested

- **0.10-0.15 cfm/ft²** - Standard for CMTA High Performance Buildings envelope
- **0.40 cfm/ft²** - Standard for most new buildings (IECC Recommended)
Importance of Testing Standards

- Standardize the way we measure things
- Everyone is on the same page
- Results can be directly compared
- ASTM Standards - American Society for Testing and Materials
Infrared Imaging (Thermography)

• Used to capture temperature differences on surfaces

• Methods outlined in ASTM Standard C1060

• Larger temperature delta results in best images
  • Condition spaces prior to thermography if possible

• Perform during pressure testing to identify exact air infiltration and exfiltration areas

Source: CMTA, Inc.
Infrared Imaging Examples

Thermal trails in a doorway during negative pressurization

Source: CMTA, Inc.
Infrared Imaging Examples

Leakage through a window (this is typical)

Source: CMTA, Inc.
Infrared Imaging Examples

Poor seal or thermal break at exterior roof line

Source: CMTA, Inc.
Infrared Imaging Examples

Poor conduit seal at J-box installation

Source: CMTA, Inc.
Commissioning of Other Building Systems

- HVAC
- Electrical
- Plumbing
- Protective systems
  - Fire
  - Security
  - Communication
  - Alarm

- Easier to detect performance issues with these systems compared to envelope
  - Manual testing or detection
  - Automated commissioning – integration with Building Automation System
    - Auto-commissioning (ACx) or Monitor-Based Commissioning (MBCx)

Special Acknowledgement

Solar Decathlon would like to thank CMTA, Inc. for sharing their commissioning expertise, photos, and videos that made this episode possible.

Questions or comments?

Please email SolarDecathlon@nrel.gov

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Building Technologies Office. The views expressed in the presentation do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.
Acknowledgements

The authors would like to acknowledge the following people for their help with this episode:

Holly Carr
U.S. Department of Energy

Stacey Rothgeb, Zachary Peterson, Ron Judkoff, Jes Stershic, Dave Roberts, Michael Deru, Jennifer Daw, Linh Truong, and Kelly MacGregor
National Renewable Energy Laboratory

David Brown
Accenture Federal Services
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