BUILDING ENERGY NEEDS
with particular attention paid to

THERMAL INSULATION

ENGS 44 Sustainable Design
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Among the life-cycle stages of a building, the greatest impact is caused during use (lifetime of 40 to 100 or more years):

- 93% of energy going into a building is consumed during use.
- For electricity, the percentage is 95%.

(Blanchard & Reppe, University of Michigan, 1998)
And, during use, the most significant environmental impact is due to heating and cooling (42% + 8% = 50% of energy consumption in USA in 2009).


Energy consumption is environmentally impacting for three reasons:

1. Heating oil and natural gas are non-renewable resources;
2. Products of combustion (fumes) are polluting the air;
3. Greenhouse gas emissions affect the climate.

A better thermal envelope is one of the best ways of achieving environmental benefits. The financial picture is very much positive!
Heating (or cooling) of buildings is necessary because heat has the nasty habit of moving away from where you want to keep it.
In other words: It leaks!

There are three physical ways by which heat moves from one place to another:
- Conduction (molecular collisions in the material)
- Convection (movement of carrying fluid, like air in/out building)
- Radiation (electromagnetic wave).

In designing buildings, we are concerned with all three.

For the moment, let us consider movement of heat by conduction.

heat flux = conductivity × (temperature gradient)

\[ Q = K \frac{\Delta T}{L} = \frac{K}{L} \left( T_{in} - T_{out} \right) \]

\[ Q = U \left( T_{in} - T_{out} \right) \]

The heat flux \( Q \) is expressed in BTUs per ft\(^2\) per hour (or W/m\(^2\)).

The \( U \)-value characterizes the ability of the wall to conduct heat from one side to the other.
Rewrite the equation for $U$:

$$U = \frac{Q}{T_{in} - T_{out}}$$

Thus, $U$-values are expressed in BTUs per ft$^2$ per hour per degree F (in Europe and most of the rest of the world: W per m$^2$ per °C).

Now, consider a wall consisting of several layers, such as:
- indoor sheetrock
- wood frame
- outside plywood
- shingles

![Diagram of a wall with layers and temperatures $T_0$, $T_1$, $T_2$, $T_3$, $T_4$ and $U_1$, $U_2$, $U_3$, $U_4$.]

$Q = U_1(T_0 - T_1) = U_2(T_1 - T_2) = U_3(T_2 - T_3) = U_4(T_3 - T_4)$

$T_{in} - T_{out} = T_0 - T_4 = (T_0 - T_1) + (T_1 - T_2) + (T_2 - T_3) + (T_3 - T_4)$

$= \frac{Q}{U_1} + \frac{Q}{U_2} + \frac{Q}{U_3} + \frac{Q}{U_4}$

$= \left(\frac{1}{U_1} + \frac{1}{U_2} + \frac{1}{U_3} + \frac{1}{U_4}\right)Q$

where $R_i = 1/U_i$
Since $R$-values are reciprocal of $U$-values, they are expressed in
\[
\text{(ft}^2 \times \text{hour} \times ^\circ\text{F}) / \text{BTU} \quad \text{in metric: m}^2 \times ^\circ\text{C}/ \text{W}
\]

The $R$-value of a material indicates its resistance to transferring heat from one side to the other.

The higher the $R$-value of a material, the better insulation it provides.

Unlike $U$-values, $R$-values are additive for materials arranged sequentially.

**$R$-values of building materials:**

<table>
<thead>
<tr>
<th>Material</th>
<th>$R$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>½-inch sheetrock drywall</td>
<td>0.64</td>
</tr>
<tr>
<td>0.5-in outside plywood</td>
<td>0.62</td>
</tr>
<tr>
<td>Rough sawn cedar siding</td>
<td>1.25</td>
</tr>
<tr>
<td>Aluminum, steel or vinyl siding (hollow backing)</td>
<td>0.61</td>
</tr>
<tr>
<td>Asphalt roof shingles</td>
<td>0.44</td>
</tr>
<tr>
<td>Concrete blocks</td>
<td>1.04</td>
</tr>
<tr>
<td>6-in concrete masonry unit (CMU)</td>
<td>2.00</td>
</tr>
<tr>
<td><strong>Dual-pane windows</strong></td>
<td>1.92</td>
</tr>
<tr>
<td><strong>Triple-pane windows with argon gas</strong></td>
<td>5.88</td>
</tr>
<tr>
<td>Brick (common size)</td>
<td>0.20/inch</td>
</tr>
<tr>
<td>Pine wood</td>
<td>0.95/inch</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.09/inch</td>
</tr>
<tr>
<td>3.5-in fiberglass batt insulation</td>
<td>13.00</td>
</tr>
<tr>
<td>Biobased® Insulation 1701</td>
<td></td>
</tr>
<tr>
<td>2.0 inches</td>
<td>12.00</td>
</tr>
<tr>
<td>3.5 inches</td>
<td>19.00</td>
</tr>
<tr>
<td>5.0 inches</td>
<td>28.00</td>
</tr>
<tr>
<td>Cellulose spray</td>
<td>3.42/inch</td>
</tr>
<tr>
<td>Icynene® – spray</td>
<td>3.6/inch</td>
</tr>
<tr>
<td>Icynene® – pour formula</td>
<td>4.0/inch</td>
</tr>
<tr>
<td>Urethane foam</td>
<td>5.3/inch</td>
</tr>
<tr>
<td>Expanded polyurethane</td>
<td>6.2/inch</td>
</tr>
<tr>
<td>Polyiso foam</td>
<td>7.62/inch</td>
</tr>
<tr>
<td>Air</td>
<td>5.5/inch</td>
</tr>
</tbody>
</table>

In general, stone, brick and concrete are poor insulators. (Way to remember: marble feels cold at the touch.)

Additional values can be obtained at: [http://www.coloradoenergy.org/procorner/stuff/r-values.htm](http://www.coloradoenergy.org/procorner/stuff/r-values.htm)
In medieval stone castles, tapestries were hung on the stone walls not just for decoration. They were an essential item in keeping the château warm. This tapestry is a small one, only a few feet wide. Some tapestries could be much bigger and cover entire walls.

Air is an excellent insulator ($R = 5.5/\text{inch}$), as long as it does not move. It has poor conduction but good convection properties.

This is why most types of insulation consist of air trapped in fiber or bubbles to prevent air from moving. *Examples*: fiberglass, cellulosic spray, and hay bales.

Slow or absent air motion near a wall, either inside or outside, creates a thermal boundary layer, with an $R$-value of its own:

- Still air $R = 0.68$ (good approximation for inside)
- 15 mph wind outside $R = 0.17$ (typical for outside in winter – used for heating calculations)
- 7.5 mph wind outside $R = 0.25$ (typical for outside in summer – used for air-conditioning calculations)

Such small $R$-values do not make a big difference along walls but do help along windows.
Example: The $R$-value of a traditional wall.

Still air inside – thermal layer 0.68
Paint negligible
½-inch sheetrock 0.64
6-mil plastic – moisture barrier negligible
3.5-inch batt insulation 13.00
½-inch exterior plywood 0.62
1-inch foamboard 5.00
Rough sawn cedar shingles 1.25
15 mph wind outside – thermal layer 0.17

TOTAL $R$-value 21.36

Corresponding $U$-value = $1 / R$-value = 0.0468 BTUs/(ft².h.°F)

Dartmouth College has adopted $R = 26$ for walls in all its new buildings. For windows, values range between 3 and 6.5 depending on operability.

Other example: The $R$-value of a traditional roof.

Still air inside – thermal layer 0.68
6-mil plastic – moisture barrier negligible
9-inch batt insulation 30.00
½-inch exterior plywood 0.62
Felt paper 0.06
Asphalt roof shingles 0.44
15 mph wind outside – thermal layer 0.17

TOTAL $R$-value 31.97

Corresponding $U$-value = $1 / R$-value = 0.0313 BTUs/(ft².h.°F)

Dartmouth College has adopted $R = 40$ for roofs in all its new buildings.
The overall $U$-value of a wall is the reciprocal of its $R$-value:

$$U = \frac{1}{R} = \frac{1}{R_1 + R_2 + R_3 + \text{etc.}}$$

The envelope of a building is composed of solid walls, windows, doors, roof, etc.

The total heat lost by a building is the sum of the heat losses through all these surfaces:

$$Q = U \left( T_{\text{in}} - T_{\text{out}} \right) \quad \text{[in BTUs per ft}^2 \text{ and per hour]}$$

Total Heat Loss = $(U_{\text{wall}} \times \text{wall area})$

+ $(U_{\text{window}} \times \text{window area})$

+ $(U_{\text{door}} \times \text{door area})$

+ $(U_{\text{roof}} \times \text{roof area})$

+ $(\text{etc.})\times(T_{\text{in}} - T_{\text{out}})$ \quad \text{[in BTUs per hour]}

Quick remark in passing:

To reduce the heat load, there is something that one can do besides using material with higher $R$-values and that is to reduce the surface area through which heat is lost ($A$ factor in preceding equation).

Examples:

The sphere is the geometric shape that minimizes the ratio of surface to volume.

If right angles are required for ease of construction, then the cube is the form that has the least area per volume.

Attached barn and garage to maximize common walls.
The quantity

$$HL = (U_{\text{wall}} \times \text{wall area} + U_{\text{window}} \times \text{window area} + U_{\text{door}} \times \text{door area} + U_{\text{roof}} \times \text{roof area} + \text{etc.}) \times \frac{24 \text{ hours}}{1 \text{ day}}$$

is called the Heat-Loss. It is expressed in BTUs per day per °F.

Knowing how the building is constructed leads to the determination of its Heat-Loss value.

The heat lost by a building in BTUs per day is thus:

$$\text{Total } Q = HL \times (T_{\text{in}} - T_{\text{out}})$$

**Example:**

**Salt-box conventional house**

Total external wall surface = 1,898 ft²  \( R = 21.37 \rightarrow U = 0.0468 \)

Total window/door surface = 271 ft²  \( R = 1.92 \rightarrow U = 0.5208 \)

Roof area = 38ft x 40 ft = 1,520 ft²  \( R = 31.97 \rightarrow U = 0.0313 \)

\[ HL = (1,898 \text{ ft}^2)(0.0468) + (271 \text{ ft}^2)(0.5208) + (1,520 \text{ ft}^2)(0.0313) \]

\[ = 277.5 \text{ BTUs/(hour x °F)} \text{ then convert from hours to days} \]

\[ = 6,660 \text{ BTUs/(day x °F)} \]
A slight complication: Air infiltration

Exchange of air between indoors and outdoors also takes place, primarily through doors being opened and closed, and through cracks where walls connect to foundation and to roof, around window frames, etc.

Warm inside air is lost, and incoming air from outside taking its place needs to be heated to inside temperature. This adds to the heating requirement of a house. It is not negligible.

Procedure:

\[ I = H_{air} \times Volume \times Rate \text{ of air exchange} \]

where

- \( H_{air} \) = heat required to raise temperature of 1 ft\(^3\) of air by 1\(^\circ\)F
  \[ H_{air} = 0.0182 \text{ BTUs/}(\text{ft}^3 \times \text{°F}) \]
- \( Volume \) = indoor volume affected (usually all interior minus attic)
- \( Rate \text{ of exchange} = 2/3 \text{ per hour} \)
  meaning that the inside air is replaced twice every three hours
- \( I \) = Infiltration loss (in BTUs per hour and per \( \text{°F} \))

Three Main Driving Forces of Airflow & Heat Loss

Wind-Induced Airflow: Wind blows on the outside of the home and pushes air through holes (infiltration). An equal amount of air will be pushed out of the holes in other places in the home (exfiltration).

Warm Air Exfiltration: Rising warm air causes pressure differences throughout the building envelope making warm air exfiltrate through ceiling and attic, while cool air infiltrates through crawl spaces and basements.

Mechanical Systems: Heating and ventilation systems create positive and negative pressures within the building envelope. In this example, the heating/cooling mechanical system is leaking warm air into the attic.

www.homepower.com Aug/Sep 2008

... in addition to opening and closing the entrance door.
An ideal air barrier

NIST Net-Zero Energy Residential Test Facility on NIST campus in Gaithersburg, Maryland (2,700 ft² 2-story home + attic, with 44,900 ft³ inner volume)

Example of infiltration calculation:

Same salt-box house, with inside air volume of \( V_{\text{olume}} = 14,492 \text{ ft}^3 \)

\[
I = (0.0182 \text{ BTUs/(ft}^3 \times ^{\circ} \text{F})) (14,492 \text{ ft}^3) (0.667 / \text{hour})
= 173.83 \text{ BTUs/(hour x } ^{\circ} \text{F)}
= 4,220 \text{ BTUs/(day x } ^{\circ} \text{F)}
\]

Adding the pieces:

Add this heat requirement to the heat leakage by conduction through walls, windows and roof:

\( HL = 6,660 + 4,220 = 10,880 \text{ BTUs/(day x } ^{\circ} \text{F)} \)

Overall, the heat requirement splits as follows:

- Walls 2,132 BTUs/(day x } ^{\circ} \text{F)} 20%
- Windows 3,387 BTUs/(day x } ^{\circ} \text{F)} 31%
- Roof 1,141 BTUs/(day x } ^{\circ} \text{F)} 10%
- Infiltration 4,220 BTUs/(day x } ^{\circ} \text{F)} 39%

TOTAL 10,880 BTUs/(day x } ^{\circ} \text{F)} 100%
Degree-Days

Degree-day is a quantitative index measuring the energy demand to heat or cool buildings.

A mean daily temperature (average of the daily maximum and minimum temperatures) of $65^\circ F$ is the base for both heating and cooling degree-day computations. Heating degree-days are summations of negative differences between the mean daily temperature and the $65^\circ F$ base. Cooling degree-days are summations of positive differences from the same base.

The assumption is that the desirable indoor temperature is $72^\circ F$, of which 7 degrees will be derived from other sources than the heating system, such as appliances, light bulbs and moving people.

For example, heating degree-days for a station with daily mean temperatures during a seven-day period of 63, 65, 60, 56, 52, 65 and 62°F, are 2, 0, 5, 9, 13, 0 and 3, for a total for the week of 32 heating degree-days.

Degree-days for Lebanon, New Hampshire:

<table>
<thead>
<tr>
<th>Month</th>
<th>Average 1981-2010</th>
<th>Year 2011</th>
<th>Year 2012</th>
<th>Year 2013</th>
<th>Year 2014</th>
<th>Year 2015</th>
<th>Year 2016</th>
<th>Year 2017</th>
<th>Year 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>1421</td>
<td>1468</td>
<td>1271</td>
<td>1390</td>
<td>1455</td>
<td>1509</td>
<td>1252</td>
<td>1139</td>
<td>1401</td>
</tr>
<tr>
<td>February</td>
<td>1190</td>
<td>1274</td>
<td>1060</td>
<td>1124</td>
<td>1326</td>
<td>1614</td>
<td>1079</td>
<td>1007</td>
<td>1031</td>
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<tr>
<td>March</td>
<td>1004</td>
<td>1060</td>
<td>740</td>
<td>1006</td>
<td>1315</td>
<td>1209</td>
<td>835</td>
<td>1152</td>
<td>1036</td>
</tr>
<tr>
<td>April</td>
<td>603</td>
<td>615</td>
<td>594</td>
<td>614</td>
<td>634</td>
<td>653</td>
<td>686</td>
<td>494</td>
<td></td>
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<tr>
<td>May</td>
<td>285</td>
<td>212</td>
<td>184</td>
<td>257</td>
<td>266</td>
<td>171</td>
<td>284</td>
<td>313</td>
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<tr>
<td>June</td>
<td>75</td>
<td>85</td>
<td>77</td>
<td>82</td>
<td>44</td>
<td>100</td>
<td>49</td>
<td>91</td>
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<tr>
<td>July</td>
<td>15</td>
<td>0</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>19</td>
<td>10</td>
<td>12</td>
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<tr>
<td>August</td>
<td>31</td>
<td>10</td>
<td>6</td>
<td>25</td>
<td>32</td>
<td>5</td>
<td>7</td>
<td>39</td>
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<tr>
<td>September</td>
<td>176</td>
<td>108</td>
<td>190</td>
<td>192</td>
<td>197</td>
<td>88</td>
<td>126</td>
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<tr>
<td>October</td>
<td>527</td>
<td>489</td>
<td>406</td>
<td>484</td>
<td>419</td>
<td>558</td>
<td>474</td>
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<tr>
<td>November</td>
<td>812</td>
<td>709</td>
<td>866</td>
<td>919</td>
<td>906</td>
<td>703</td>
<td>701</td>
<td>874</td>
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<tr>
<td>December</td>
<td>1209</td>
<td>1073</td>
<td>1079</td>
<td>1254</td>
<td>1094</td>
<td>852</td>
<td>1204</td>
<td>1418</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>7,348</td>
<td>7,103</td>
<td>6,476</td>
<td>7,351</td>
<td>7,691</td>
<td>7,481</td>
<td>6,707</td>
<td>6,930</td>
<td></td>
</tr>
</tbody>
</table>

See also: http://www.weatherdata depot.com/
From the Heat-Loss value of the building and the degree-days of the climate in which it sits, one can determine the heating requirement of the building, called the **Heat Load**:

\[
\text{Heat Load} = HL \times (\text{degree-days})
\]

**Example:** Salt-box house in Lebanon, NH:

\[
\text{Heat Load} = (10,880 \text{ BTUs/(day x } ^\circ F)) \times (7,348 \text{ degree-days}) = 79,946,240 \text{ BTUs for the average year} = 84,348 \text{ MJ/year} = 23,430 \text{ kWh/year}
\]

The questions are now:

1. How can we reduce this heat load?

And, for a given heat-load requirement:

2. How can we provide this heat from the sun or other clean source of energy?

Answers in forthcoming lectures!
Proof that it can be done in Hanover, New Hampshire!

And in Norwich, Vermont:

The Landau House

http://www.zeroenergy.com/p_landau.html (now obsolete)