The Economic Thickness of Thermal Insulation

Designers frequently ask questions like “what is the optimum level of insulation to provide?” Others are interested only in cost so they look for the economic thickness or “payback” on increasing insulation levels. Still others want an insulation level to achieve a certain level of performance (e.g. 50% of Code-level energy consumption). If the answer was simple there would be one common insulation level for all components of all buildings in a given climate. That is not the case so what is going on? Some variables argue in favor of increasing wall and attic insulation levels such as:

- Attic and wall cavities are easier to insulate than windows and doors so that makes it possible to achieve higher thermal resistance versus other components.
- The savings in energy brought about by insulation might bring about the ability to reduce sizing (and cost) of mechanical systems, thus justifying higher insulation costs.
- Above-grade elements are more exposed than below-grade elements so insulation provides an even greater benefit above grade.

Some variables argue against increasing insulation:

- Measures that thicken wall assemblies eat into available floor space which comes at a cost.
- Thicker walls might require thicker foundations and modifications to windows adding cost.
- If measures are not taken to air tighten an assembly, the effect of added insulation may be negligible.
- Some insulation materials are more costly per unit of R-value so they do not provide sufficient pay back to justify high levels of insulation.

Beyond the building and site-related variables are issues like:

- Energy costs: With historically low energy prices there has not been as much incentive to conserve energy. Clearly that is changing and will continue to change in the future.
- Non-energy benefits: Typically, better insulated and air sealed buildings are more comfortable and more durable so building owners may be willing to pay a premium for such benefits.
- Some buyers are willing to pay a huge premium to be “energy independent” or off-the-grid.

- Borrowing costs: If the money to make an improvement is borrowed, it comes at a cost which must be factored against energy savings.

This Design Note is not intended as a recommendation of a particular R-value or method of designing buildings. Rather, if a designer has formulated an opinion on what type of building(s) he is building (built to minimum Code or some standard above Code i.e. LEED, NAHB Green, etc.) it suggests alternate ways of justifying/achieving equal or better performance.

Code Minimums

In any design project, it is necessary to consider what is the minimum, Code-prescribed, level of insulation that should be installed.

In the US, the International Residential Code prescribes the following levels of insulation in various climate zones:

Table 1: Prescriptive Insulation Levels in the IRC 2009.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Ceiling</th>
<th>Walls</th>
<th>Basement</th>
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<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>13</td>
<td>5/13*</td>
</tr>
<tr>
<td>4</td>
<td>38</td>
<td>13</td>
<td>10/13*</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>20 or (13+5)*</td>
<td>10/13*</td>
</tr>
<tr>
<td>6</td>
<td>49</td>
<td>20 or (13+5)*</td>
<td>15/19*</td>
</tr>
<tr>
<td>7</td>
<td>49</td>
<td>21</td>
<td>15/19*</td>
</tr>
<tr>
<td>8</td>
<td>49</td>
<td>21</td>
<td>15/19*</td>
</tr>
</tbody>
</table>

Notes:  
* Continuous vs. Cavity insulation only
** Cavity insulation + Continuous insulation

Anyone looking for one specific R-value as a minimum might find this table confusing—it suggests that continuous insulation at a lower R-value is equivalent to cavity fill insulation at a higher R-value—but there are good reasons for the Code to be written in this way. As we insulate wall and ceiling cavities to higher levels, we find that the remaining heat flow through structural elements becomes a much higher percentage of the total. Rather than increasing insulation levels in the cavity
spaces, it becomes much more important to provide continuous insulation over structural features that otherwise act as “thermal bridges” through the insulation.

That is one of the areas where Icynene® spray foams can be used to greatly improve heat loss/gains. Continuous spray foam insulation applied over structural elements can help eliminate thermal bridging through structural elements, controlling heat loss/gains. For example the underside of roof rafters can be insulated in an unvented attic application. This also makes buildings more comfortable.

“Equivalent” Assemblies
The arguments of “equivalent” Code minimum levels also apply to higher levels of insulation. Table 2 provides groupings of wall assemblies that are roughly equivalent in terms of conductive heat loss.

Table 2
Roughly Equivalent Wall Assemblies

| Group A | 2x6 Wall 24” OC with R-20 Cavity  
2x4 Wall 16” OC with R-13 Cavity + R-5 Continuous |
|---------|---------------------------------------------------|
| Group B | 2x4 Wall 16” OC with R-12 Cavity + R-10 Continuous  
2x6 Wall 24” OC with R-20 Cavity + R-5 Continuous  
2x6 Wall 24” OC with R-30 Cavity |
| Group C | 2x6 Wall 24” OC with R-20 Cavity + R-10 Continuous  
2x4 Wall 16” OC with R-13 Cavity + R-15 Continuous |
| Group D | 2x6 Wall 24” OC with R-20 Cavity + R-15 Continuous  
2x4 Wall 16” OC with R-13 Cavity + R-20 Continuous |

As can be seen in the insulation levels identified as Group B in this table, it takes a very high insulation level in a wall cavity (R-30) to be equivalent to a wall assembly with continuous insulation over the studs (R-12+R-10 Continuous.)

One might also expect that a wall insulated to a very high level such as those listed in Group D might have reduced energy use by a very high percentage. But in reality, once wall cavities are filled, conductive heat loss through walls is a small percentage of the total heat loss of a building so the impact of adding R-value alone tends to diminish as insulation levels increase.

Consider the conductive heat flow equation:

$$Q = \frac{A \times \Delta T}{R}$$

Where:
- $Q$ = Rate of heat flow (BTU/hr)
- $A$ = Area ($ft^2$)
- $\Delta T$ = Difference in Temperature ($°F$)
- $R$ = Resistance to conductive heat flow (hr.$ft^2 °F$/BTU)

Even a 300% increase in R-value only reduces conductive heat loss through walls 75%. If you consider that heat loss/gains through walls is a fraction of the total heat loss/gains of a building, the effect might be in the range of a 10% saving on total building energy use.

Adding insulation to walls follows a pattern of diminishing returns. As an example, consider 1000 ft$^2$ of insulated area with a temperature differential of 40°F. We will start with a 1” layer of Icynene® increasing the insulation thickness by 1” increments at R-3.7/inch up to 14” and that is R-51.8. The heat flow rates are shown in Figure 1.

Figure 1
Conductive Heat Flow Reduction

Figure 1 illustrates how heat flow is reduced as R-value is increased. Around R ~ 20, the curve begins to flatten and diminishing returns are gained from increased insulation thickness. At that point it makes much more sense to begin to provide continuous insulation over the wall to address thermal bridging.
Reduced Air Infiltration

Thus far, the discussion on heat loss/gains has focused on conductive heat loss but heat transfer occurs by other means as well. In many buildings, uncontrolled convective heat loss accounts for as much as 40% or more of total energy consumption. Icynene® spray foams are able to fill any number of irregular shaped cavities and they adhere to most construction materials, thereby, forming an insulation layer with very low air permeance.

Conventional fibrous insulation materials are air permeable, so they cannot control air flow. Furthermore, the air sealing details required to control air flow with fibrous insulation products can be very time consuming, labor intensive and costly. Icynene® spray foams are a more reliable way to consistently deliver a building with exceptional energy performance.

Combined Effects

Oak Ridge National Laboratory (ORNL) conducted an experiment\(^1\) to determine the efficiency of a roof assembly insulated with low density, loose-fill fiberglass insulation and discovered that up to 50% of the heat loss occurred as a result of convection; air circulation through the insulation. This study showed that convective heat transfer had a significant negative impact on insulation performance.

In Canada, the National Research Council Institute for Research in Construction (NRC-IRC) conducted a series of research projects to assess the overall performance of insulated wall assemblies.

Wall assemblies insulated with low density and medium density polyurethane foam insulation consistently out performed fibrous insulation assemblies when they were tested when air pressure was applied. NRCC produced a Wall Energy Rating factor that compared the performance that was delivered during testing versus the expected performance based on Nominal R-value. Spray foams consistently performed at more than 90% of nominal R-value where as fibrous insulation had performances in the range of 35% to 65% of nominal R-value.

Computer Simulations

The selection of the optimal level of insulation can be complicated but software tools such as REM/Design, HOT 2000 and EnergyGuage can be a powerful way of simplifying trade-off analysis. Such analyses are useful for allowing designers to examine how adding insulation and air sealing reduces required capacity in heating and cooling systems.

The following evaluation was generated using the REM/Design energy analysis software as reflected in the charts (2.1 – 2.4). This evaluation deals with three identical houses, located in different North American cities with three different levels of insulation and air-infiltration. A fully detached, approximately 3,500 ft\(^2\), two storey house with a conditioned basement was studied in 10 different cities. The analysis considered the merits of increasing insulation versus increasing air tightness. The comparable data used in the computer analysis was as follows:

<table>
<thead>
<tr>
<th>Specification for Comparison Houses</th>
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<table>
<thead>
<tr>
<th></th>
<th>Nat. R-Value</th>
<th>R-Value Wall</th>
<th>R-Value Ceiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Base Case</td>
<td>0.55</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>2. Higher R-value</td>
<td>0.55</td>
<td>19</td>
<td>43</td>
</tr>
<tr>
<td>3. Icynene</td>
<td>0.10</td>
<td>11</td>
<td>18</td>
</tr>
</tbody>
</table>

Both the base case and upgraded mineral fiber insulation case used an air infiltration rate of 0.55 ACH at natural pressure. A recent study by NAHB indicated this was the average value for newly constructed residential buildings in the U.S.\(^2\)

The Icynene\(^1\), house used Lower R-values than even the base case or the upgraded insulation house. The key difference was the use of Icynene light density spray foam—an air-impermeable insulation. An air infiltration rate of 0.1 ACH at natural pressure was used for Icynene\(^1\) based on its air sealing capability, as determined by NAHB\(^2\).

\(^1\) ORNL’s Building Envelope Center
Fighting the Other Cold War

\(^2\) NAHB Research Center, November, 2007;
Air Infiltration Data Analysis for Newly Constructed Homes Insulated With Icynene Spray Foam. The efficiencies of heating and cooling systems were 92 AFUE for the furnace and 13 SEER for A/C unit respectively with utility rates set at $0.10 per kWh for electricity and $1.50 per Therm for natural gas.
Heating and cooling costs and the required heating and cooling equipment capacities were estimated for each set of house specifications in 10 different cities.

Savings on heating costs were up to 30%-40% with Icynene® compared to the “Base Case” and even when compared to the “Higher R-Value” insulation systems. The colder the climate, the greater the heating cost savings are with Icynene®.

As far as the sizing of heating and cooling equipment is concerned, the use of Icynene® provides a significant opportunity to reduce the capacity of both heating & cooling systems. Load reduction for both heating & cooling equipments can reach up to 35%.

Why Icynene

Whether you are looking to meet Code or go off-the-grid, Icynene®’s air-sealing capability virtually eliminates convective heat transfer within the insulation and reduces unwanted air leakage through the building envelope.

The on-site spray applied application of Icynene® spray foam creates an excellent air seal that provides a low air infiltration rate through the building envelope.
for years of durable, energy efficient comfort. For more than 20 years Icynene has set the standard for spray foam insulation.
COMMITTED TO THE RESPONSIBLE USE OF SPRAY FOAM CHEMISTRY FOR OVER 25 YEARS.

Icynene products have an excellent health and safety record spanning more than 350,000 insulation projects over more than 25 years. Nonetheless, safe handling practices during and immediately following installation are required to eliminate the possibility of health effects from exposure to isocyanates. Asthma, other lung problems, and irritation of the nose and throat can result from inhalation of isocyanates. Direct contact with the skin and eyes can result in irritation. Different individuals will react differently to the same exposures; some will be more sensitive than others.

Everyone (other than Icynene-certified spray technicians) must vacate the job site, remaining completely out of the building or at least 50 feet away, while the spray is applied and for at least 24 hours after spraying is completed to allow active ventilation of the job site and to ensure the foam chemicals are completely cured. No exceptions.

Independent studies indicate that with 24 hours’ active ventilation after spraying is completed, Icynene spray foam insulation is safely cured.