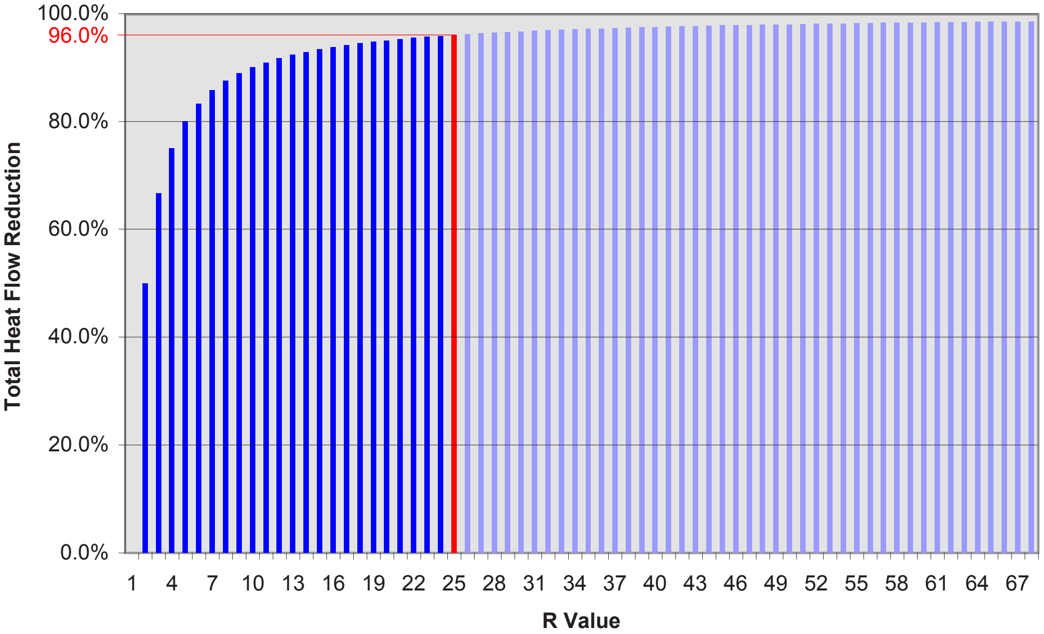
Economics of Energy-Efficient Envelopes

Chasing Diminishing Returns of Over-Insulation

This paper addresses cold-climate conditions present in the northern tier of the United States.

We insulate our building envelopes against conductive heat flow (loss or gain). As a measure of this flow we use the R-value, which is established by the test procedures specified in ASTM C 518.

Most people imagine that the value of insulation is linear, so that, for example, doubling the R-value will double the amount of energy saved. The physics of the situation is quite different. While R is the measure of resistance to heat transfer for a product of a given thickness, the U-factor is the measure of overall heat transfer, and its value is the inverse of R. As a result, the conductive heat flow reduction achieved by adding insulation to the assembly increases at a decreasing rate. As Figure 1 indicates, 96 percent of all possible heat flow reduction is achieved at R 25. After that, as more and more insulation is added, the reductions will slowly, and at a decreasing rate, approach, but never reach, 100 percent. To illustrate, if you double the insulation to R 50, the heat flow is further reduced by only 2 percent. If you double it again, to R 100, the further reduction is only 1 percent more than R 50. So for the addition of *four times* the amount of insulation, the heat transfer reduction improves by only 3 percent.



$Q=A \times \Delta T/R$

where:
Q = Rate of heat flow (Btu/hr)
A = Area (ft^2)
ΔT = Difference in Temperature ($^\circ$F)
R = Resistance to conductive heat flow (hr ft^2 $^\circ$F/Btu)

Total Heat Flow Reduction = $1 - (Q_R / Q_1)$

Figure 1: *Decreasing Return of Increased R Value*

Excessive insulation is often applied to or within the roof structure, largely because the deeper framing in the roof or attic floor accepts more depth of insulation fill, and on the mistaken belief that it will be more effective because "hot air rises." Heat transfers in all directions from higher to lower temperature, seeking equilibrium (Second Law of Thermodynamics). The greater the difference in temperature (Δt) between the two objects, the greater the flow of heat. Hot air rises in relation to cooler air, which, being denser, displaces it (Archimedes' Principle). In a well-insulated, relatively airtight structure with modern environmental control systems, this stratification is largely absent.

Another building component that is often over-insulated, particularly in so-called "Passive Houses," is the basement floor. Here the constant soil temperature is only about 20 degrees lower than the indoor design temperature ($\Delta t = 20$). While the same insulation performance curve applies, the absolute heat transfer for any given R-value is only 28.5 percent of what it is for the above grade walls ($\Delta t = 20 \div \Delta t = 70$). The actual basement slab heat transfer is so comparatively small that it is equal to the exterior wall with R 25 insulation when the slab has only R 7 insulation. The same is true for the lower portions of the basement wall, but this changes throughout its height, becoming more like the above-grade wall as it passes above the frost line.

The second important strategy for reducing conductive heat flow is the thermal break. In a wall of framed construction, whether steel or wood, the studs and other framing members are far more conductive of heat than the cavity spaces which are filled with insulation. To interrupt these lines of heat flow, a thermal break must be introduced between the outside air and the conductive framing members. One method to achieve this break is to apply rigid insulation, such as expanded polystyrene or polyisocyanurate foam board, over the outside of the framing. A second method is to install lines of furring strips horizontally across the studs, on their outside surfaces, so that most of their surface can be covered by the cavity insulation. Without this thermal break, much of the value of added insulation within the wall cavity is diminished.

Looking at Windows

The greatest source of heat-transfer in a building envelope is the windows. A high-quality window with low-e-coated insulating glass can achieve a U-factor of 0.330 Btu/(hr x sq. ft. x deg. F), or the equivalent of a section of solid wall with R 3 insulation, which is only a 67 percent heat flow reduction. There is 8.33 times more thermal flow through the window than through the surrounding wall with R 25 insulation. In view of this, there is a temptation to reduce the window area to an absolute minimum, but this has its disadvantages. People crave natural light, and studies show that building inhabitants are more productive, creative, and able to learn in environments with abundant natural light. In addition, ample natural light in well designed buildings for occupancies like classrooms and offices can reduce or eliminate the need for artificial lighting during most of the daylight hours. In a typical office building, lighting accounts for more than 40 percent of the electrical load, and offsetting this with natural light can realize significant energy savings.

Even in residences, where the lighting load may be a lower percentage of the overall electrical consumption, there is great benefit to be reaped from natural light. Here, the solution may be to use even higher-performance windows, albeit at significantly increased cost. Installing triple-glazed windows with heat-mirror technology can reduce the U-factor to 0.20 Btu/(hr x sq. ft. x deg. F), or the equivalent of a wall with R 5 insulation, which is an improvement of 40 percent in R value and 13 in overall heat flow reduction when compared to the standard insulating glass window.

Another reason to strive for lower U-factors in windows is the radiant transfer toward the cold (or relatively colder) surface of the glass. The colder the surface, the more heat transfer, by radiation, from the occupants of the building to the glass. This makes the occupants feel cold. But, since even with the highest performing windows, the heat flow reduction (80 percent) is significantly lower than the solid wall (96 percent), the compensating strategy is to place a heat-producing source below the glass surface and let the convective heat flow warm the glass surface sufficiently to offset its cooling effect on the occupants, and to prevent condensation of indoor water vapor on the surface of the glass. [Relative humidities up to 40% can be maintained without excessive window condensation on double-glazed windows down to 0° F (-18° C), and on triple-glazed windows down to -22° F (-30° C).][1]

Conclusion

Adding insulation – increasing R-value – has long been the low-hanging fruit for improving energy performance of the building envelope. However, because increasing insulation thickness suffers diminishing returns of performance at higher values, there is a point at which the economic choice is to redirect resources toward other systems where greater gains can be realized. Windows are the obvious next choice, because there is so much improvement to be attained, though at a significantly higher incremental cost than was the case for added insulation. Still, at a point where doubling the amount (and cost) of insulation and building envelope to enclose it, to achieve only a 2 percent improvement in heat flow reduction, the cost of choosing premium-grade, triple-glazed windows for a 13 percent improvement becomes more feasible.

The next most important factor in optimizing the energy-efficiency of the building envelope is airtightness, which is the subject of another white paper.

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[1] Handegord, G.O., "Air Leakage, Ventilation, and Moisture Control in Buildings," Moisture Migration in Buildings ASTM STP 779, M. Lieff and H.R. Trechsel, Ed., American Society for Testing and Materials, 1982, pp. 223-233.