Photo 1: Equinox shell consisting of 12 in. (300 mm) thick wall and roof SIPs.

Photo 2: 12 in. (300 mm) thick walls allow for two full size doors to improve air sealing and insulation value.

Photo 3: Interior window sill detail showing wood trim extension needed for 12 in. (300 mm) wall thickness.

Walls & Roof

By **Ty Newell,** Member ASHRAE; and **Ben Newell,** Associate Member ASHRAE

In the previous column, we described the overall expected performance of Equinox House relative to current construction practices. The next few columns will pick apart the components and the bases for our design decisions. Here, we examine our choice of wall and roof insulation levels. Successive columns will examine windows (and overhangs), foundation design, and ventilation/infiltration characteristics. We will then bring things back together with performance measurements obtained from Equinox.

Something that our readers will notice as you follow our columns is that we are relying on the hard work that many of you have contributed to ASHRAE through its handbooks, technical committees and publications. We are not reinventing the wheel with Equinox, but are making use of the expertise, knowledge and tools that so many of you have contributed to our society.

It would seem that after a few millennia of building shelters there would not be much to discuss. However, arguments continue as new materials and products are developed and because we cannot agree on the ground rules for determining "optimal" insulation.

For example, what is the economic "lifetime" that should be used for such a calculation? Should it be the length of the mortgage (~20 to 30 years), the expected lifetime of the house (100 years), or the time you expect to live in the house (five years)? And what interest rate, escalation rate, inflation rate, opportunity cost, and other economic parameters should be assumed?

Equinox House is built with SIPs (structural insulated panels), and our cost analysis is based on that. The same analyses can be applied to other insulation systems. Our discussion is related to energy performance rather than the important practical aspects of how walls and roofs should be constructed for durability. For this information, we refer readers to Joseph W. Lstiburek's excellent ASHRAE Journal column, such as his recent Building Sciences column discussing the differences between walls and roofs. We extensively used Lstiburek's Builder's Guides book series for educating ourselves and our contractors on construction techniques for SIPs in cold climates.

This is the third in a series of columns. Find previous columns at www.ashrae.org/ashraejournal.

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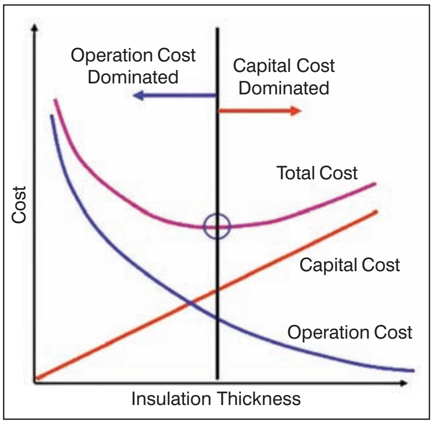

Figure 1: Capital cost (insulation) and operation cost (energy) trends for optimization of insulation thickness.

The view we used to determine the optimal thickness of the walls and roof is the expected lifetime of the house, which we have assumed to be 100 years. We assume no time value of money with no interest, escalation or inflation factors. By using simple costs, one can always probe the sensitivity of the designs to variations of these factors.

We need two basic items to determine the optimal wall and roof thickness: 1) the cost related to the insulation thickness for a wall or roof and 2) the cost of energy. *Figure 1* shows how these two costs combine over the assumed lifetime. Because the cost of more insulation reduces the lifetime energy cost, a minimum total lifetime cost occurs. As expected, operational costs dominate with "thin" insulation and capital costs with "thick" insulation.

For the case of SIPs, we treat the walls and roof as being similar in cost while adding a cautionary note that this is generally not the case for other construction methods. We also treat the walls and roof as being independent of the rest of the house energy factors. Although, one needs to be careful in doing this as energy generation sources in the house (people, appliances, lights, etc.) and solar gains from windows may be sufficiently large in super-efficient homes that they must be linked to the energy impact on the walls. We are simplifying this analysis by assuming this independence. Note that our full economic optimization of the structure has taken these energy dependencies into account with similar results for the wall and roof thickness.

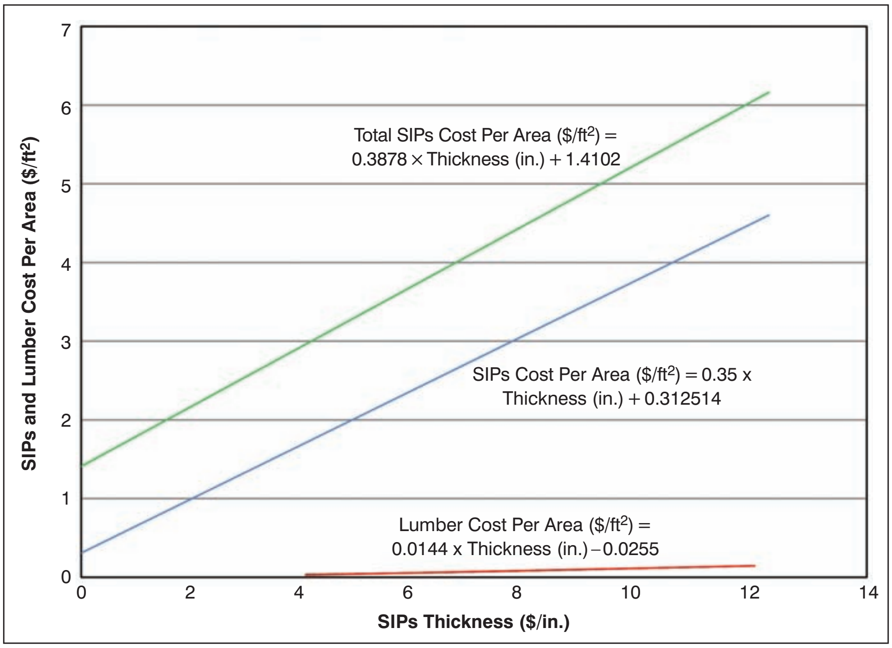

Figure 2: Cost of structural insulated panels (SIPs) as a function of thickness.

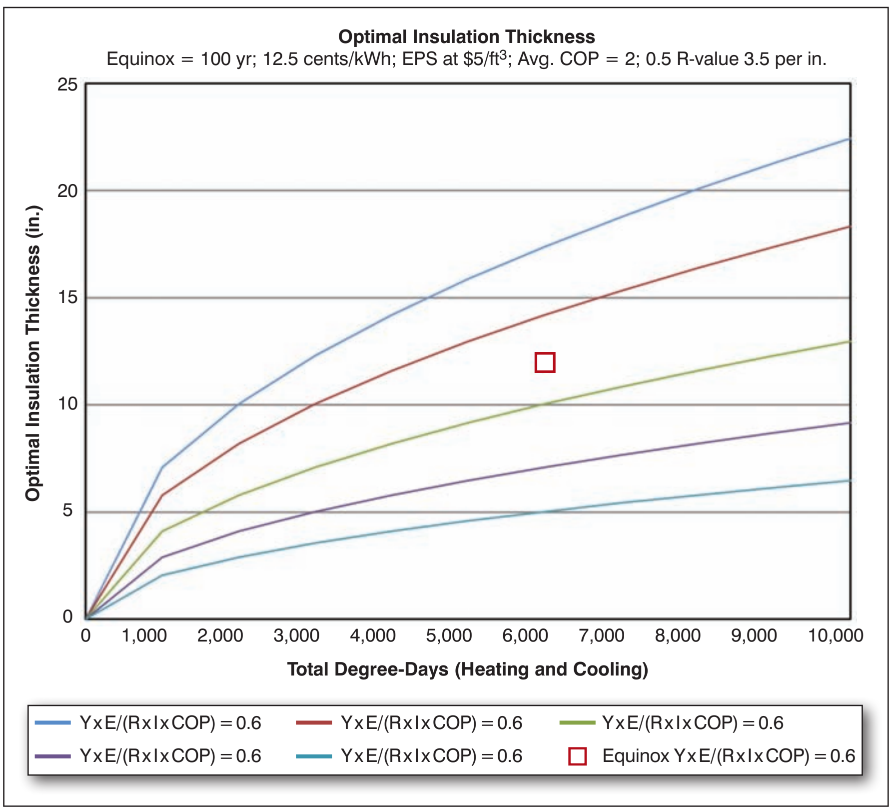

Figure 3: Optimal insulation thickness versus total degree-days and a cost parameter based on assumed lifetime, energy cost, insulation value, insulation cost and comfort conditioning system efficiency.

Figure 2 shows the cost of SIPs from quotes we received for Equinox. Three lines are shown based on a breakdown of the quote items. The SIPs cost per panel area (blue line) is the basic cost relative to the SIP panel thickness. Equinox SIPs are made with expanded polystyrene foam (EPS) that is sandwiched between two

OSB (oriented strand boards) that are each 7/16 in. (11 mm) thick. The green line shows the total SIPs cost that includes sealants, adhesives, fasteners, design services, taxes, shipping, etc. The slope of the panel cost lines is the primary factor of interest, as it provides the cost per insulation value information. The intercept values represent fixed costs (such as design services, cost of OSB panels, etc.) that do not vary with panel thickness. These fixed costs do not impact the optimal choice of an insulation system. Finally, the red line indicates the cost of additional lumber needed for SIP installation, but is a very small percentage of cost.

Overall, this information indicates that the EPS insulation in this SIPs panel system costs \$0.35 to \$0.39 per inch thickness per square foot panel area. The labor to install the panels is assumed to be a fixed cost that is relatively independent of thickness and comes to roughly \$2/ft^2 to \$3/ft^2 (\$22/m^2 to \$32/m^2).

For the energy cost, our installed cost for solar PV was \$4.45/W, or \$3.12/W after applying the 30% federal tax credit. We spent \$29,000 for the 8,200 W array's solar panels, inverters, wire, and panel supports; \$2,500 for ground-mount support steel and aluminum; \$1,000 for trenching, post holes and concrete in post holes; and \$4,000 for labor at \$30 per hour for a total of \$36,500. With the U.S. federal tax credit of 30%, the system cost is \$25,500.

The solar panels are warranted for 20 years (the inverters for 10 years). So, on the same simple basis as we've been using, if the panels provide 10,000 kWh per year for 20 years of maintenance-free operation (Yes, we know. That's not a good assumption, but all the numbers are here, so you can add your own maintenance and replacement factors.), with an installed cost of \$25,500, we have an energy cost of \$0.128 per kWh. At the end of 20 years, as the infrastructure for recycling solar panels and inverters matures, and the technology and manufacturing advances continue, your next system may cost even less in today's dollars.

With the insulation and energy cost information, we can move on to the optimization calculations. Minimization of the life-cycle cost for the wall or roof thickness results in the following relation:

$$\text{Optimal Wall or Roof Thickness (inches)} = \text{square root } [(DDh + DDc) \times Years \times E\$/(11.9 \times R \times COP \times I\$)]$$

where

- DDh = Annual heating degree-days (F-day)
- DDc = Annual cooling degree-days (F-day)
- Years = House lifetime (100 years from our viewpoint)
- E\$ = Energy cost per kWh (solar electricity ~\$0.125 to \$0.15 per kWh)
- R = Thermal resistance value per inch thickness (e.g., R=3.5 per inch for EPS)
- COP = Ratio of comfort conditioning energy required to electrical energy for maintaining comfort (assume something in the 1 to 5 range, equivalent to SEER and HPSF range of 3.4 to 20)
- I\$ = Insulation cost per volume (\$4/ft^3 to \$5/ft^3 [\$141/m^3 to \$177/m^3] for EPS SIPs from *Figure 2*)
- 11.9 = A number for all the unit conversions

In central Illinois, we have approximately 5,000 F-days for heating and about 1,000 F-days for cooling. This is a pretty mushy number because super-insulating the house shifts the "no load" reference temperature built into the simple degree-day parameter.

Figure 3 shows the trends in optimal insulation thickness based on the dimensional parameter ratio from the above relation versus total degree-days. The optimal insulation thickness for Equinox house is in the range of 11 in. to 13 in. (275 mm to 325 mm). The parameter ratio used for *Figure 3* shows the significance of each of the factors in the optimal thickness relation. When varying parameters, an increase in the parameter ratio results in an increase in the optimal thickness.

The sensitivity to the choice of insulation thickness is shown in *Figure 4* in which the total cost of wall insulation and lifetime energy (100 years of energy based on a solar system with a 20-year lifetime) is plotted versus the wall thickness. Equinox has a wall and roof surface area of 4,400 ft^2 (410 m^2), which coupled with the parameters assumed for the optimal wall and roof thickness results in the lifetime cost shown in *Figure 4*. For Equinox, the lifetime cost of the wall and roof and the energy to keep the space conditioned due to the wall and roof is \$42,000.

Figure 4 also shows that the minimum cost solution for walls and roof is not very sensitive to insulation thickness. That is,

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if one chooses a wall that is 10 in. (250 mm), rather than 12 in. thick (300 mm), the overall lifetime cost is essentially the same because the cost of the solar system increases to make up for the increased energy load.

In summary, we have chosen a SIPs thickness of 12 in. (300 mm) based on the analyses discussed previously. Other construction and insulation systems must use a cost analysis characteristic of the variable costs required to reach different levels of thermal resistance. In the next column, we'll discuss our choice of windows and the importance of overhangs relative to window orientation and window performance characteristics.

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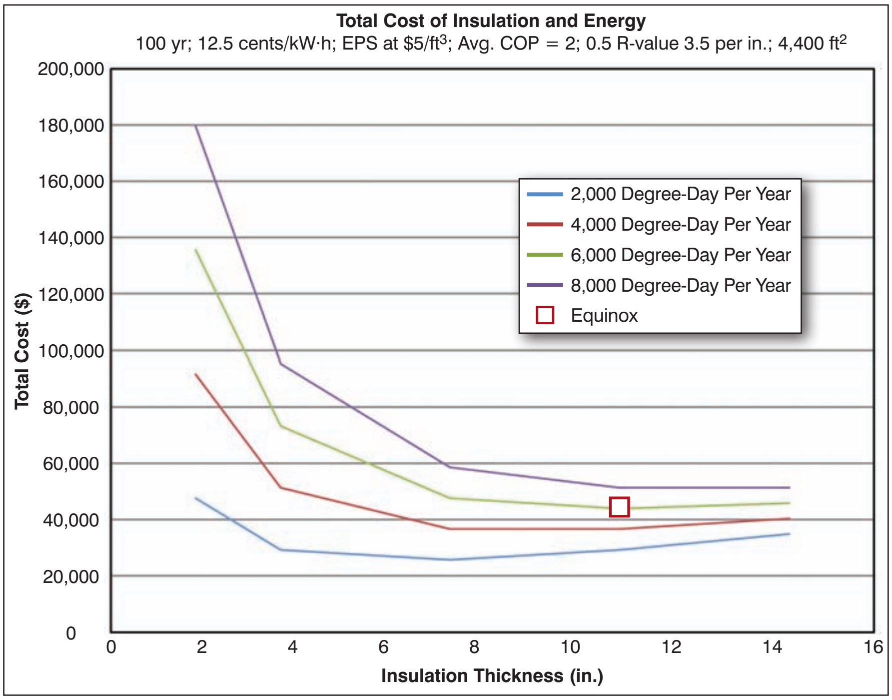

Figure 4: Total lifetime costs versus insulation thickness with different curves representing total climatic degree-days.