GREEN BUILDINGS: A SYSTEMIC APPROACH TO SUSTAINABLE PRODUCTS AND SYSTEMS INTEGRATION

Louise F. Goldberg, Ph.D. (Eng)[1]

INTRODUCTION

This article is not intended as a definitive discourse on the subject of green building design, but rather as an overview of the author's preferences and design practice.

A common error in green building design is the selection of individual envelope components or pieces of equipment based on their comparative isolated energy performance (both embodied and operational). Such an approach can yield a nominally sustainable building based on the prescriptive rules established for a given standard (such as the LEED rating system), but, in practice, very often this methodology does not yield the expected energy savings. The reasons for this are best understood in terms of an example such as the one shown in Figure 1 (Goldberg and Huelman, 2005).

Figure 1 depicts the overall relative heating season space conditioning energy demand for a standard residential building (the typical Minnesota basis energy performance house, Goldberg and Huelman, 2005). Noting that the abscissae are on the y-axes and the ordinate is on the x-axis, the graph essentially shows the relationship between increased building envelope material thermal performance (in this case, using foundation insulation as a proxy), indirect material selection consequences (infiltration), and plant and equipment choices (energy recovery ventilation (ERV) compared with exhaust only ventilation (EOV)). The following systemic observations are relevant:

a. Doubling the thermal resistance for approximately 40% of the building envelope surface area from R_{US}-5 to R_{US}-10 reduces the overall building space heating energy demand by less than 5%.
b. The 2002 industry average for a well sealed residential building of 0.31 cfm/ft^2 at 50 Pa accounts for about 95% and 79% of the heating energy demand with ERV and EOV respectively.
c. ERV can reduce the energy demand by as much as 45% compared with EOV regardless of envelope thermal resistance (assuming that infiltration is independent of thermal resistance that usually is not the case).

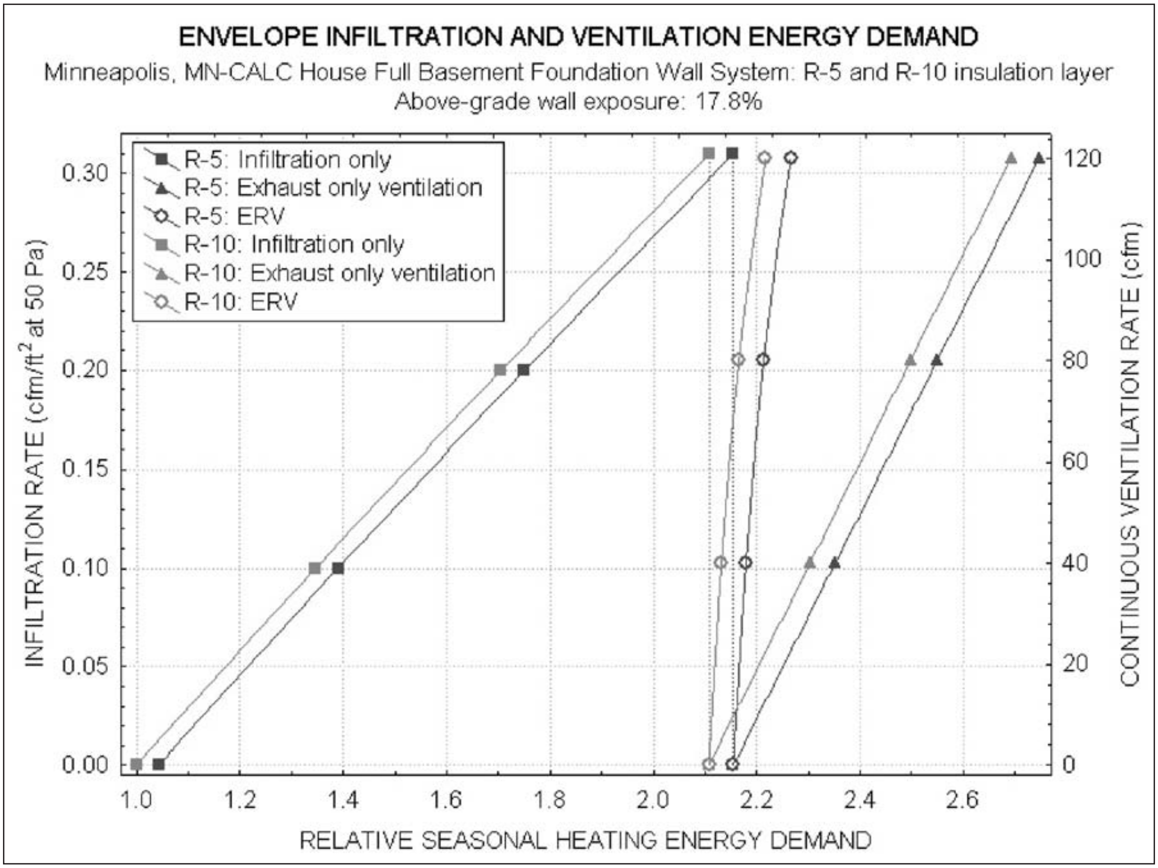
Another confusing but important issue in systemic sustainable design practice is the relationship between building envelope thermal resistance and building equipment energy efficiency, often referred to as an energy "trade-off," as this bears directly on the sustainability impacts of the decision on whether to prioritize passive or active energy conservation measures. A particularly egregious example of this can be found in Section N1102.2.6 of the Minnesota "Proposed Permanent Rules Relating to Residential Energy Code" (State of Minnesota, 2008). In essence this rule contains an exception that permits the reduction of exterior or integral foundation wall insulation from R_{US}-10 to R_{US}-5 in the southern half of Minnesota provided that the minimum attic thermal resistance is increased by R_{US}-5 and the minimum heating plant efficiency is 85% for a boiler and 90% for a furnace.

In the first place, it may be observed that energy conservation as exemplified by increased envelope thermal resistance that avoids the consumption of energy is not equivalent in sustainability terms to energy efficiency that still requires the consumption of energy, only less. Secondly, the energy balance is incorrect. The furnace efficiency requirement is practically ineffective as most installed boilers and furnaces in new residential construction at least meet and usually exceed the stipulated efficiencies (so rendering that aspect of the trade-off exception

---

[1] Principal, Lofrango Engineering, Senior Research Associate and Director, Building Physics and Foundations Research Programs, University of Minnesota, louisegoldberg@peoplepc.com.

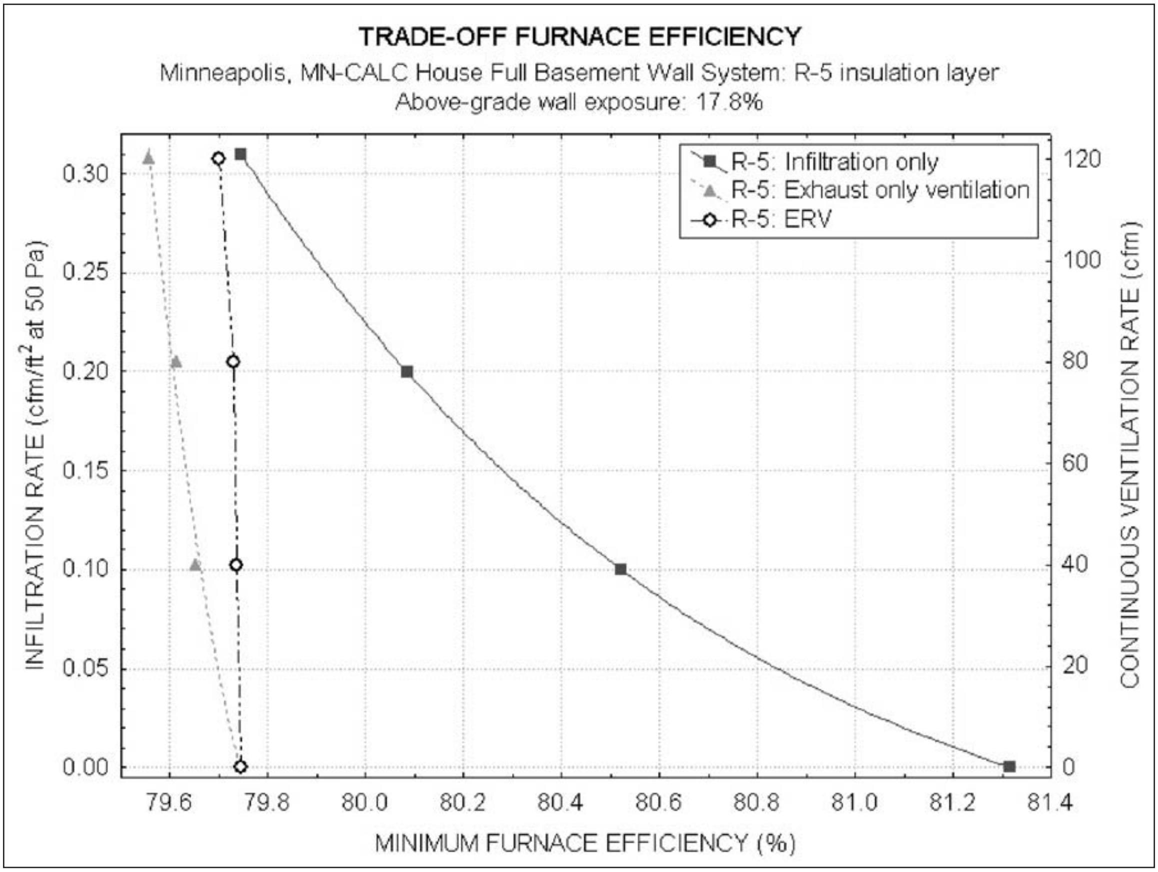
FIGURE 1. Systemic relationship between envelope and equipment energy conservation measures.



moot), and the energy savings from increasing the minimum attic thermal insulation from R_{US}-38 (Table N1102.1 of the proposed Rule) to R_{US}-43 are much less than those from increasing the foundation wall thermal resistance from R_{US}-5 to R_{US}-10.

Another view of the trade-off dilemma is shown in Figure 2 (Goldberg and Huelman, 2005). The abscissae on the y-axes are the same as in Figure 1 while the ordinate on the x-axis in this case is the minimum furnace efficiency relative to a baseline efficiency of 78%. Figure 2 depicts the required furnace efficiency to offset an R_{US}-5 decrease in foundation insulation thermal resistance and shows that as the energy demand increases with infiltration and ventilation (so decreasing the fraction of energy savings realized from an R_{US}-5 insulation increase), the required compensating increase in furnace efficiency diminishes. Increasing the infiltration from zero to 0.31 cfm/ft^2 decreases the required minimum furnace efficiency from 81.3% (3.3% over baseline) to 79.75% (1.75% over baseline). With ERV, the range diminishes to 79.75–79.55%, while with EOV the range is a negligible 79.75–79.72%. Thus, in the presence of real levels of infiltration and ventilation, the required furnace efficiency trade-off to compensate for an R_{US}-5 foundation insulation thermal resistance increase is minimal in absolute terms (less than 2%). To put it another way, plant efficiency improvements can always trump envelope conservation improvements in terms of property line metered energy usage until 100% plant efficiency is achieved. This is not a

FIGURE 2. The trade-off dilemma.



sustainable practice as it would never produce an energy demand decrease as the net volume of conditioned space increases with new construction, unless all installed plant operates at 100% efficiency, which is unlikely in the foreseeable future. This reinforces the non-equivalency argument between conservation and efficiency, that is, sound sustainability design requires conservation and efficiency, not conservation or efficiency.

Hence, conservation should be maximized first within the prescribed economic constraints (since it avoids energy expenditure) while efficiency should be independently maximized as a secondary but essential activity, until in the limit (such as in "Passive Design"), a dedicated space heating plant can be eliminated altogether.

A SYSTEMIC SUSTAINABLE DESIGN STRATEGY

These data provide guidance on a viable systemic strategy for selecting building equipment and envelope components that can achieve consistently high levels of sustainability in green building design. Such a strategy may be prioritized as follows:

a. Minimize infiltration.[2] The ideal case is a hermetically sealed envelope in which all ambient air exchange is controlled. Note that this does not predicate mechanical ventilation; natural

---

[2] Note that by definition, infiltration refers to uncontrolled air exchange with the ambient surroundings while ventilation refers to controlled air exchange.

ventilation strategies such as opening windows are perfectly admissible.

b. Provide ventilation using energy or heat recovery strategies and avoid direct venting of interior conditioned air (such as with EOV). Again, passive heat recovery strategies can be used.
c. Dynamically minimize ventilation to meet given standards of indoor air quality in terms of humidity, CO, CO_2, and volatile organic compounds (VOCs).
d. Maximize envelope thermal resistance.
e. Maximize heating, ventilation, and air conditioning plant efficiency.

Each of these topics will be discussed in terms of generic products and systems in the following sections.

INFILTRATION MINIMIZATION

There are prescriptive and performance approaches to minimizing infiltration. The prescriptive approach is commonly applied in building codes. For example, consider section N1102.4 of the 2006 IRC that opens with the exhortation that "The building thermal envelope shall be durably sealed to limit infiltration," and is followed by a laundry list of locations to be sealed terminating with a catchall "Other sources of infiltration." In practice, this offers no real guidance and no guarantee that the resulting infiltration will be adequately low.

A performance approach, on the other hand, is based on empirical measurements of the infiltration (for example, DePani and Fazio, 2005). After the envelope has been nominally closed, a blower door apparatus and associated pressure transducer network is installed and the infiltration leaks tracked down and sealed using visualization techniques such as infrared thermography and smoke tracing until the measured leakage rate reaches the design target. This can produce very low infiltration rates, for example, ~0.1 to 0.15 cfm/ft^2 in an affordable housing development in St. Paul, MN (Carmody, et al., 2007).

There are basically just two methodologies for achieving durable building sealing, mechanical and adhesive. In the mechanical approach, sealing materials such as rubber gaskets are mechanically compressed between two surfaces to create an air-tight joint. This approach is usually found in doors and windows but can in fact be used elsewhere such as in the installation of deck ledger boards and within framing systems such as between the bottom plate and the underlying platform. Generally, mechanical sealing can produce reliable and durable seals with a lower tendency for environmental degradation over time.

Adhesive seals generally fall into two classes, elastomeric and rigid. Elastomeric seals such as modified bitumen coated polyethylene membranes can be very effective in sealing cracks and joints, particularly around rough openings. However, not all products of this type in the marketplace have the same adhesive qualities and some tend to lose adhesiveness over time. A good practical test of adhesion is to perform a pull-off test from extruded polystyrene insulation. An adequately adhesive product will shear the insulation even after years of service.

Currently caulk is used ubiquitously as a seal at every conceivable location. Both elastomeric and rigid caulks are on the market and both have their applications. In certain conditions, such as between materials that are mechanically fastened, caulk can be effective in the long term. However, in exposed locations, weathering can cause the caulk to lose its adhesion and elasticity and fail over time. All caulks are not created equal and even those rated for exterior usage (such as those that are polyurethane based) can (and in the author's experience, do) fail over time. In general, caulks that cure to a rigid structure should not be used in exposed locations since the resultant thermal cycling will eventually cause these caulks to crack and lose their sealing properties.

Hence, the preferred sealing strategy is to use mechanical sealing first, then elastomeric membranes, and finally, as a last resort, exposed caulking.

DYNAMICALLY CONTROLLED HEAT AND ENERGY RECOVERY VENTILATION

The obvious application of this approach is the installation of a commercial heat or energy recovery ventilator (HRV/ERV) of adequate flow capacity in compliance with building code requirements. However, since such devices can consume a fair amount of grid electrical energy when operating continuously, to make them truly sustainable requires that they be powered from a renewable source such as a photovoltaic array. Another way of minimizing the energy cost is to control the ventilation rate dynamically such that it is determined by monitored levels of humidity, CO, CO_2, and VOCs. In this case, ventilation is only applied as required and then at the minimum flow rate necessary to maintain desired indoor air quality levels. Such an arrangement requires an ERV/HRV with variable speed blowers that likely would have to be custom manufactured as most commercial units feature at most dual speed blowers.

However, purely passive heat recovery ventilation is possible as well. An example of this is an earth cooling tube (Veach and Goldberg, 1986) in which warm exterior air is drawn through a long, below-grade duct where it is cooled and partially dehumidified. The system is driven by buoyant flow via a stack with the exhaust above the building roof. Higher flows can be achieved by using turbine ventilators and the like. A modification of this system with a concentric pair of earth cooling tubes can enable winter intake air preheating as well, although in this case, the exhaust stack would have to be at the cooling tube inlet remote from the building. When using earth cooling tubes, however, care must be taken in the design to properly manage condensate generation to avoid mold growth in the tube.

One of the issues in heat or energy recovery ventilation is the natural human desire to open the windows to allow the ingress of fresh air when ambient conditions are favorable. Usually, this has no adverse effect on the indoor air quality but can result in wasted energy with a statically controlled ERV/HRV. Thus, implementing the dynamic HRV/ERV control scheme alluded to above would avoid this problem since as the IAQ improves with opened window natural ventilation, the ERV/HRV automatically would be shut down.

MAXIMIZED ENVELOPE THERMAL RESISTANCE

The key to cost effectively maximize envelope thermal resistance by optimizing the insulating level of the various envelope components is to select a given level of incremental unit-cost, unit-area thermal conduction reduction and apply that uniformly to each component in turn. In other words, suppose the desired value of this parameter is $\$x/W.ft^2$. Then the level of insulation for a particular component could be increased until the cost of incremental thermal resistance (R-value) exceeds the target of $\$x/W.ft^2$. An example of this for full basement foundation insulation in a very cold U.S. climate (International Falls, MN) is shown in Figure 3 (Goldberg and Huelman, 2005).

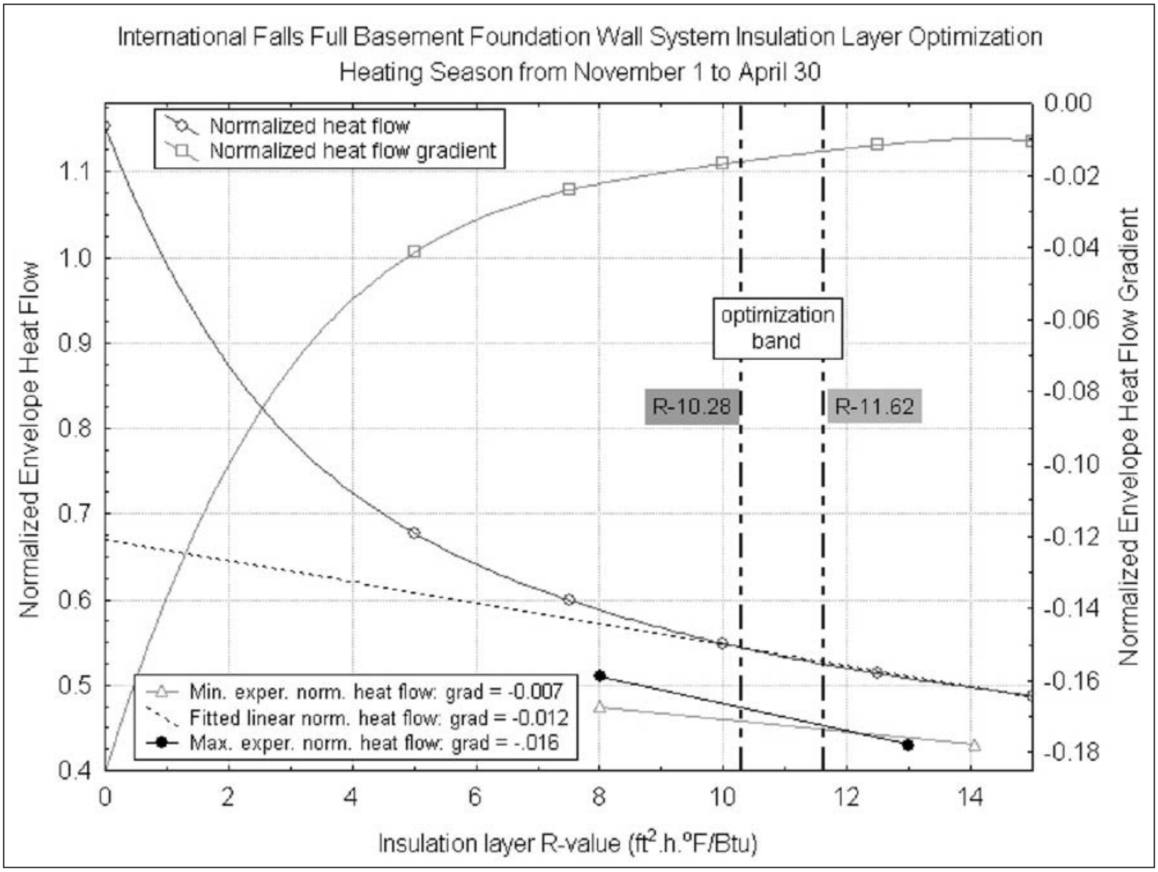
In this case, as the R-value is increased, the conduction heat loss decreases inverse exponentially eventually approaching a zero gradient asymptote at very large R-values. So as more insulation is added, the cost is increased but the resultant incremental energy savings fairly rapidly declines towards the target incremental cost. In this case, the maximum thermal resistance that would be justified would be about R_{US}-10.

Similar analyses can be applied to all components of the building envelope including windows and doors, as well as wall and ceiling/roof insulation. This incremental cost approach ensures that the insulation is optimally distributed around the envelope so that maximum benefit from the insulation is achieved. In practice, this produces the largest insulation levels in the ceiling (particularly with attics), lower insulation levels in the walls, and the least amount of insulation around the foundation.

The choice of insulation materials and envelope component system designs is governed by the hygrothermal performance of the envelope system and not on achieving a desired level of thermal resistance. In other words, arbitrarily increasing the thermal resistance without simultaneously modifying the design to achieve adequate moisture durability is a recipe for failure. In general, the larger the thermal resistance, the more strenuous the hygrothermal design requirements so that vapor management and bulk water control strategies that may be effective with typical or code-required minimum insulation levels can produce severe service failures when insulation levels are increased. This can be particularly problematic for interior foundation insulation, particularly in wet or moist soil conditions (Goldberg, 2007).

Insulating materials that have intrinsic vapor retarding properties are generally less prone to hygrothermal failures as the R-value is increased than vapor open insulating materials. Examples are extruded and expanded polystyrene foam insulation (permeance of 1.1 and 3.5 perms/in. respectively for 15psi compressive resistance board per ASTM C578)

FIGURE 3. Foundation wall optimization.



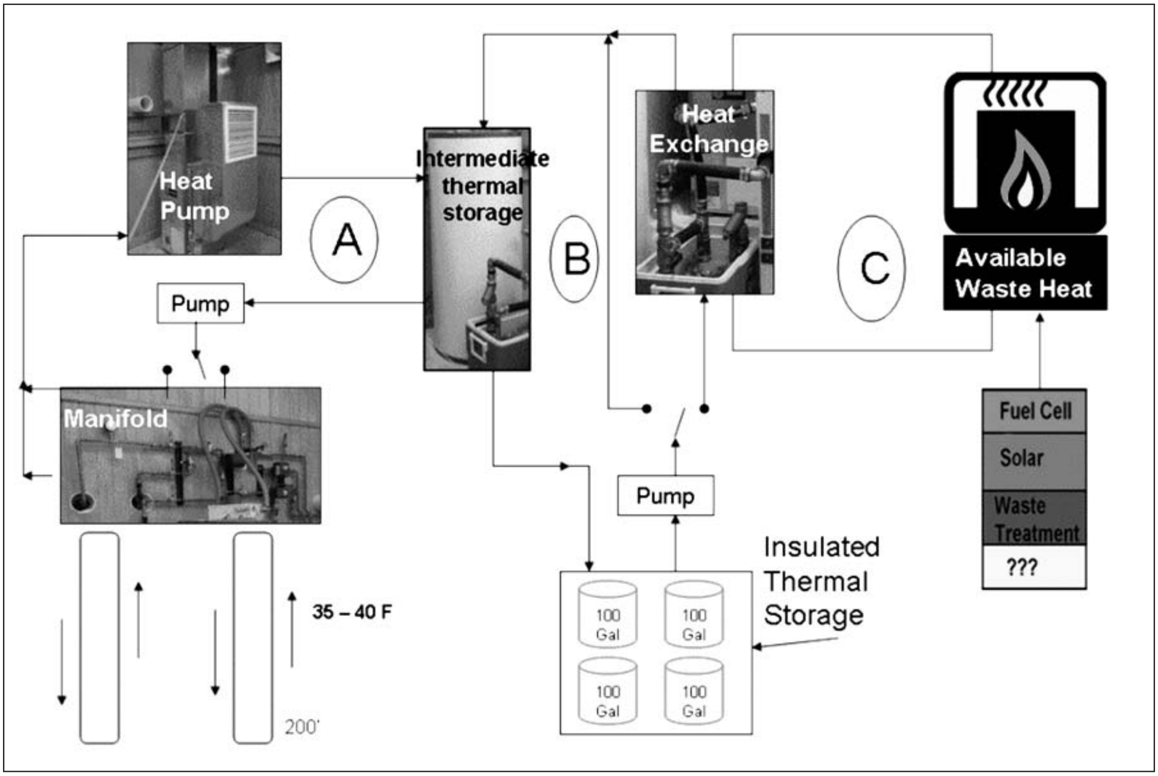
and closed-cell spray polyurethane foam (permeance of ~3 perms/in. for ~2 lb/ft^3 density). However, caution must be exercised with these materials since their surfaces can act as condensation planes and the maximum thickness (and hence thermal resistance) can be constrained by flame spread and smoke development ratings (per ASTM E84).

MAXIMIZE HEATING, VENTILATION, AND COOLING PLANT EFFICIENCY

There are numerous conventional ways of improving heating, ventilation, and cooling (HVAC) plant efficiency. However, recent research (Ottesen, et al., 2008) has shown the particular performance advantages of liquid coupled heat pumps in providing efficient heating, air conditioning, and dehumidification and hence this class of hybrid plant is the author's preference for use in sustainable buildings. The essential concept demonstrated in the research as encapsulated in a U.S. patent (Licari, et al., 2008) is the combination of a geothermal source/sink with waste heat generated by any number of sources within the building (exhaust air, gray water, solar thermal, combined heat, and power generation, etc.). A simplified schematic of the Hybrid Energy System Study (HESS) Phase II research plant embodying these concepts is shown in Figure 4.

Loop A includes the liquid coupled heat pump, an intermediate thermal storage vessel, circulation pump and two 200 ft vertical geothermal source/sink wells. The flow to the heat pump can be continuously varied by a proportioning valve enabling thermal energy to be routed from either the intermediate storage, or the wells, or a combination of the

FIGURE 4. Hybrid Energy System Study Phase II research plant.

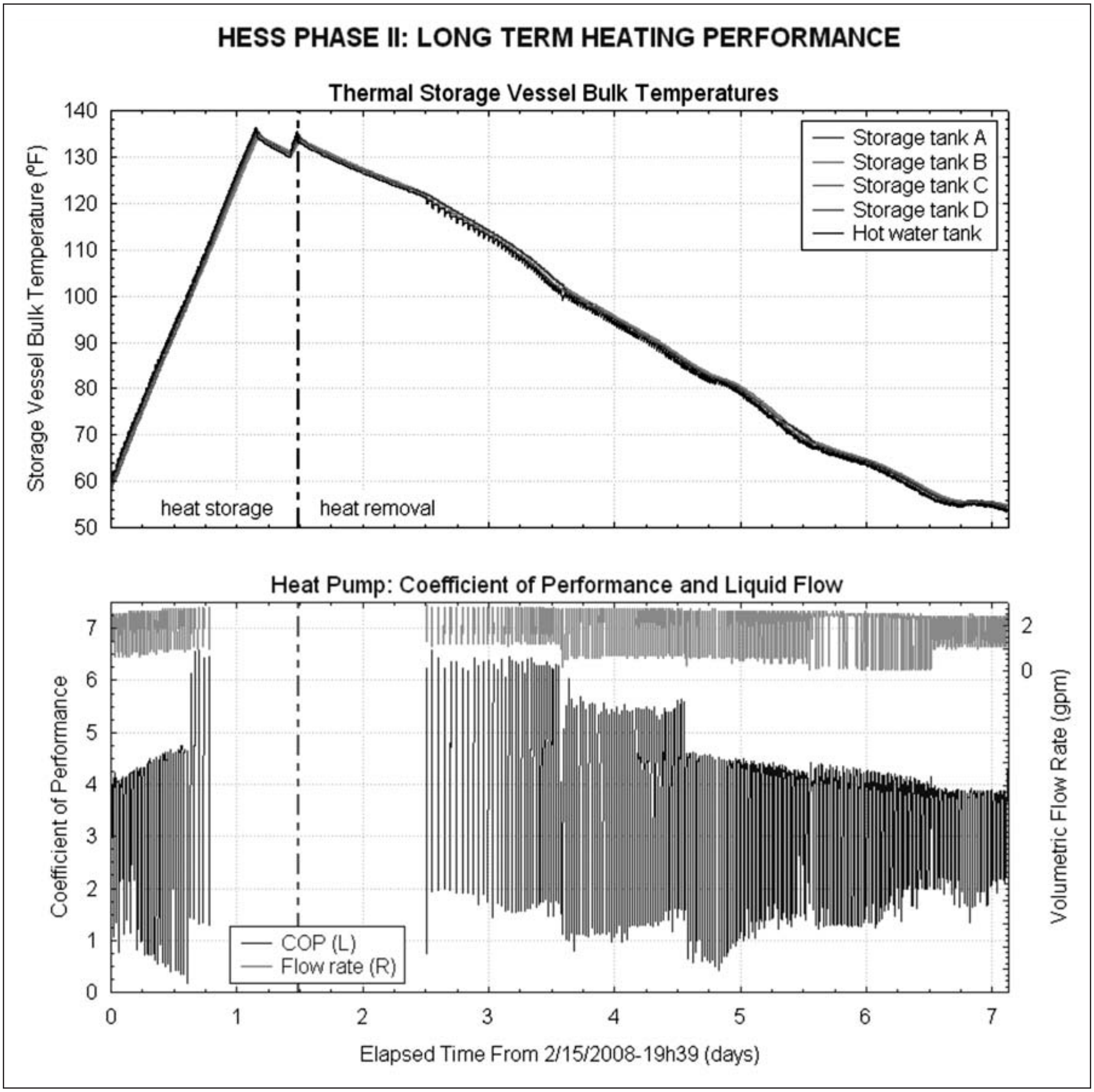


two. Loop B couples the intermediate thermal storage to a 400 gallon bulk thermal storage system and a heat exchanger. Loop C in turn couples the heat exchanger to the source(s) of waste heat.

In heating mode, the long-term experimental performance of this system is shown in Figure 5. From day 0 through day 1.5, heat was recovered from a waste heat emulator and stored in the thermal storage. After a 1-day quiescent period, space heating commenced at day 2.5 and continued through day 7. During this period, the ambient temperature ranged from –18 to 25°F with a mean temperature of about 5°F while the conditioned space setpoint temperature was 68°F. Over the heat withdrawal period, flow was circulated through the liquid side of the heat pump heat exchanger at 2.4 gpm with a starting inlet temperature of 110°F at day 2.5 decreasing to 50°F at the end of the test. Under these conditions, Figure 5 reveals that from day 2.5 through day 3.5 when the heat pump inlet temperatures were largest, the heat pump achieved a maximum transient coefficient of performance in excess of 6, declining to a maximum of about 3.9 as the stored heat temperature declined. Note that the data reveals the actual transient performance of the heat pump when heating a space enclosed within an envelope that significantly exceeds commercial building energy code requirements. This is quite different from the rated steady-state performance quoted by most manufacturers, since in real transient or cycling mode operation the heat pump never reaches a steady-state. The empirical transient performance may be compared with the manufacturer's steady-state rated COP of 3.5 at 2.7 gpm with a liquid inlet temperature of 45°F typical of a vertical geothermal well under steady-state conditions (Trane, 2005).

Thus these data demonstrate the level of plant efficiency that is possible when incorporating waste heat recovery with liquid sourced heat pumps in sustainable buildings.

FIGURE 5. Long-term heating performance.



SUMMARY

A procedure is presented for selecting products and systems for incorporation into sustainable buildings that is based on a systemic approach to reducing the overall energy footprint prioritized by the magnitude of the energy savings achievable from each part of the system. The conservation and efficiency aspects of the design are treated in a complementary fashion so that efficiency increases are never used to offset conservation improvements. This approach enables the sustainability of any design to be maximized within the specified cost constraints.

REFERENCES

Carmody J., A. Forsyth, M. Guzowski, P. Huelman, and L. LaVine. 2007. "The Affordable Housing Initiative", www.ahi.umn.edu.

DePani, S. and P. Fazio. 2005. "Air tightness testing of two- and three-unit buildings with a single fan." *Journal of Architectural Engineering,* vol. 11, no. 1, pp. 19–24.

Goldberg, L. F. 2007. "Building Systems Research Case Study: Building Foundations." *Architectural Graphic Standards, 11th ed.,* Wiley, pp. 962–964.

Goldberg, L. F. and P. H. Huelman. 2005. "Minnesota Energy Code Building Foundation Rule: Amendment Proposal Development Project Final Report." *BPFRP research report,* www.buildingfoundation.umn.edu. University of Minnesota.

International Code Council. 2006. "International Residential Code for One- and Two-Family Dwellings."

Licari, J. P., H. H. Ottesen, and J. Walters. 2008. "Hybrid Geothermal and Fuel-Cell System." United States Patent no. US 7,334,406.

MN Dept. of Labor and Industry. 2008. "Proposed Permanent Rules Relating to Residential Energy Code." Rule 1322, 7/1/2008 (revisor).

Ottesen, H. H., L. F. Goldberg, and J. P. Licari. 2008. "Hybrid Energy Systems Study Phase II: Final Report" (in preparation). University of Minnesota, Rochester.

Trane. 2005. "High Efficiency Horizontal and Vertical Water-Source Comfort System," document no. WSHP-PRC001-EN.

Veach, K. C. and L. F. Goldberg. 1986. "A Simplified Experimental Evaluation of an Earth Coupled Heating Tube in Minnesota." *Proceedings of the Second International Earth Sheltered Buildings Conference.* Minneapolis, MN, July 1986.