The Last Big Leak: Exposed Slab Edges

Marc Hoeschele and David Springer, Davis Energy Group
Jeff Thornton, Thermal Energy Simulation Specialists

ABSTRACT

Improvements to wall systems, window systems, and insulation installation standards have been encouraged by state building standards, ENERGY STAR®, and other programs over the past decade, resulting in significant strides in new home building performance. These improvements in above grade envelope performance have resulted in slab edge perimeter losses becoming an increasingly larger fraction of heating energy usage in slab on grade homes. Recognizing the need for better solutions for slab edge perimeter insulation, the DOE's National Energy Technology Laboratory funded Davis Energy Group to develop, demonstrate, and evaluate the performance of a slab edge insulating system for new homes and buildings. This paper focuses on two tasks of the 2005-2009 NETL development project: modeling of thermal performance in various climates and monitoring of energy impacts in a prototype mockup.

Modeling evaluations were completed using the advanced TRNSYS simulation coupled with a 3-dimensional ground model. Projected TRNSYS savings for R-10 edge insulation averaged ~ 60 therms/year for a single-story 2,000 ft^2 home modeled in five U.S. climates. Monitoring of the R-10 prototype mockup indicated slab edge loss reductions of close to 90% in the Sacramento climate. Monitored heat loss reduction for the uninsulated (R-0) prototype in radiant floor heating mode suggests ~50% higher edge heat flux relative to forced air mode operation.

Increasing pressure to improve building energy efficiency will drive the building industry to pursue underutilized strategies such as slab edge insulation systems. Increasing market pull will help reduce production costs and improve cost-effectiveness relative to competing measures.

Introduction

Concrete slabs represent the primary foundation type in residential buildings in the fast-growing markets throughout the southern and southwestern United States with ~75% of U.S. population growth was occurring prior to the recent housing downturn. Virtually all of these homes have uninsulated slab perimeters resulting in a steady flow of heat from indoors to out during much of the heating season due to the relatively low thermal resistance of concrete. In addition to the conventional footed slab, recent construction industry shifts have indicated a trend towards monolithic post-tensioned slabs. The post-tensioning process involves installation of steel tendons at slab mid-height prior to the pour, with cable tensioning occurring after the pour. These monolithic slabs are typically thicker (8-12" is common) than standard footed slab.

According to DOE's Building Energy Databook[1], it is estimated that foundations represent 15% of residential heating loads and new home foundations add 0.016 quads annually to U.S. national energy consumption. We project that roughly ¼ of the slab on grade foundation loss is through the slab edge. Unlike other building envelope components that have experienced efficiency improvements over the years, slab edge heat loss has largely been ignored. Builders

[1] http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=2.1.14

rarely install slab edge insulation on new homes due to added cost, installation difficulties, construction slowdown, appearance concerns, and termite issues. A cost-effective, installer-friendly system could have huge market appeal. Also states such as California feature an additional driving force within the statewide (Title 24) residential energy code which offers credits for perimeter slab insulation.

Product Description and Development Project Overview

A slab edge form concept, developed with funding from the U.S. Department of Energy's National Energy Technology Laboratory (NETL), was designed to replace conventional wood form boards with a twelve foot long PVC profile extrusion filled with termiticide treated extruded polystyrene rigid insulation. The lightweight product includes linear couplers, and interior and exterior corners, to facilitate the installation process and provide a professional looking installed product. The NETL final report (Hoeschele & Lee, 2009) documents the development work with the basic system design shown in Figures 1 and 2.

Figure 1. Schematic of Insulating Form Board

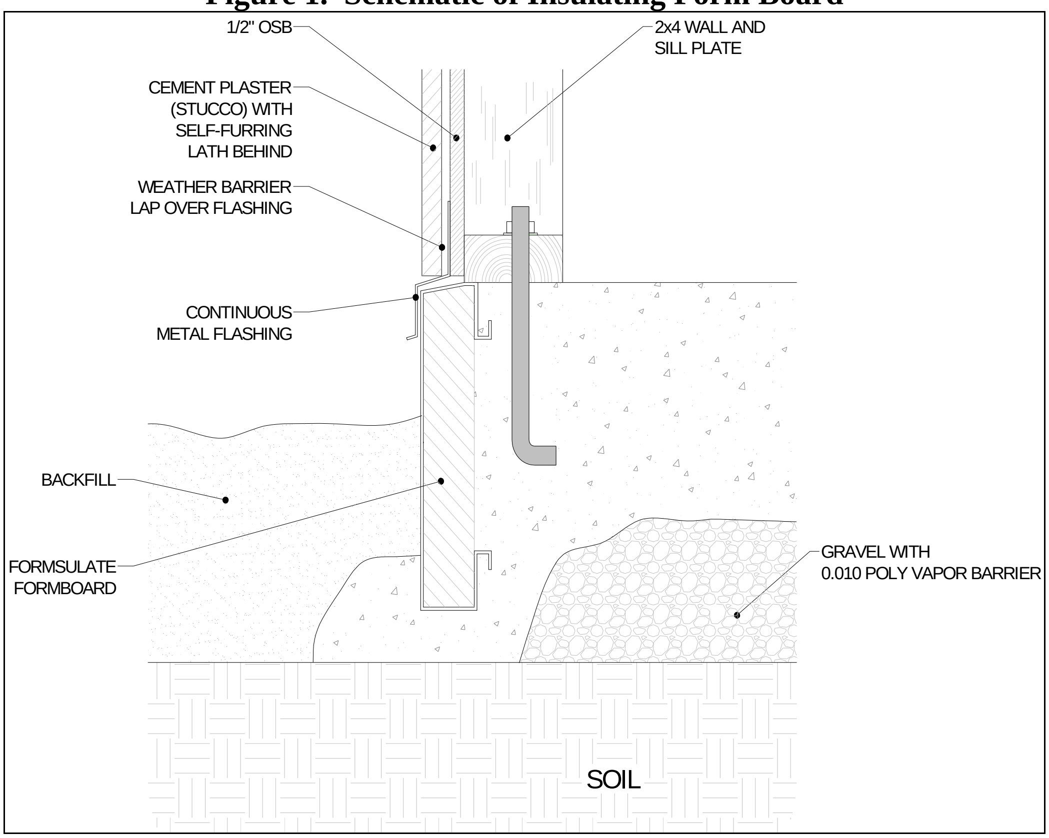


Figure 1. System Components – Short 1' Form Board Section, Exterior Corner, and Linear Coupler

The product was installed in several custom home projects during the NETL development project. Figure 3 shows a Northern California installation where the 12' insulated form board was mitered to a 45 degree angle to allow installation in a more complicated application. Concrete subcontractor feedback to the system was positive with ease of installation and handling most highly regarded.

Figure 3. Insulated Form Board Field Installation

Slab Heat Loss Modeling

One of the more complicated aspects of building energy simulation modeling is to accurately model heat fluxes between a house slab, the soil below, and the slab perimeter edge. These heat fluxes are a function of many factors including the following:

- Soil thermal characteristics (density, diffusivity, moisture content, homogeneity)
- Deep ground temperature (primarily a function of latitude)
- Climate
- The impact of varying soil strata and water table effects
- House geometry[2]
- Conditions surrounding the house (snow, shading, pavement, precipitation, etc.)

A 2005 review of existing building simulation models found that most simulation models provide only one-dimensional modeling of slab heat loss. One-dimensional models are limited in their ability to handle the modeling complexities and the impact of the house footprint on the undisturbed soil conditions. Communications with leading simulation expert Michael Deru (Deru, 2005) suggested four models with advanced ground heat transfer modeling capabilities. The four included SUNREL[3] (a model under development from NREL), EnergyPlus[4] (utilizes a simplification of a more sophisticated model developed at Penn State University by Bill Bahnfleth (Bahnfleth, 1989), ESP-r[5] (a Canadian model that includes a regression-based algorithm based on work completed by Beausoleil-Morrison and Mitalas, 1997), and TRNSYS[6] (a modularized model developed for simulating building and thermal systems).

We consulted with Thermal Energy Simulation Specialists, the distributors of TRNSYS, to provide us a customized TRNSED model that incorporated the 3-D TRNSYS ground model. The TRNSED module concept allows for customized and simplified data input and output, providing greater ease of use for the operator[7]. Two simplifications of the TRNSED model provided include a constraint of modeling only rectangular building footprints, and a configurational limitation whereby the specification of the footing or slab defined the height of the insulated form board, as shown in Figure 4.

For a given form board height (for our design, 11.35"), the modeling assumption of insulation depth equal to the bottom of the slab or footing would tend to overestimate the impact of perimeter insulation on footed slabs relative to monolithic slabs due to the greater effect on reducing the heat flow path through the soil for the footed slab.

[2] A house with a square footprint would have a different thermal influence on the soil beneath the house than a house with a large perimeter to area ratio.

[3] http://www.nrel.gov/buildings/sunrel/publications.html

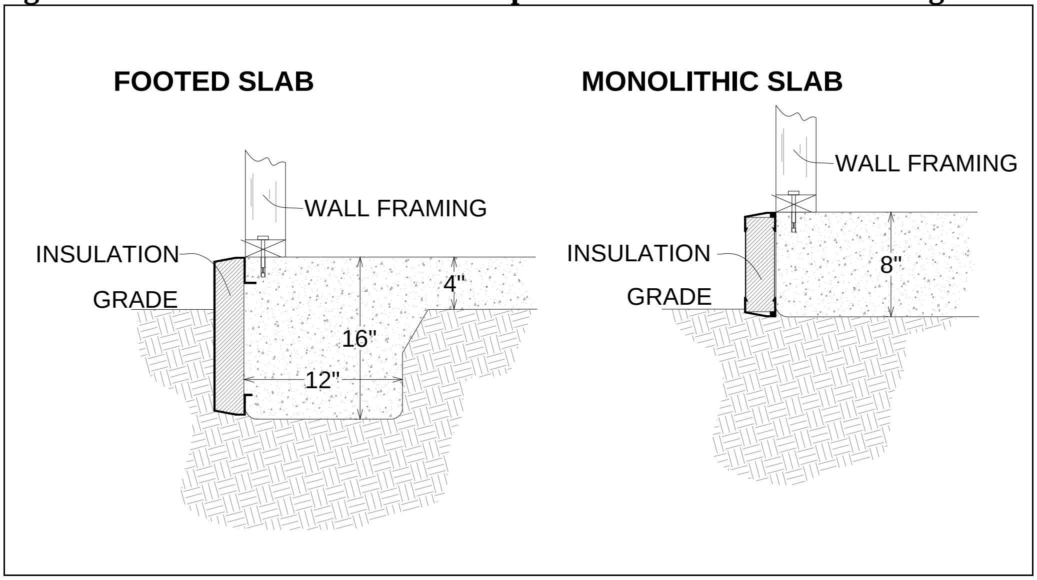
[4] http://apps1.eere.energy.gov/buildings/energyplus/

[5] http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=39/pagename=alpha_list

[6] http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=58/pagename=alpha_list

[7] A more sophisticated and flexible version of the model to be included in the TRNSYS 17 release was not fully operational at the time of the drafting of this paper. The TRNSYS 17 model offers greater user flexibility in defining the geometry of the house slab and the configuration of the slab edge insulation relative to the footing. This model has been extensively tested and validated as part of the HERS BESTEST process and found to be one of the most highly accurate models (Neymark & Judkoff, 2008).

Figure 4. TRNSED Insulation Assumptions for Different Slab Configurations



The TRNSED building energy simulation routine models the energy transfer from the slab of a multi-zone building to the soil beneath the surfaces. The energy transfer from the slab to the soil and within the soil is assumed to be conductive only with moisture effects ignored. The far-field soil temperature is set using the Kasuda correlation (Kasuda & Archenbach, 1965) which estimates the temperature of the soil at a given depth given the time of year and other factors. With the zone soil heat transfer, thermal history of the soil field and the properties of the soil known, the temperatures of each of the "nodes" of the 3-dimensional soil field can be calculated by this model. Based on the calculated soil temperatures and the zonal heat flows, the average zonal surface temperatures can be calculated and passed back to the model. This iterative methodology is then solved with the standard TRNSYS convergence algorithms.

The model was exercised for the five climates shown in Table 1 by running a 2000 ft^2 single story home with the following assumptions:

- Perimeter of 210 feet
- 20% glazing, uniformly distributed (100 ft^2 for each orientation)
- R-12 average walls (including framing factors and assumed insulation defects)
- R-25 average ceiling (including framing factors and assumed insulation defects)
- Fixed heating and cooling thermostat settings of 70°F and 76°F, respectively
- 70% of slab area covered by R-2 carpeting; remainder hard surface flooring
- Soil conductivity of 0.75 Btu/hr/ft-°F
- Density of 131 lbs/ft^3
- Thermal diffusivity of 0.60 ft^2/day
- Heat Capacity of 0.23 Btu/lb-°F

Table 1. Heating Degree Days by Location

Location	Heating Degree Days (base 65°)
Sacramento, CA	2666
Santa Maria, CA	2783
Reno, NV	5600
Atlanta, GA	2827
Ft. Worth, TX	2370

Table 2 summarizes the annual projected heating energy use for the uninsulated (perimeter) base case, as well as savings for both footed and monolithic slabs at insulation R-values of R-5, R-10, and R-15. The 2-8% range in base case heating energy use reflects the assumed difference in edge exposure between footed slabs (6") and monolithic slabs (8"). Table 2 projected savings range from 7-13% for the monolithic slab cases to 12-21% for the footed slab cases. As with any insulation application, the first R-5 increment provides the greatest benefit. Insulation incremental cost, energy efficiency needs, and strength all factored into the decision to utilize R-10

The final 11.35" tall form board design suggests that the footed slab savings are likely high and the monolithic slab savings projections are likely low. We project that for the climates evaluated, typical annual heating savings are roughly 60 therms, equal to 13% of base usage. The enhanced TRNSYS 17 model will allow us to update these projections in the near future.

Table 2. TRNSED Energy Use Projections and Savings

Location	Annual Base Heating Energy Use (therms)	Footed Slab Savings (therms/year)			Monolithic Slab Savings (therms/year)		
		R-5	R-10	R-15	R-5	R-10	R-15
Sacramento, CA	478 – 500	59	69	73	36	41	43
Santa Maria, CA	430 – 451	61	71	75	36	42	44
Reno, NV	842 – 858	101	117	124	58	65	68
Atlanta, GA	340 – 359	51	59	62	35	39	41
Ft. Worth, TX	197 – 212	35	40	42	24	27	29

Prototype Thermal Performance Monitoring

We completed thermal performance monitoring on uninsulated and insulated slabs constructed adjacent to our workshop facility in Davis, CA. The insulated slab section utilized the Formsulate product developed in the NETL development project. We poured a 10' x 20' (3.05 m by 6.1 m) slab and fabricated an insulated "structure" to simulate above grade construction. The slab was divided in half with R-10 rigid insulation (1.76 K-m^2/Watt) resulting in a 10' x 10' (3.05 m by 3.05 m) exposed slab edge section and a 10' x 10' (3.05 m by 3.05 m) insulated slab edge section. The structure's longitudinal axis was oriented east-west to minimize differential solar gain impacts that might create unbalanced heating loads for the base case section relative to the insulated slab edge section. Figure 5 depicts the slab prior to concrete pour with hydronic tubing and thermocouples installed (insulated section at the rear). We installed PEX hydronic tubing to allow for testing in radiant floor heating mode, as well as conventional forced air heating mode via electric resistance space heaters. We configured the tubing circuits allow for independent heat delivery to the insulated and uninsulated slab sections. We located three thermocouples on the slab steel reinforcing mesh (slab center and ~1 foot inboard from the north and south edges) with additional set of three thermocouples located in the soil ~12" below the sensors located in the middle of the concrete slab. We insulated the above-grade shed walls and roof with R-13 batts or R-10 rigid extruded polystyrene (2.29 and 1.76 K-m^2/Watt, respectively), and covered the slab floor with a carpet and pad to mimic typical thermal connection between the interior space and the floor slab.

Figure 5. PEX Hydronic Tubing and Slab Thermocouple Installation

We cross-calibrated all of the thermocouples prior to the sensors being installed in the slab and soil below. Factory calibrated heat flux sensors, located at mid-height of the exposed slab edge, provide a snapshot of the edge heat flux through that portion of the slab. (To fully characterize the slab edge heat loss, a more expanded, and expensive, grid of sensors would have been needed on both insulated and uninsulated slab sections.) For the insulated section, the heat flux transducer was installed on the PVC form board exterior face, and for the uninsulated section the sensor was installed on the bare concrete slab edge. To minimize air voids underneath the transducer, the rough slab edge surface was finished with a fine-grain cementitious product that provided better thermal contract with the bare concrete slab edge. Outdoor temperature and interior temperatures in each section were monitored using Type T thermocouples. Interior temperature sensors were used as control inputs to activate relays controlling the electric resistance heater or the hydronic circulating pumps, depending upon the heating operating mode. Monitoring hardware specifications are provided in Table 3.

Table 3. Sensor Specifications

Type	Application	Accuracy/Sensitivity
Special Limits of Error Type T Thermocouple	Indoor, outdoor (shielded), in-slab, and in-ground temperatures	±0.5°C, or 0.4% of reading, whichever is greater
Vatell BF03 heat flux transducer	Perimeter edge heat flux	Factory calibrated to NIST traceable reference. Sensitivity of~70mV/W/cm^2
Onicon System – 30 Btu meters	Energy delivered to space	Flow: ±0.5% at calibrated velocity Differential temperature: ±0.15°F Computational error: ±0.05%

We planned to characterize the relative impact of slab edge insulation in both forced air and radiant heating modes by conducting experiments in each mode. The testing began with forced air heating operation beginning in the late winter of 2007. The electric resistance heater located in the center of the structure was controlled to maintain a uniform 68°F temperature with the help of a continuously operating oscillating fan. In January 2008, heating delivery was switched from forced air to hydronic delivery. With individual Btu meters installed on each of the two hydronic loops, an R-10 insulated interior above-grade partition was installed to thermally isolate the two sides, allowing for calculation of the thermal energy required for both the insulated and uninsulated sides. Circulating pumps were individually controlled based on the corresponding interior temperature.

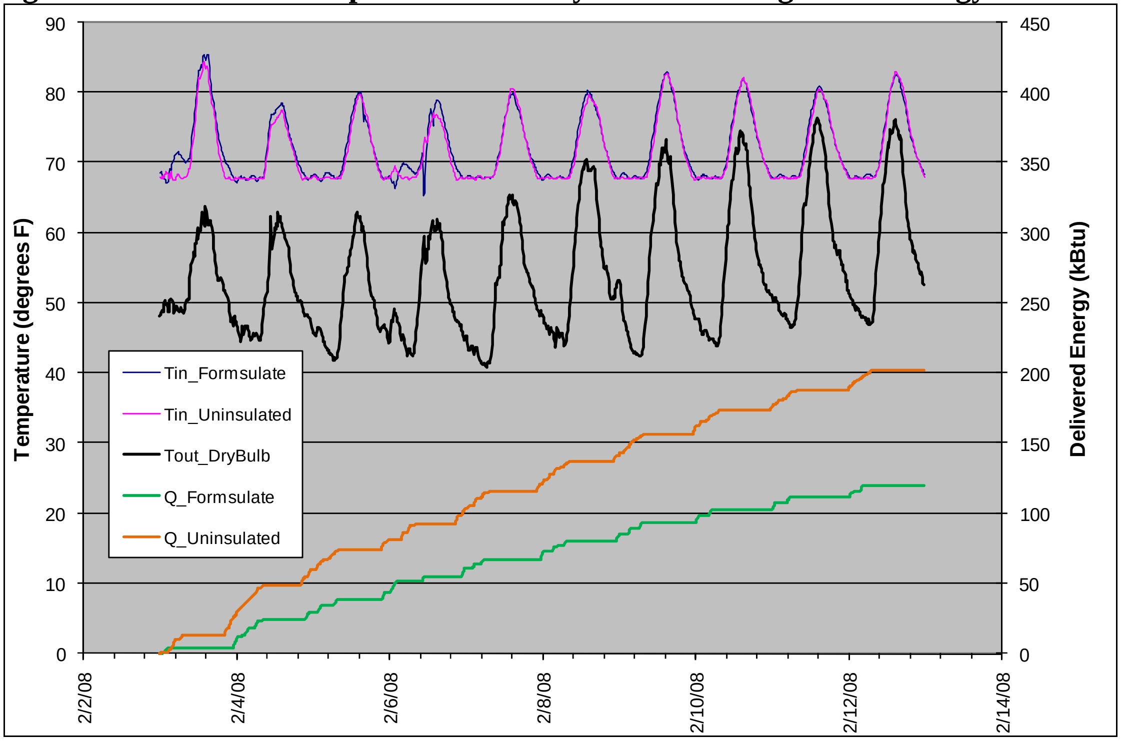
Figure 7 plots ten days of the 15-minute interval hydronic monitoring data from February 3rd- 13th, 2008. Outdoor temperature was logged, as well as indoor temperature for each side (insulated and uninsulated), and Btu's delivered to each side, as reported by the Btu meters. Outdoor temperatures during the period ranged from 40 to 75°F[8] (4.4 to 18.3°C). Indoor temperature variations between the two sides were minimal, even during daytime periods when roof solar gains would typically drive interior temperatures to ~80°F (26.7°C). The rate of morning interior temperature "warm-up" and afternoon "cool-down" are almost identical for the two sides, suggesting that the above-grade thermal characteristics were fairly consistent. Heating via the individual hydronic loops occurred each night as interior temperatures fell below the heating setpoint. In Figure 6, the orange and green lines represent the energy delivered to the uninsulated and insulated halves, respectively. Over the ten day period, the amount of energy delivered to the insulated side was ~ 40% less than the uninsulated side. This result should not suggest that expected savings are on the order of 40%, since the test setup is biased towards ground losses relative to above grade envelope losses (i.e. above grade heat loss per ft^2 of slab area is considerably less than that for a real house due to the small footprint and the reduced above grade heat loss).

Heat flux data during periods unaffected by solar gains (9 PM to 6 AM) were then plotted against outdoor temperature to characterize the energy benefits of the insulated form board. Figure 7 plots the average heat flux for the forced air mode of operation and Figure 8 plots similar data during hydronic heating operation. (Negative values indicate heat flow from indoors to outdoors.) The uninsulated slab edge data show a greater spread in results than the insulated data. This may be due to a variety of factors including proximity of the heat flux

[8] The first five days were characterized by more typical February weather with high temperatures around 60°, while the latter five days exhibited high temperatures exceeding 70°F.

sensor to a slab heating tube, greater heat transfer variability due to edge temperature fluctuations, and changing edge radiative effects as weather conditions and cloud cover change. Slab edge heat loss is about 85-90% lower for the insulated case than for the uninsulated case based on the regression lines. Comparing the hydronic heating regression line to the corresponding forced air regression line suggests that slab edge losses in radiant heating mode are ~50% higher (at a 40°F outdoor temperature) than in forced air mode. This result is consistent with our prior experience that radiant heated slab heat loss is considerably higher than from a conventional forced air heated structure.

Figure 6. Monitored Temperatures and Hydronic Heating Mode Energy Delivered



A final step in the performance assessment process was to compare field monitoring results to the TRNSED model projections. Hourly TRNSED output data generated from two simulations using Sacramento TMY2 weather data (uninsulated and with R-10 edge insulation) were compared to assess the magnitude and source of projected heating season benefits. The TRNSED model outputs hourly building heating load, and slab top, side, and bottom heat fluxes. The regression relationships identified in Figures 7 and 8 were used with the hourly weather data to projected hourly edge heat losses for both hydronic and forced air modes of heating operation.

Figure 7. Hourly Heat Flux as a Function of Outdoor Temperature (Forced Air Mode)

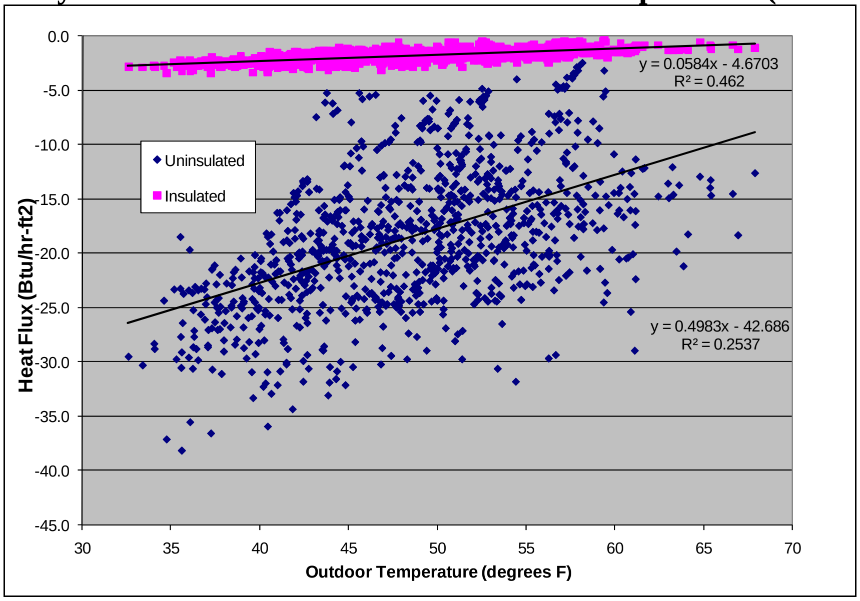


Figure 8. Hourly Heat Flux as a Function of Outdoor Temperature (Floor Heating Mode)

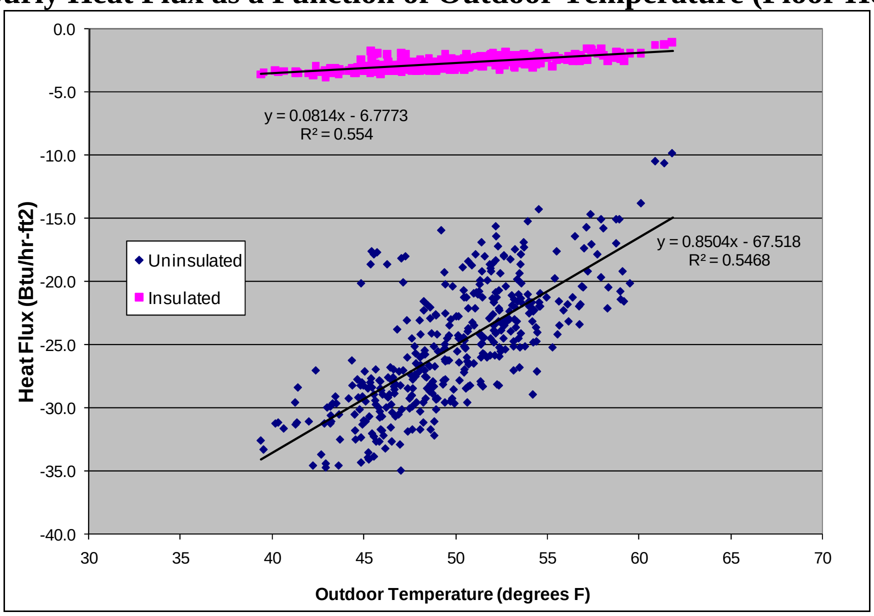


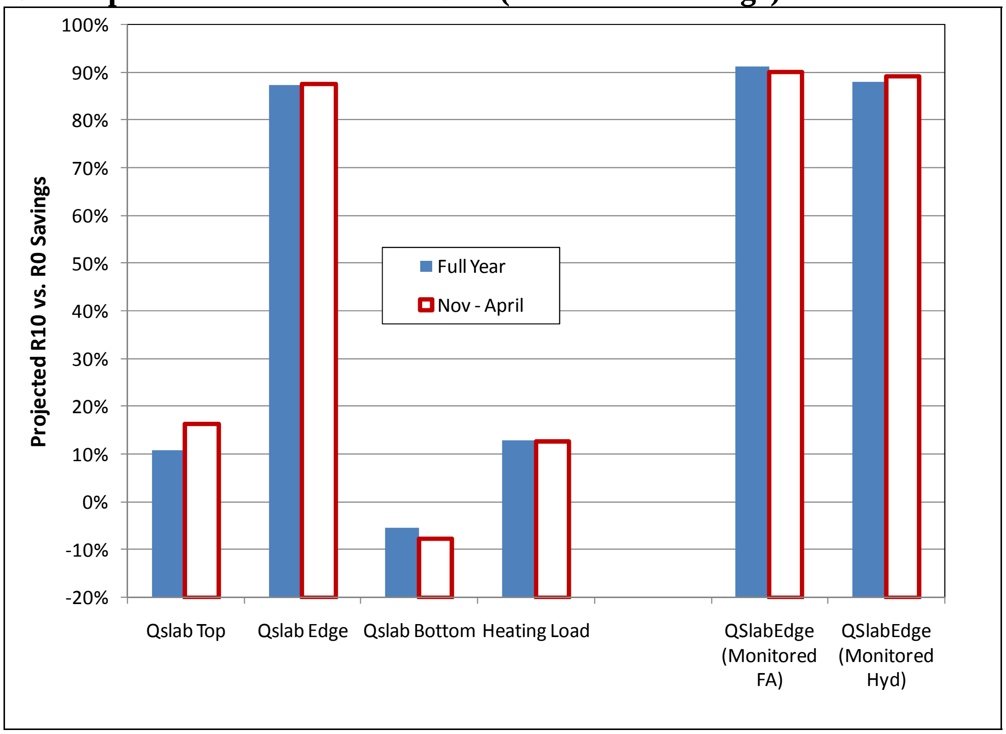
Figure 9 plots the full year and winter season (November-April) energy impacts with "+" values indicating a reduction in energy use or heat flux and a "-" value indicating an increase. "Qslab Top" (the heat flux from the house slab to the ground and slab edge) is projected to be reduced by 11% on an annual basis with R-10 insulation, and 17% during the November – April heating season. Slab edge heat loss reductions are projected to be reduced ~88% relative to the uninsulated base case[9]. Slab bottom (downward) heat loss is actually projected to increase 5-8% with the addition of perimeter insulation, as the heat flow path is directed more downwards

[9] During the November-April winter period, the TRNSED model projects that 25% of the slab top heat flux flows to the edge in the uninsulated case, and only 4% in the R-10 case.

rather than towards the slab edge. The projected combined impact for this Sacramento case is an overall 13% reduction in house heating load with the addition of R-10 insulation.

The rightmost two bars in Figure 9 depict the regression-based monitored edge loss projections for both the forced air ("FA") and the hydronic ("Hyd") cases. The hourly slab edge heat loss was calculated using the Sacramento TMY2 weather data. The 88% TRNSED projected edge loss reduction is very comparable to the percentage reductions generated by the regression relationships, providing additional confidence in the modeling projections.

Figure 9. Comparison of TRNSED Results (R-0 and R-10 Edge) and Monitored Results



Discussion

The slab edge insulation system presented in this paper offers the potential of significantly reducing slab perimeter losses for new slab on grade homes. US Census Bureau data suggests that in the boom new construction period five years ago, ~850,000 slab on grade homes were being built annually. With projected savings of 60 therms per year, the technical savings potential is roughly 51 million therms annually. Prime introductory markets include the radiant heating market (perimeter insulation is already used) where the system can simplify the installation process. A harder sell is the cost-competitive production home market. Energy codes such as Title 24 provide an incentive for implementation, but market growth is needed to bring the fabrication and distribution costs lower to increase the system's relative cost-effectiveness versus other measures. Finally, optimizing the solution for the retrofit and post-tensioned markets will greatly expand the energy savings potential.

Conclusions

Improvements in envelope R-values, installation quality standards, improved windows and HVAC equipment, and reduced duct and envelope leakage, have all contributed to reduced heating loads and heating energy consumption. Slab edge heat loss remains one of the last remaining thermal shorts in new energy efficient homes, and due to the reduction in other components, an increasingly important one. Similar to a window remaining partially open during the winter, the heat loss is small, constant, and largely preventable.

The insulated form board product developed in this NETL-sponsored project provides a viable option for insulating slab perimeters. Project modeling and monitoring activities confirm the benefits of slab edge insulation. Modeling results suggest that potential heating energy savings in typical new homes are on the order of 13% for the climates evaluated. Model results also identify slab edge insulation's impact on increasing downward heat flows. Monitoring results confirm the model's edge loss calculations and indicate typical reductions in winter edge heat loss by ~90%. A monitoring comparison of forced air and radiant floor heating delivery indicates on further document the potential savings, especially in homes with radiant heated floors where mid-winter slab edge heat fluxes were found to be roughly 50% higher than for forced air heating systems.

Barriers to widespread acceptance of the technology include added cost, and builder and contractor acceptance. Energy codes that promote slab edge insulation will provide an incentive to builders. As with any new technology, building a market is critical in achieving production cost reductions. Finally, to maximize the energy savings potential of this technology, a retrofittable strategy needs to be developed and demonstrated.

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