RESEARCH

THE ENERGY SAVINGS POTENTIAL OF OPTIMIZED SLAB-ON-GRADE FOUNDATION INSULATION RETROFITS

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ABSTRACT

A recently developed 3-dimensional earth contact simulation program that operates as a subroutine of the EnergyPlus whole building energy simulation program was used to evaluate the energy performance and cost-effectiveness of retrofit slab-on-grade (SOG) foundation insulation. An optimized retrofit insulation design utilizing hydro-vacuum excavation was developed that generated 8.4 % larger metered (or site) energy savings at a $428 lower cost than the IECC 2012 requirement in a Minneapolis, MN climate for a 400 ft^2 test building. The energy performance and cost effectiveness of single and multi-family buildings was assessed for climate Zones 4 – 7. With reference to the Building America B10 benchmark, the highest site energy savings of 5 % was realized for a single family home in Duluth, MN, and the lowest savings of 1.4 % for a 4-unit townhouse in Richmond, VA. SOG foundation insulation retrofit simple paybacks ranged from 18 to 47 years. Thus it is likely that larger energy savings of 10% or more with concomitantly reduced simple paybacks can only be realized in well-insulated buildings.

KEYWORDS

slab-on-grade; insulation; energy; cost

INTRODUCTION

The last comprehensive review of the energy savings potential of slab-on-grade (SOG) foundation insulation was reported in the Building Foundation Design Handbook (Labs, *et al*, 1988). This review was conducted using the DOE 2.1C energy simulation program in combination with a standalone, 2-dimensional ground simulation code developed by Shen (1986). This simulation methodology was applied to a (1540 ft^2) single-family, single-story house with, for example, a 48 in. stem wall SOG foundation covered with external R_{US}-10 rigid insulation in a Minneapolis, MN climate. In these circumstances, the simulation predicted an annual (heating and cooling season) energy use savings of -3.9% (that is, the energy

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use increased because the cooling season energy increase more than offset the heating season energy savings). When applied to the same house in the same climate with an unconditioned full basement with R_{US}-10 interior rigid insulation, the predicted annual whole house energy use savings was -15.3% (again an increase). In contrast, using modern whole building simulation techniques including 3-dimensional ground simulation, Goldberg and Steigauff (2013), for the same full basement insulated wall configuration in the same climate, reported a whole house annual metered (or site) energy savings of 7.46%. The significant difference in predicted annual energy savings for full basements was expected to apply SOG foundations as well, thus yielding the potential for annual site energy savings from SOG foundation insulation.

In addition, modern excavation techniques, such as hydro-vacuum excavation, offer significant installation cost savings for retrofitted foundation insulation compared with more traditional techniques (Schirber, *et al*, 2014). Thus the potential for higher energy savings than previously predicted combined with the availability of less expensive installation techniques offer the potential of extracting meaningful annual metered energy savings from retrofitting SOG foundations with insulation.

SIMULATION METHODOLOGY

The BUFETS[3] (BUilding Foundation Energy Transport Simulation) program has been used previously for developing recommendations for the foundation rules in the 2009 Minnesota Energy Code (Goldberg and Huelman, 2005) as well as for several research projects conducted for the National Renewable Energy Laboratory (NREL) as part of the Building America program (for example, Goldberg and Steigauf, 2013). In this configuration, BUFETS is run independently from the EnergyPlus[4] whole building energy simulation program and generates libraries of foundation enclosure coupling ground temperatures and thermal resistance values for each foundation geometry in each climate. These foundation heat transfer libraries are subsequently used by EnergyPlus to generate the foundation enclosure heat fluxes at each simulation time step, usually at one-hour intervals (Goldberg and Steigauf, 2013).

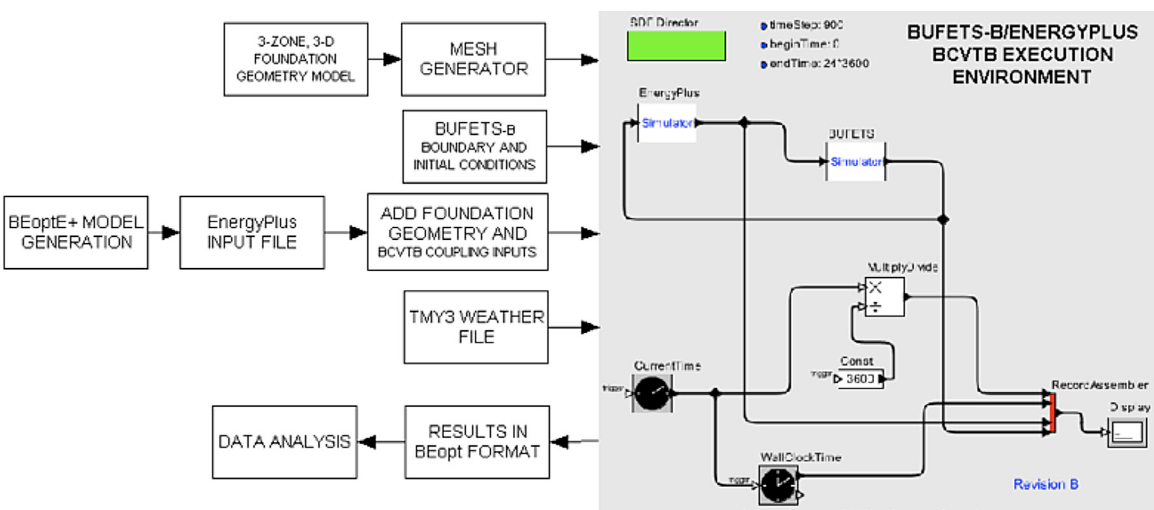
For this mechanism to be completely accurate, it is necessary for the interior foundation enclosure boundary conditions to be identical in both BUFETS and EnergyPlus at every time step. This is reasonable when the foundation enclosure (basement, crawl space or first floor) is conditioned to a known temperature setpoint schedule. However, most foundation enclosures (basements and crawl spaces) have uncontrolled temperatures because thermal space conditioning is supplied only when the thermostat, typically located in an above-grade portion of the building, calls for it. Therefore, the basement temperatures are transient and cannot be determined with any accuracy *a-priori*. Ideally, this requires an iterative execution of BUFETS and EnergyPlus until basement temperature convergence is achieved. In view of the long BUFETS execution times (approximately 30 hours for 100,000 or more control volumes), such an iterative approach is not tractable when a large number of cases must be simulated. Therefore, for a once through methodology to be numerically stable, it is strictly necessary for the BUFETS foundation interior air temperatures to be equal to or greater than the EnergyPlus foundation interior air temperatures at every time step. In this case, the model is stable and

3. BUFETS is a proprietary, non-commercial software program developed by Lofrango Engineering, Minneapolis, MN.
4. EnergyPlus is a whole building energy simulation program available from NREL, U.S. Dept. of Energy, http://apps1.eere.energy.gov/buildings/energyplus.

the simulated heat fluxes through the interior foundation surfaces will be in error nonlinearly proportionate to the difference between the temperature profiles. In the case when the EnergyPlus floating temperature boundary conditions are greater than the boundary condition temperatures used in BUFETS, the coupling mechanism becomes unstable and the combined simulation yields physically invalid results.

Detailed descriptions of BUFETS may be found in Goldberg and Steigauf (2013), Goldberg and Harmon (2015) and Goldberg and Mosiman (2015). In mid-2014, the BUFETS developer released a new version of the program termed BUFETS-B (BUFETS – Building Controls Virtual Test Bed[5]). The BCVTB platform, developed by the Lawrence Berkley Laboratory (LBL), allows EnergyPlus to be linked to other simulation programs via public domain coupling libraries. In this configuration, BUFETS-B functions as a subroutine of EnergyPlus enabling data exchange between the programs at every time step (Figure 1). EnergyPlus sends the current boundary conditions (ambient, foundation interior and enclosure surfaces) to BUFETS-B and BUFETS-B returns the resulting foundation interior surface heat fluxes. This unconditionally stable methodology enables EnergyPlus to model the ground around the foundation in 3-dimensions and provides BUFETS-B access to the full EnergyPlus interior foundation enclosure surface energy balance. This balance includes long- and short-wave radiation heat flows that are essential to modeling summer cooling loads accurately, especially for example, when sunlight falls on a slab surface.

Figure 1: BUFETS-B/EnergyPlus simulation environment.



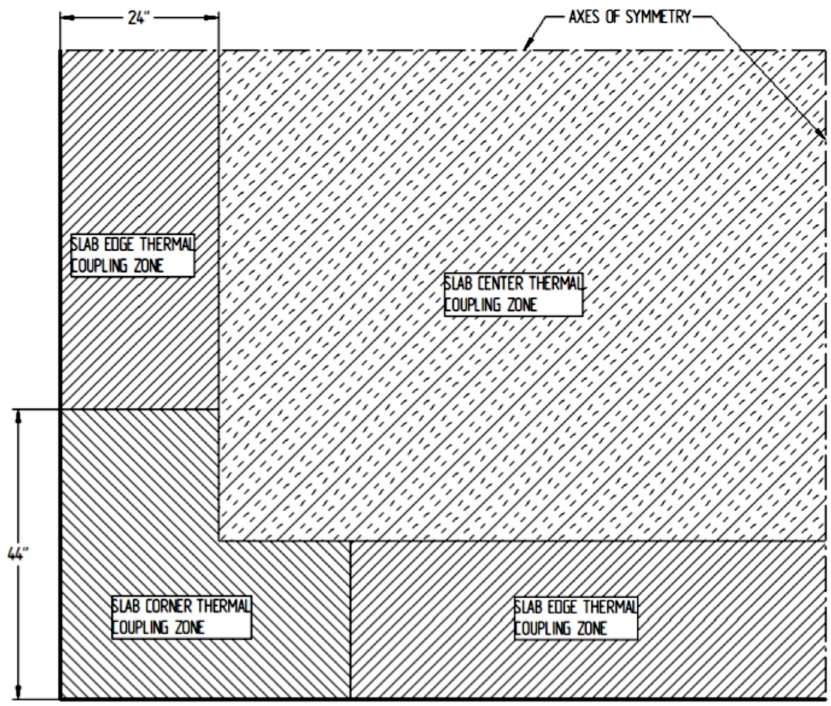
The BUFETS-B/EnergyPlus thermal coupling for SOG foundations used is shown in Figure 2. As all the foundations modeled were rectangular, only one quadrant of the foundation was simulated in BUFETS-B. Three heat flow zones (slab center, slab edge and slab corner) were used to aggregate the BUFETS-B heat flows as this has proved to be an adequate resolution in previous research (Goldberg and Steigauf, 2013). Thus the entire slab modeled in EnergyPlus was represented by a total of 9 zones (4 corner, 4 edge and the center). The average corner and edge zone surface temperatures were passed to BUFETS-B which returned the average zone heat fluxes to EnergyPlus. While this simplification is effective in reducing

5. http://simulationresearch.lbl.gov/bcvtb

the simulation time to a reasonable value (about 24 h per simulated year), it is not necessary and the coupling methodology permits an unlimited number of coupling zones.

Each simulation was run for a period of 2 calendar years with the first year serving to initialize the ground temperatures. Standard EnergyPlus Typical Meteorological Year (TMY3) weather data were used for the ambient boundary conditions and the simulation was run with a 15 minute time increment to adequately capture thermal transients (Tabares-Velasco, 2013). Other details of the simulation such as the soil material properties, water table heights and ground simulation domain discretization are reported in Goldberg and Mosiman (2015).

Figure 2: Thermal coupling zones.



COMPARISON OF BUFETS AGAINST AN ANALYTIC SOLUTION

An analytic solution for a SOG surface cast as a semi-infinite solid heat transfer problem was used by Neymark and Judkoff (2008) as a means of establishing an "analytical verification base case" (GC10a) for 3-dimensional earth contact simulation programs as shown in Figure 3. The analytic solution was developed by Delsante, Stokes *et al* (1983) using Fourier transforms to solve the Fourier thermal conduction equation for a semi-infinite solid subject to the surface thermal boundary conditions shown in Figure 3. Constant temperatures on the slab and ground surfaces are connected via a linear gradient across the stem wall top surface. The thermal conductivity of the solution domain is a single-valued constant. The analytic solution provides the area-integrated, steady-state heat transfer across the slab surface.

The two physical parameters critical to yielding accurate simulation solutions are the depth and far field width of the simulation domain which, analytically, are of infinite extent. Thus these parameters must be increased until the solution converges. The standard transient version of BUFETS was applied to the problem defined in Figure 3, but only ¼ of the slab was simulated because of the symmetries in the geometry. The simulation was iterated until temperature convergence was achieved. As BUFETS admits exact Dirichlet boundary conditions, no boundary condition approximation is required as shown in Figure 4 for the temperature gradient on a line perpendicular to the stem wall. The same boundary conditions apply on a diagonal through the corner, except the spacing between the simulation boundary temperatures is increased by a factor of √2.

The results of the BUFETS/analytic solution comparison for case GC10a are compiled in Table 1. The results compare well with those of the TRNSYS simulation program that yielded a -0.24% error with a far field width and a domain depth of 40 m (Neymark and Judkoff, 2008).

Figure 3: Case GC10a - steady state analytical verification base case (Neymark and Judkoff, 2008).

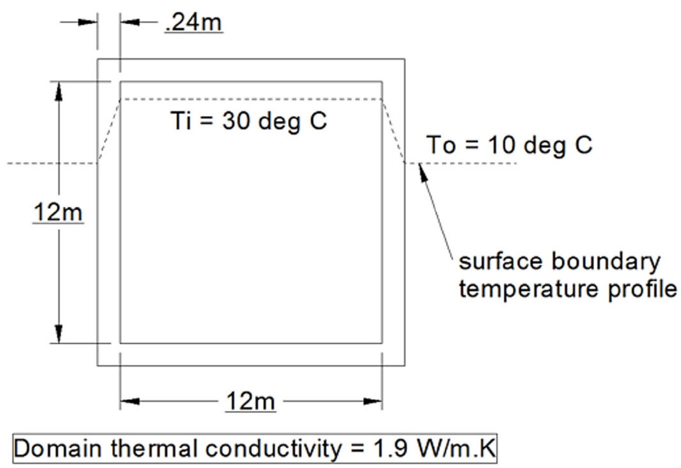


Figure 4: Analytic solution and BUFETS temperature boundary conditions on a line at right angles to the wall.

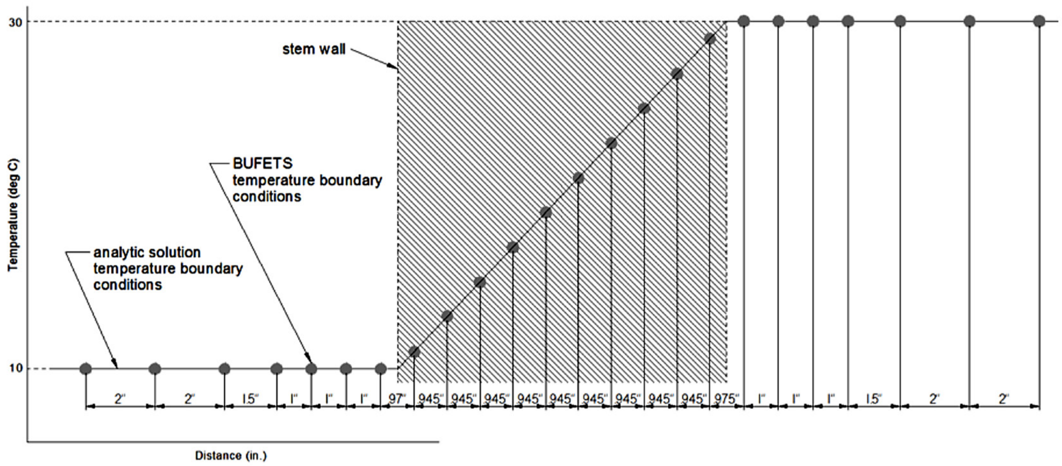


Table 1: Slab surface heat transfer comparison

Far Field Width (m)	Depth (m)	No. of Discrete Volumes	Numerical Convergence		Slab Surface Heat Flow		
			Temperature (K)	Heat Flow (W)	Analytic Solution (W)	BUFETS (W)	Error (%)
20.3	21.0	217328	10^{-5}	10^{-4}	2432.52	2432.60	+0.003
30.5	30.7	346788	10^{-5}	$<10^{-4}$		2428.30	-0.17

COMPARISON OF BUFETS-B AGAINST EXPERIMENTAL DATA

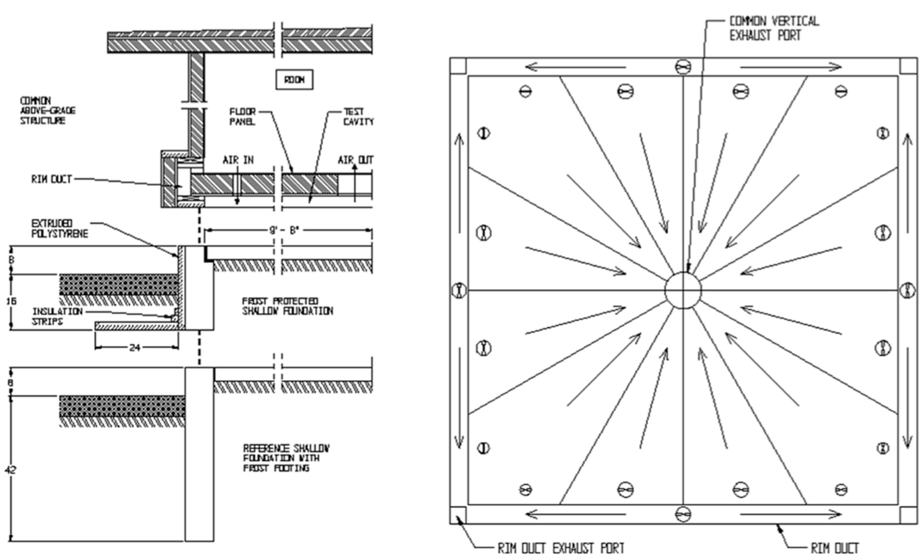
It is desirable to replicate the analytical comparison with an equivalent experimental comparison, that is, the comparison of the simulated BUFETS-B slab heat flow against measured whole slab surface heat flow data. This is particularly important in building energy simulation in which the full slab surface heat flow is the primary determinant of the impact of SOG foundation insulation on the site energy consumption.

Comparisons of experimental and simulation SOG foundation temperatures exist (for example, Adjali, *et al*, 2000), but these omit area-integrated slab surface heat flows. Emery, *et al*. (2007) report measured basement slab point heat fluxes, but area-integrated slab surface heat flows, again, are not reported.

Owing to the absence of published experimental data for the energy performance of whole buildings with SOG foundations including full or area-integrated slab heat flows (Goldberg and Mosiman, 2015), the only whole-building SOG experimental energy performance data suitable for validating the BUFETS-B/EnergyPlus (BEB) simulation known to the authors is reported in an unpublished University of Minnesota research report (Goldberg, et al, 1994). Data from this report were used by Adjali *et al* (1998) for full basement earth contact simulation testing.

The experimental data was generated at the University of Minnesota's Foundation Test Facility (FTF) in Rosemount, MN from 1991 to 1994 for "reference" and "test" SOG test modules as shown in Figure 5. The above-grade portion of the test modules was nominally identical and constructed of 7 large structural insulated panels (SIP) with very well sealed joints. The slab surface was covered with 5.5 in. SIPs creating an air gap above the slab through which heated interior air was blown radially from the perimeter to the center at a high flow rate. The air gap edge was guarded thermally by a rim duct. The change in enthalpy across the air gap cavity as well as the vertical heat flow through the covering SIP was measured at about 1 second intervals allowing a real-time energy balance on the slab air cavity to be performed. The energy balance yielded the aggregate heat flow through the slab surface.

Figure 5: Experimental test modules.



CROSS-SECTION THROUGH MODULES AIR DISTRIBUTION PLENUM ON THE SLAB SURFACE

The test modules were heated electrically enabling the module energy consumption to be measured directly by a rotating disc watthour meter during the heating season. No cooling season energy performance experiments were performed.

The ground beneath the modules was engineered to be nominally the same and consisted of a 42 in. deep cavity with sloped sides, backfilled with pit-run sand and covered with a 6 in. layer of native loam. Thus, by design, the only difference between the modules was their foundations. The reference module had a standard, code-required 42 in. deep frost footing while the test module consisted of a 16 in. deep frost-protected shallow foundation with R_{US}-10 vertical and horizontal wing insulation. Neither foundation included spread footings to simplify the soil heat transfer modelling. The two modules were built about 40 ft apart on a staggered grid so that their air flow patterns did not interact for the prevailing north-westerly wind direction.

The theoretical basis of the experiment was to use the reference module for data normalization so that differences in transient weather and soil moisture conditions could be factored out of the results allowing them to be compared over multiple seasons. To this end, as described, both the test and reference modules were engineered to be as close to identical as possible including the imported sand backfill, so that, in theory, the only significant difference between the modules was the foundation configuration. Thus a normalized comparison of the data strictly demonstrates the effect of the insulated frost protected footing in the test module on the module energy performance. A further benefit of the experimental design is that it allows the normalized data to be used for simulation validation as well, provided that the simulation data is also normalized and that the only difference between the reference and test simulation models is in the foundation configuration. That is, the weather, the surrounding soil and the soil moisture content used in the simulation can all be different from those in the experiment as long as they are the same in all the simulations. Further, for the site energy consumption predictions only, there can be differences in the above-grade building model relative to the experiment if the test and reference above-grade models are identical. Accurate predictions of the slab heat flow also require that the simulation replicates the enclosure heat transfer physics of the experimental modules as precisely as possible. Whether the nominal similarity between the experimental above-grade structures was achieved in practice is unknown as all the qualification data were lost. In particular, whether the modules had the same measured infiltration rate (that is the most likely as-built difference) is unknown. Hence the effect of different infiltration rates in the two modules was investigated parametrically.

Table 2: Normalized SOG module experimental data

Test Heating Season	Site Energy Consumption Ratio (γ) (Test/Reference)	Slab Heat Flow Ratio (σ) (Test/Reference)	Reference Module Slab Energy Fraction (β_R) (Slab/Site)	Test Module Slab Energy Fraction (β_T) (Slab/Site)
1991/92	0.857	0.623	0.198	0.144
1992/93	0.863	0.568	0.180	0.118
1993/94	0.869	n/a	n/a	n/a

The relevant normalized experimental results are given in Table 2. The mean site energy consumption ratio γ over the three heating seasons had a value of 0.863±0.006 yielding a maximum deviation from the average of 0.7%.Thus the measured average heating season site energy savings for the insulated frost protected shallow foundation were 13.7%. As the

1992/93 heating season results corresponded to the mean, these results were used for the validation exercise.

The following changes were made to the above-grade portion of both test modules in the simulation:

- The slab heat flow measurement apparatus was removed. This was a matter of necessity as it is not possible to accurately replicate the heat transfer conditions above the slab in EnergyPlus not only because of a lack of capability, but also because, in any case, all the relevant data, such as the measured system flow rates and temperatures, have been lost. A configuration with a separate cavity zone above the slab with an estimated air flow rate of 1882 cfm[6] between the slab cavity and the room was simulated for comparison with the single zone convective coupling approach used. Numerically, the single zone and dual zone approach yielded site energy (watthour meter reading) results within 3% of each other for a January test period. Thus, for the sake of simplicity and consistency between the test and reference modules, the single zone approach was adopted.
- The door was removed.
- The modules were assumed to be fairly airtight with a base effective leakage area of 3 cm^2 as no experimental infiltration data could be found.

Other than these modifications, the design of the reference and test experimental modules was the same as the simulated modules in terms of geometry and material property specifications. The experimental and simulation results are compared in Table 3.

Table 3: Validation data

Data Source	Site Energy Consumption Ratio (γ) (Test/Reference)	Slab Heat Flow Ratio (σ) (Test/Reference)	Reference Module Slab Heat Flow Fraction (β_R) (Slab/Site)	Test Module Slab Heat Flow Fraction (β_T) (Slab/Site)
Experiment	0.863	0.568	0.180	0.118
Simulation	0.923	0.835	0.480	0.434

The primary validation metric, namely, the energy consumption ratio (γ), shows a discrepancy of 0.06 corresponding to a simulation error of 7%. An examination of the reference and test module slab energy fractions (β_R and β_T) reveals the impact of the different slab heat transfer mechanisms between the experiment and the simulation as expected. In the experiment, the measured slab heat flows were less than 20% of the site energy consumption, while in the simulation they were more than 40% of the site energy consumption. Further, the slab heat flow ratio (σ) is 0.267 larger in the simulation. This can be explained in terms of Table 4. This table shows that simulated σ for the edge and corner quadrants (see Figure 2) of 0.54 and 0.56 is within 5% of the measured value while the slab center slab σ is about 2 (~4 times larger than the experiment), that is, the simulated heat flow through the slab center in the test module is twice as large as that in the reference module. The center σ difference is thus the cause of the overall aggregate σ discrepancy. This discrepancy arises because in

6. As far as can be remembered, 6 in. diameter, 115VAC fans were used for all the center segments and two 4 in. fans were used in each of the corner segments (Figure 3). A variac was used to regulate the speed of all the induction fans simultaneously, and a setting of 70% of full flow was assumed. Based on these recollections and assumptions and the performance of current fans with these specifications, the estimated total flow rate was about 1882 cfm.

Table 4: Simulated slab heat flows (12/1 to 4/30)

Slab Section	Simulation Reference Module (kWh)	Simulation Test Module (kWh)	Simulated Slab Heat Flow Ratio (σ) (Test/Reference)
Center	68.25	135.87	1.99
Edge	179.87	100.71	0.54
Corner	101.21	57.13	0.56
Quadrant	349.43	293.71	0.84

the simulation, the air temperature across the slab was uniform, while there was a perimeter-to-center temperature gradient across the slab in the experiment, with the perimeter being warmer than the center. So at the perimeter where room temperature was introduced into the experimental air gap, the air temperatures above the slab in the simulation and the experiment were approximately the same and the values of σ are in agreement. However, at the center of the slab, the air temperatures in the simulation were greater than those in the experiment yielding larger heat flows. Finally, in accordance with the entropy minimization principle, the heat flow adjusts to maximize the heat transfer across the full slab surface leading to higher flows distant from the insulated perimeter compared with the heat flows with an uninsulated perimeter (see, for example, Bejan, 2002). In the experiment, the heat flows at the slab center were smaller than in the simulation owing to the decreased air temperature there.

Accounting for the differences in the simulation and experimental values of β_R and β_T given that the ratio of the experimental and simulation values of γ would be unity in a perfect simulation with independently measured and calculated values, yields the result (Goldberg and Mosiman, 2015):

$$\frac{\gamma_{EXP}}{\gamma_{SIM}} = \frac{\sigma_{EXP}}{\sigma_{SIM}} \Big/ \frac{\beta_{R,SIM}}{\beta_{T,SIM}} \frac{\beta_{T,EXP}}{\beta_{R,EXP}} = 0.938 \quad (1)$$

where the variables are defined in Table 2 and the subscripts *EXP* and *SIM* indicate experimental and simulation respectively. The ratio is different from unity by 6.2%, less than the error in γ of 7%.

The parametric evaluation of the impact of differing module infiltration rates is reported in Table 5. Therefore including the uncertainty introduced by a substantial difference infiltration rate between the test and reference modules bounds the simulation error in the site energy ratio to 7 -3.2/+3.4%. The results show that in terms of the overall building energy consumption, the BEB simulation yields a maximum error of 10.4% distributed over errors in both EnergyPlus and BUFETS-B as well as uncertainty in the experimental infiltration rates.

Table 5: Effect of different module infiltration rates

Case	Reference Module Equivalent Leakage Area (cm^2)	Test Module Equivalent Leakage Area (cm^2)	Simulation Site Energy Consumption Ratio (γ) (Test/Reference)	Simulation/Experiment γ Error (%)
1	14.85	3	0.896	3.8
2	3	14.85	0.953	10.4

INSULATION OPTIMIZATION

The experimental reference module used in the validation exercise was used as the basis for the SOG foundation insulation optimization in the same Zone 6 climate (Minneapolis, MN). The key requirement in the adaptation was to maximize the slab heat flow/site energy ratio (β) in order for changes in site energy consumption produced by changes in the stem wall insulation to be maximized, that is, the signal-to-noise ratio of the insulation changes also would be maximized. The other consideration was to make the optimization more like an actual residential building. The resulting above-grade structure is shown in Figure 6 and includes the following modifications to the experimental above grade structure:

- addition of a standard exterior wooden door
- removal of the guard cavity at the base of the walls
- an increase in the equivalent leakage area (ELA) from 3 cm^2 to 36.8 cm^2 to represent an infiltration level typical of new construction in 2000 (Sheltersource, 2002).
- addition of 4 standard windows (each 56.875 in. tall by 25.625 in. wide) to the south wall allowing solar gain on the slab surface.

The reference uninsulated SOG foundation is depicted in Figure 7. It includes a poured concrete stem wall with a conventional spread footing located 42 in. below-grade in compliance with the MN Building Code. These modifications to the experimental building increased the simulated slab energy fraction (β) from 0.480 (experimental) to 0.527 (optimization) with a corresponding increase in the center slab heat flow during the heating season from 281.2 to 417.1 kWh. These increases provided an adequate signal-to-noise ratio enabling the impacts of small changes to foundation insulation strategies to be clearly discriminated by changes in the site energy savings.

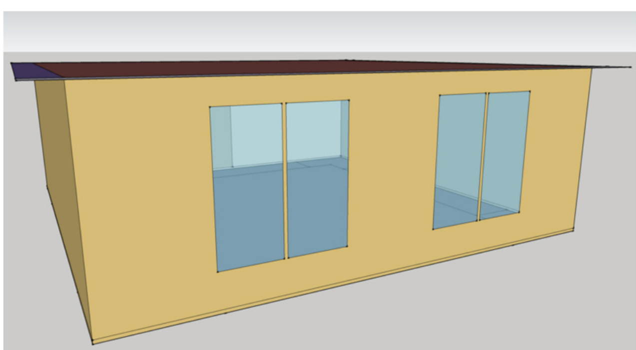


Figure 6: Optimization module above-grade structure.

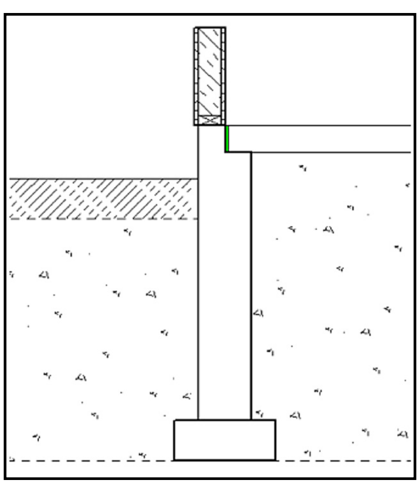


Figure 7: Optimization module uninsulated foundation.

Ten different SOG insulation strategies shown in Figure 8 were developed and their energy performance results compared with the uninsulated base case. Options a. through j. utilize hydro-vacuum excavation (Schirber et al, 2014) to remove just sufficient soil to form a trench of adequate size to accommodate the insulation. Options a. and b. reflect the conventional practice of insulating stem walls with one or two inches of extruded polystyrene rigid board insulation with R_{US} values of 5 and 10 respectively, with the latter value being in compliance with the 2012 International Energy Conservation Code (ICC, 2012). Options c. and d. introduce a 1.-in. layer of pourable polyurethane (PPU) foam insulation between the rigid board and the wall as this has two benefits: PPU has a nominally 20% larger thermal resistance than XPS increasing the overall R-value of the insulation per unit width of insulation; and, it fills all the seams between the XPS sheets yield a more consistent insulating layer. In this manner, the RUS values of options c. and d. are 11 and 16 respectively.

Options e. through f. take advantage of the ability of the hydro-vacuum process to cut relatively precise angles in the soil, enabling the creation of a tapered insulation trench. The advantage of tapered insulation is that the thermal effectiveness[7] of the installed insulation increases with decreasing depth below grade. That is, the thermal effectiveness of the insulation system as a whole increases if the insulation thickness decreases with depth below grade. After excavation, one- or two-inch XPS is placed against the sloping trench wall, and PPU is poured into the tapered gap between the XPS and stem wall. XPS is fastened to the above-grade stem wall with a thickness equal to that of the tapered insulation at the grade surface. In the sequence e. to f., the above-grade insulation width increases as the depth decreases from the full below-grade height, to ¾ and finally ½ of the below-grade height. Options h. and i. are a half below-grade wall height variation of Option d. and Option i. adds 1in. of XPS insulation to the slab surface for energy savings comparison purposes. Finally, Option j. corresponds to a vertical plus 18-in. wide wing insulation configuration typical of that used in frost-protected shallow foundations. However, to maintain energy performance consistency with the other options, 3 in. of XPS (R_{US}-15) was deployed. In this case, conventional manual excavation techniques are necessary.

The results of the optimization simulations are shown in Table 6 which includes both energy performance and cost data. The heating season energy performance data only was used for assessing the thermal performance for optimization purposes because, in Zone 6, SOG foundation insulation generally produces an increase in energy consumption during the cooling season caused by an increase in air-conditioning load.

Option g. (single underline) yielded the largest site energy savings of 36.3%, 8.4% larger than the 2012 IECC code requirement at a $428 (or 24%) lower installation cost. While the slab surface insulation in Option i. (double underline) contributed to this option yielding the largest slab heat flow savings of 69.4% (10% larger than its nearest competitor, Option f.), the increased slab heat flow savings still produced a site energy savings 2% lower than those for Option g. This results from the solar gain on the slab being shielded from loss to the ground, but at the same time, the solar gain contribution to decreasing the overall building thermal load during the heating season evidently is not significant. Option j. (frost-protected shallow foundation insulation configuration) showed just 1.3% lower site energy savings than Option g., but at more than 3.5 times the cost. Hence in terms of the primary site energy savings

7. Thermal effectiveness is defined as the ratio: one-dimensional heat flux/three-dimensional heat flux for the same thermal resistance.

Figure 8: SOG foundation insulation design configuration.

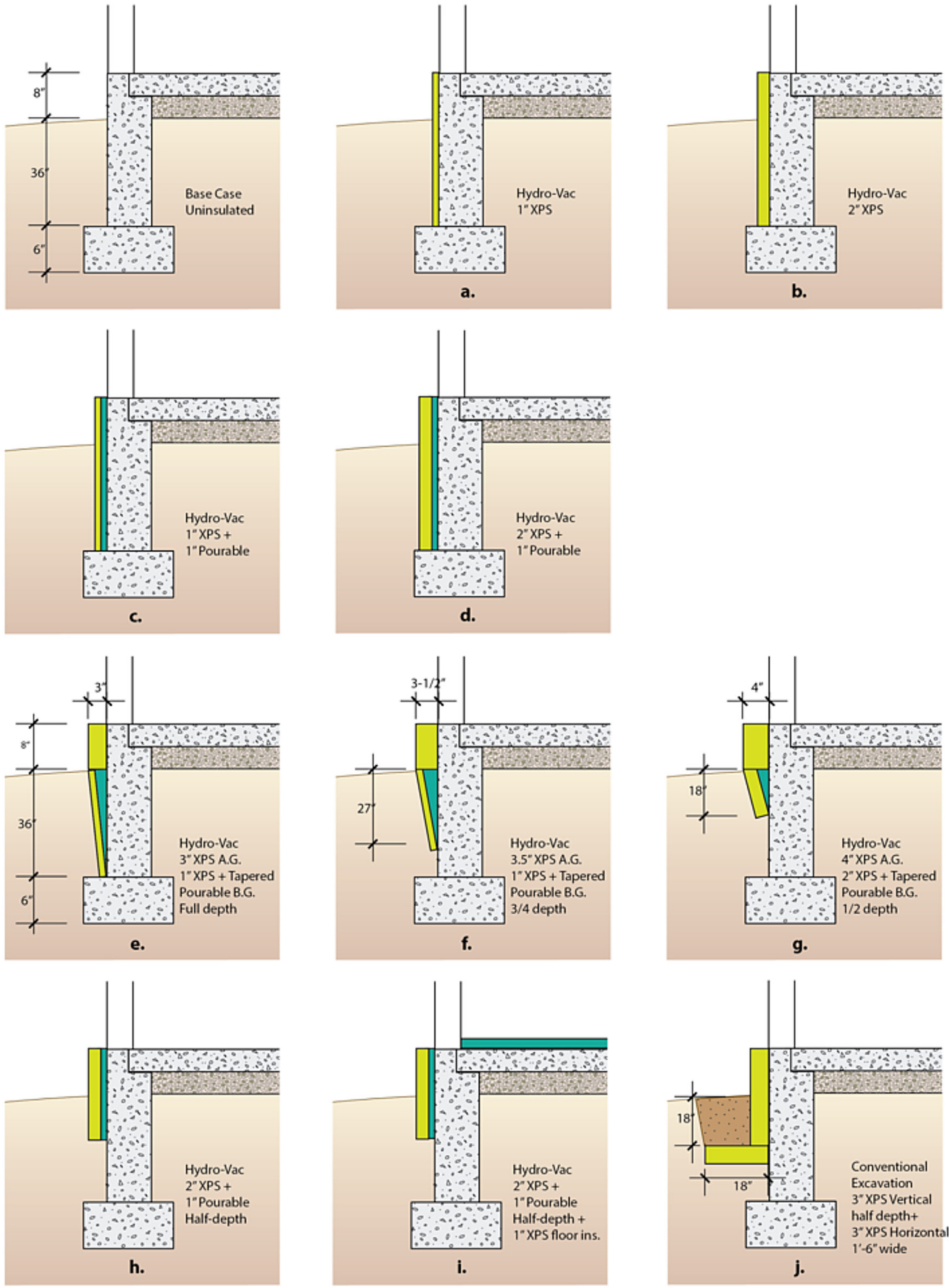


Table 6: Optimization results

Configuration[A]	Heating Season Slab Heat Flow Savings (%)	Heating Season Site Energy Savings (%)	Installation Cost ($)	Simple Payback (yr)[B]
a. vertical 1" XPS, full-wall	45.2	22.6	$1,124.35	16.8
b. vertical 2" XPS, full-wall (2012 IECC)	53.8	27.6	$1,450.09	17.7
c. vertical 1" XPS + 1" PPU, full wall	54.5	27.9	$1,762.09	21.3
d. vertical 2" XPS + 1" PPU, full wall	58.7	31.0	$2,126.64	23.1
e. tapered 1" XPS + 2" PPU, full BG wall, 3" XPS AG	58.8	33.2	$1,725.72	17.5
f. tapered 1" XPS + 2.5" PPU, 3/4 BG wall, 3.5" XPS AG	59.2	35.3	$1,534.96	14.6
g. tapered 2" XPS + 2" PPU, 1/2 BG wall, 4" XPS AG	57.6	36.3	$1,334.50	12.4
h. vertical 2" XPS + 1" PPU, 1/2 wall	54.7	31.7	$1,186.58	12.6
i. vertical 2" XPS + 1" PPU, 1/2 wall and 1" XPS slab surface	69.4	34.1	$3,128.93	31.0
j. vertical 3" XPS, 1/2 wall and 18" wide 3" XPS wing	58.2	35.0	$4,891.83	47.0

A. XPS: extruded polystyrene; PPU: pourable polyurethane; AG: above-grade; BG: below-grade

B. Including the cost of money with amortization over 10 years at 6 % per annum and an electricity cost of $0.10/kWh.

performance metric (that relates directly to the occupants' energy costs), Option g. yielded the optimum performance.

Cost models for Minneapolis, MN were developed to assess the cost-effectiveness of each strategy. Combined labor and material costs developed in Schirber, *et al* (2014) were used for the hydro-vacuum excavation and PPU foam installation and these costs are strongly related to insulation and removed soil volumes. The cost of XPS was obtained from a contractor supply house and a ten percent markup was applied to the wholesale cost. Miscellaneous labor was generally charged at three times the material cost, however, it is inferred that labor costs are going to be similar for similar operations; for instance labor costs are the same to install one-inch XPS as to install two-inch XPS.

The costs are reported in Table 6 in terms of the retrofit installation cost as well as the simple payback. The simple payback calculation assumes that the installation cost was borrowed by the building occupant using a home equity loan at 6% and amortized over a period of 10 years, thus the payback period is based on the sum of the installation costs and loan interest. The payback is determined by dividing the total cost by the annual electricity energy savings (as the optimization building included an electric furnace in compliance with the experimental building)[8]. The lowest installation cost was realized by Option a. but with 13.7% lower site energy savings than the Option g. Option h. can be installed at a small $62 premium over Option a. but with 4.6% lower site energy savings than Option g. In terms of simple payback, Option g. also demonstrated the lowest period of 12.4 years. Therefore, since Option g. allows the occupants to begin realizing net heating energy cost reductions earliest and these cost reductions are the largest of all the configurations evaluated, Option g. was selected as the optimum SOG foundation retrofit insulation installation.

8. Basing the payback on natural gas would produce lower payback periods, but would not change the relative magnitudes of these periods that are of interest for optimization purposes.

EVALUATION CLIMATES, BUILDINGS AND DATA

Building America climate zones ranging from M/H (mixed/humid, IECC Zone 4) to VC/C (very cold/cold, IECC Zone 7) were selected because of the increased likelihood of higher site energy savings from heating loads compared with warmer climates with predominantly cooling loads. The specific locations chosen in Zones 4 to 7 were based on the 2009 Residential Energy Consumption Survey published by the Energy Information Administration (US EIA, 2009). These data often combine multiple states into one statistical category, and often that category includes more than one climate zone. For these reasons, the states of Virginia (Zone 4), Ohio (Zone 5) and Wisconsin (Zone 6) were chosen. Ohio is combined with Indiana in the data, however all the major population centers are in Zone 5. Duluth, Minnesota was chosen as the largest population center in Zone 7, despite the fact that Minnesota is combined with Iowa, North Dakota, and South Dakota in the EIA data (Zones 5,6, and 7). The specific cities chosen were: Richmond, Virginia; Cleveland, Ohio; and Madison, Wisconsin. These cities are significant population centers, and therefore likely to have a large population of houses built on slab foundations.

The EIA also reports housing by foundation type using Building America climate zone designations. Overall, there are 38.8 Million housing units in the VC/C climate zones, and 35.4 million in M/H climate zones. Of these, 9 million in VC/C and 11.3 million in M/H report "concrete slabs" as the primary foundation type. This represents 23.2% of foundations in VC/C, and 31.9 percent in M/H, or 27.4% overall. These data can be correlated with other survey reports that break up the housing numbers by year of construction, again by Building America climate zones. The survey reports 113.7 million housing units in the VC/C and M-H climate zones. Of these, 33.5 million, or 29 percent, were built before 1970. Assuming the proportion of slab foundations to all houses is consistent over time, 9.2 million housing units on a slab foundation exist in these climate zones that were built before 1970. This is meaningful because it is unlikely that houses built before 1970 on concrete slab foundations included significant slab insulation, making them candidates for an insulation retrofit. Even in Minnesota, a state-level code addressing energy efficiency was not adopted until 1976 (MN DLI, 2012) In addition, materials suitable for use as below-grade insulation were generally unavailable until about the same time (Dow, 2014). It is also likely that slab foundations continued to be uninsulated after 1970, especially in warmer climates, so this estimate can be considered conservative.

Two building types were selected for evaluating retrofit SOG optimized insulation energy performance and cost effectiveness, namely:

- a single-story, single-family home
- a two-story, multi-family townhouse with two center and two end units.

The above-grade simulation models were developed using the NREL Building Energy Optimization (BEopt) tool that generates the EnergyPlus models used in the BEB simulation. All the designs enclose 1800 square feet of living space. The single-story single-family home has a footprint of 30 feet by 60 feet. The multi-family units are two-story, with a footprint of 20 feet by 45 feet. The Building America B10 Benchmark default inputs (Wilson, *et al*, 2014) that correspond with the 2009 IECC requirements were used with a few exceptions to more accurately reflect the characteristics of existing homes. In order to better reflect the target retrofit housing so as not to exaggerate the SOG insulation site energy savings, the parameters shown in Table 7 were modified.

Table 7: B10 Benchmark input modifications

Component	B10 Benchmark	Zones 4 and 5 Inputs	Zones 6 and 7 Inputs
Exterior walls	Uninsulated	R7 Fiberglass, grade 1	R7 Fiberglass, grade 1
Attic floor	R11	R19.6 Fiberglass	R25 Fiberglass
Windows	1 pane clear, metal frame	2 pane clear, non-metal frame	2 pane clear, non-metal frame
Infiltration	15 ACH50	7 ACH 50 (3 ACH 50 for multi-family)	7 ACH 50 (3 ACH 50 for multi-family)
Ducts	20% Leakage, R4, in Unconditioned Attic	Inside Conditioned Space	Inside Conditioned Space

The optimized insulation Option g. (Figure 8) was used in all climates except Richmond, VA because, here, the code-required frost depth of 18 in. including a frost footing yields a below-grade wall height (approximately 11 in.) too shallow to make excavation of an inclined trench practical. Therefore, in Richmond, two insulation options were evaluated. These comprised 4. in of XPS insulation (R_{US}-20) extending from the top of the stem wall to half- and full-wall below-grade depths.

The critical foundation simulation values for the four simulation climates are shown in Table 8 (extracted from Goldberg and Mosiman, 2015). These values are in accordance with the soil domain geometry and moisture requirements necessary for valid earth contact thermal simulation (Harmon, 2015). The Dirichlet temperature boundary condition at the base of the soil domain was taken to be the deep well water temperature[9]. These temperatures are given in Labs, et al (1988) who, in turn, sourced the data from a contour map published by the National Well Water Association (that appears to be extinct). More recent data for well water temperatures could not be found in the literature. Other than the values tabulated, the remainder of the soil domain geometry and soil properties were identical in all the climates.

The cost effectiveness of the SOG insulation retrofits were determined using the regional energy cost data shown in Table 9 that were obtained from EIA data sets (US EIA, 2014a/b).

Table 8: Critical foundation simulation values

Climate Zone	Footing Depth (in.)	Average Lowest Ground Water Depth (ft)	Depth of Water Table Beneath Footing (ft)	Height of Water Table above Base of Soil Domain (ft)	Well Water Temperature (°F)
7: Duluth, MN	60	5.33	0.33	24.67	48
6: Madison, WI	48	29.17	25.17	0.83	51
5: Cleveland, OH	42	20.58	17.08	9.42	53
4: Richmond, VA	18	6.8	5.33	23.17	60

9. Average ground water temperature data are not appropriate because they are measured too close to the surface.

Table 9: Regional average gas and electric costs

Energy Source	Ohio	Wisconsin	Minnesota	Virginia
Electricity ($/kWh)	0.1225	0.1462	0.1277	0.1208
Natural gas ($/therm)	0.92	0.84	0.80	1.14

SINGLE FAMILY HOME ENERGY PERFORMANCE AND COST EFFECTIVENESS

The energy performance results for single family homes are shown in Table 10. The annual slab heat flow savings for the optimized insulation configuration ranged from 31.4 % in Duluth to 27.4% in Cleveland. These savings decreased as the heating season climate severity decreased, as expected. The slab heat flow savings translated into modest annual site energy savings of 5.0% in Duluth declining to 3.8% in Cleveland. These modest savings are a result of a small uninsulated slab heat flow fraction (β) of 16 to 17%, that is, the share of the enclosure space conditioning load affected by the insulation retrofit was too small to yield a significant metered energy reduction.

The annual slab heat flow savings in Richmond were significantly lower at 13.8 and 16.8% for the half- and full-height insulation options respectively compared with the other climate zones owing to the relative mildness of the heating season climate. Even though the value of β was about double those of the other climates at 0.307, this was insufficient to offset the decline in the climate severity. Hence, the annual metered energy savings of 3.1 and 3.7 % for the half- and full-height insulation options respectively were less than those of the other climates.

The effect of SOG foundation insulation on cooling energy consumption is also reported in Table 10 in which the change in cooling energy consumption is tabulated for the contiguous cooling periods in each climate. In Zones 6 and 7 which are predominantly heating climates, SOG foundation insulation increases the energy consumption by 3.2% or less for the periods shown, while in Zones 4 and 5, it decreases the cooling energy consumption by up to 1.6%. Thus these data show that SOG foundation insulation can be beneficial from a cooling energy consumption perspective as well in mixed/humid climate zones.

Table 10: Single family home energy savings and simple payback with optimized insulation

Climate/Insulation Configuration	Contiguous Cooling Period	Cooling Energy Consumption Change (%)	Heating Season Uninsulated Slab Heat Flow Fraction (β)	Annual Slab Heat Flow Savings (%)	Annual Site Energy Savings (%)	Simple Payback (yr)[A]
Zone 7: Duluth, MN / Optimized	6/24 – 9/1	+3.20	0.169	31.4	5.0	45.4
Zone 6: Madison, WI / Optimized	6/23 – 8/1	+0.34	0.161	30.0	4.4	45.4
Zone 5: Cleveland ,OH / Optimized	6/8 – 9/5	-0.19	0.165	27.4	3.8	47.1
Zone 4: Richmond, VA / Half-wall	6/15 – 9/10	-1.46	0.307	13.8	3.1	35.1
Zone 4: Richmond, VA / Full-wall	6/15 – 9/10	-1.59	0.307	16.8	3.7	17.9

A. Excluding the cost of money.

With small energy savings, the simple paybacks of the foundation insulation retrofit assuming that the installation is financed on a cash basis, are not financially attractive. In climate Zones 5 and colder, the paybacks exceed 45 years. Only in Richmond are the paybacks less than 40 years with the smallest payback period of 18 years realized for the full-wall insulation retrofit.

MULTI-FAMILY HOME ENERGY PERFORMANCE AND COST EFFECTIVENESS

The energy performance results for the multi-family townhouse are given in Table 11. The results follow the same pattern as those for the single family home, except generally, with lower energy savings. The annual slab heat flow savings ranged from a maximum of 27.6% in Duluth to a minimum of 12.1% for the half-wall option in Richmond. The values of β were about 4% lower than the single family home in Zones 5-7 and 5% larger in Zone 4. However, the effect of party walls in a townhouse overrides any increase in β, so the net effect in all the climate zones is a notable decrease in metered annual energy savings compared with single family homes.

Table 11: Multi-family home (townhouse) energy savings and simple payback with optimized insulation

Climate/Insulation Configuration	End Unit Contiguous Cooling Period	Cooling Energy Consumption Change (%)	Heating Season Uninsulated Slab Heat Flow Fraction (β)	Annual Slab Heat Flow Savings (%)	Annual Site Energy Savings (%)	Simple Payback (yr)[A]
Zone 7: Duluth, MN / Optimized	6/24 – 9/2	+3.17	0.121	27.6	2.6	45.6
Zone 6: Madison, WI / Optimized	6/15 – 9/9	+0.73	0.120	27.4	2.2	46.6
Zone 5: Cleveland ,OH / Optimized	6/3 – 9/5	+0.46	0.131	25.1	1.9	47.4
Zone 4: Richmond, VA / Half-wall	6/15 – 9/29	-0.23	0.322	12.1	1.4	36.7
Zone 4: Richmond, VA / Full-wall	6/15 – 9/29	-0.22	0.322	14.7	1.7	18.5

A. Excluding the cost of money.

The site energy savings thus ranged from a maximum of 2.6% in Duluth to 1.4% for the half-wall insulation option in Richmond.

The cooling energy consumption increased in Zones 5-7 (it changed from a decrease in a single family home to an increase for the townhouse in Cleveland) and decreased only in Richmond. However, the cooling energy decrease in Richmond of 0.2% was much less than the single home decrease of 1.5 to 1.6%. The payback periods for the townhouse were slightly larger than those for the single family home (1.6 years at most). The shortest payback period of 18.5 years was also realized for the half-wall insulation option in Richmond.

OTHER BENEFITS

In addition to energy savings, foundation insulation can confer other benefits. Specifically, insulating the perimeter typically increases slab temperatures in the winter. This increases thermal comfort because a warmer finished slab surface reduces the radiant heat exchange with the bodies of the occupants. The comfort is assessed in terms of the time that occupants would not be comfortable according to the simple model of ASHRAE Standard 55-2004 as calculated by EnergyPlus (Table 12). The comfort improvement (decrease in discomfort time) as a result of SOG foundation insulation increases from 3.6% in zone 7 to 8.3% in zone 4 with full wall SOG insulation. Thus the comfort improvement increases with the warmth of the climate.

Table 12: EnergyPlus Comfort Performance

Zone: Insulation Configuration	Time Not Comfortable by Simple ASHRAE Standard 55-2004 (Hours)	Comfort Improvement (%)
Zone 7: No SOG Insulation	4,669.00	
Zone 7: with SOG Insulation	4,501.75	3.6
Zone 6: No SOG Insulation	3,979.50	
Zone 6: with SOG Insulation	3,794.25	4.7
Zone 5: No SOG Insulation	3,224.50	
Zone 5: with SOG Insulation	3,046.75	5.5
Zone 4: No SOG Insulation	2,207.25	
Zone 4: with Half Wall SOG Insulation	2,056.25	6.8
Zone 4: with Full Wall SOG Insulation	2,023.50	8.3

In addition, cold slabs can cause water vapor to condense if their temperature is below the dewpoint of the ambient air. This is especially true if carpet is installed on the slab (as was the case for the simulated buildings) because the small insulating value of carpet further depresses the slab surface temperature. In addition, carpet and pad materials block the flow of air to the slab, enhancing the tendency of the area to become wet and also offer a rich nutrient source that will support mold growth.

Figure 9 and Figure 10 show the insulated and uninsulated slab surface temperatures in the northeast corner for the single family home in Zones 7 and 4 respectively. For Zone 7 (Figure 9), the plot begins on October 17 and shows a decrease in surface temperature of

Figure 9: Zone 7 single family dwelling slab corner temperatures

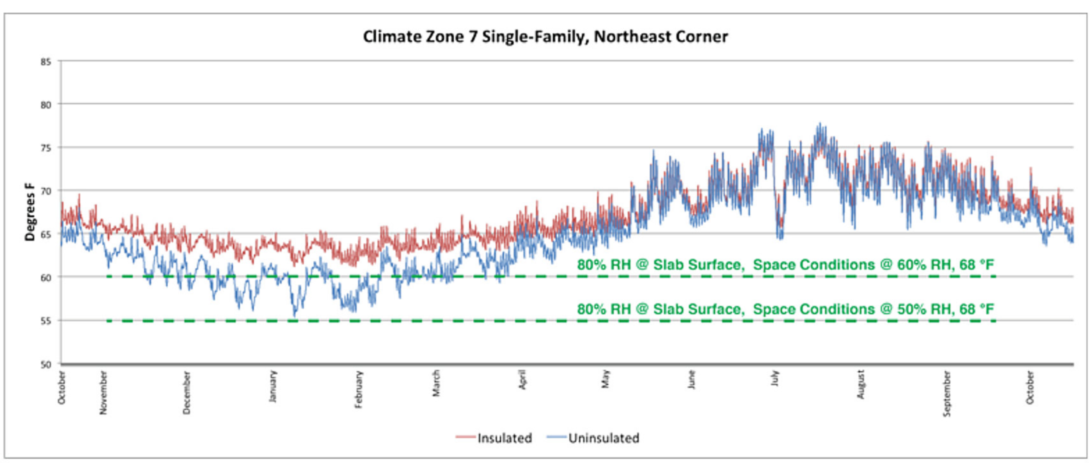
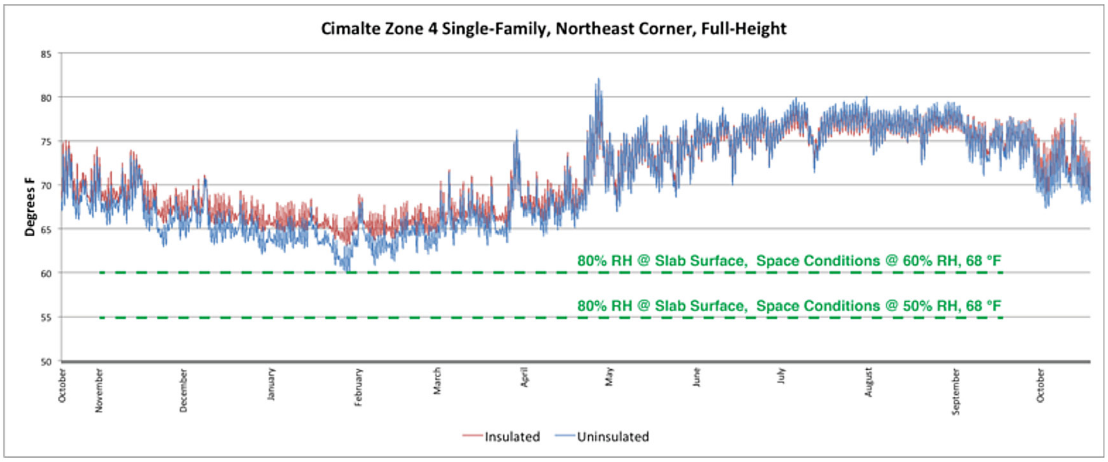


Figure 10: Zone 4 single family dwelling slab corner temperatures



up to about 5° F during the subsequent heating season resulting from the SOG foundation insulation.

In the milder heating season climate of Zone 4 (Figure 10) where the plot commences on October 19, the foundation insulation reduces the slab surface temperature by about 2-3° F at most that, while smaller than in Zone 7 as expected, is still significant from a condensation suppression perspective.

DESIGN SYNTHESIS

The simulation results for the 4 climate zones may be represented by the following approximation derived by multivariate analysis of the full simulation data set (Goldberg and Mosiman, 2015):

$$(1-\gamma i) \approx \beta u\,(1-\sigma i) \qquad (2)$$

where:

γi= <insulated SOG foundation site energy>/<uninsulated SOG foundation site energy>
βu= <uninsulated SOG slab heat flow>/<uninsulated SOG foundation site energy>
σi= <insulated SOG slab heat flow>/<uninsulated SOG slab heat flow>

The approximate values of β_u required to achieve a nominal 10% site energy savings for single and multi-family homes based on the average computed values of σi using the SOG foundation insulation systems evaluated is shown in Table 13.

Table 13: Approximate values of β_u for 10% site energy savings

Building	Zones	Average computed σ_i	Approximate β_u
Single family	5 - 7	0.771	0.44
Single family	4	0.888	0.89
Multi-family	5 - 7	0.735	0.38
Multi-family	4	0.866	0.75

These data show that 10% site energy savings become possible in Zones 5 to 7 when the uninsulated slab heat flow is at least 38% of the site energy consumption. This means that occupant lifestyle energy impacts and the thermal integrity of the above-grade enclosure (mainly thermal insulation and infiltration) must consume no more than 62% of the site energy before SOG foundation insulation may be considered as a reasonable option from an energy savings perspective. In Zone 4, the threshold is more severe so that SOG foundation insulation becomes viable in energy savings terms when the above-grade enclosure and occupant lifestyle energy consumption is no more than 11 and 25% of the site energy for single and multi-family homes respectively. If occupant lifestyle effects are ignored, then achieving the required levels of enclosure thermal integrity may only be possible in houses that have well-insulated above-grade enclosures.

CONCLUSION

The simulation results paint a very different view of SOG foundation insulation thermal performance than previously reported by Labs, et al (1988). The results show that SOG foundation insulation yields positive annual energy savings in climate Zones 4 -7 rather than the negative savings previously reported. However, in a candidate retrofit home complying with the 2009 IECC energy code, the expected annual site (or metered) energy savings from a SOG foundation insulation retrofit are modest, ranging from 5% for a single family home in Duluth, MN to 1.4% for a 4-unit townhouse in Richmond, VA. A meaningful annual site energy savings of 10% or more from an optimized SOG foundation insulation retrofit requires an above-grade enclosure with a very high thermal integrity that likely only can be realized in well-insulated homes.

The results also show that standard 2012 IECC code-required SOG foundation insulation is not optimum in terms of energy performance. The optimized foundation insulation configuration developed for climate Zones 5 – 7 was shown to yield 8.4% greater heating season energy savings at a 24 % lower installation cost than the 2012 IECC configuration in Minneapolis, MN. SOG foundation insulation also yields improvements in occupant comfort and moisture durability as it increases the slab surface perimeter temperature in all the climates evaluated.

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