Field Testing of External Foundation Insulation

J. M. Lacy, Idaho National Engineering and Environmental Laboratory
G. A. Twitchell, Mid-America Manufacturing Technology Center
R. G. Kobbe, University of Wyoming

ABSTRACT

In order to mitigate indoor moisture problems, it is now recommended that basement and crawlspace walls be insulated on the outside face, rather than from the inside. Previous studies of energy savings from foundation insulation have produced variable results, with interior insulation outperforming that on the exterior, and overall savings less than predicted. To further examine the effectiveness of exterior insulation, a field experiment was conducted to examine the side-by-side thermal performance of a buried concrete crawlspace foundation with and without rigid insulation board installed on the exterior. The experiment emphasized measurement of the temperature profile along the heat conduction path from the living space to the exterior soil.

A heated, insulated box was constructed along one wall of an existing building to simulate the living space of a home. The crawl space beneath the living space was divided into two sections. One featured external foundation insulation, while the other side had none. 36 temperature and heat flux sensors were installed to measure the temperature profile and heat flow out of the living space. Temperature data was then acquired continuously from December 2002 through May 2003. The temperature profile through the foundation was then used to calculate the total heat flow out of the foundation for both cases.

Heat flux calculated from the collected temperature profile data showed energy savings from exterior foundation insulation consistent with expectations, providing a factor of 3 reduction in the heat loss through the foundation wall. This result supports previous explanations of "missing energy savings" determined in earlier studies.

This study makes one of several possible comparisons among foundation insulation schemes. Recommendations are made for future studies to compare various floor and foundation insulation schemes for cold climates with respect to both heat and moisture flux.

Background

While insulation of basement and crawlspace walls is necessary for a warm and energy efficient home, the common practice of insulating the inside face of the foundation wall can lead to serious moisture-related problems (Yost 2003). Issues can range from a damp, moldy smell, to decay of wood structural members in the basement wall. The fundamental cause of these troubles is that they create a cool concrete foundation surface exposed to warm moist room air on one side, and cool moist soil on the other. Thus moisture from the room air tends to condensate on the concrete surface. If a moisture barrier is placed anywhere in the wall to prevent room air from reaching the concrete, then any moisture that may get into the wall has no path to dry to, and is trapped.

A solution to this dilemma, as detailed in the EEBA Builder's Guide (Lstiburek 2001), is to place insulation on the outside of the foundation wall, rather than the inside. Previous studies of the energy performance of foundation insulation in general, and exterior foundation insulation in particular, have reported variable and lower-than-predicted performance.

Moody et al (1983, 1985) studied the heat transfer through the floor of occupied homes for insulated (interior) and uninsulated crawlspaces in Murfreesboro, TN. Each home was instrumented with two heat flux transducers and a single hygrothermograph to measure the crawlspace temperature. The measured heat flux through floors over insulated crawlspaces was much less than that predicted by a steady-state heat flux calculation. Several possibilities for this anomalous result were presented, with a recommendation for further study to measure the temperature gradients through the crawlspace to determine if heat were supplied to the crawlspace from the earth.

Quaid and Anderson (1988) tracked the energy usage of 15 occupied homes in the Minneapolis area retrofitted with basement insulation. Eight homes employed interior foundation insulation, five used exterior, and 2 used a combination of both due to the presence of obstacles. Whole-house energy consumption before and after the retrofits was tracked and compared. The results showed interior insulation to be 50% more effective than exterior insulation. This was attributed to several factors, including depth of the exterior insulation, obstacles around the foundation perimeter, and home size. Actual savings were approximately three-fourths the predicted value.

Robinson et al. (1990) followed Quaid with a similar study that controlled the effects of reduced foundation air leakage. The study measured the change in overall energy consumption before and after retrofit for homes with full basements. Temperature data was not included in the study. By removing the effects of air leakage from the data, the apparent performance of the foundation insulation was reduced. Though widely variable, the average savings was reported to be about one-third of that predicted.

Both Quaid and Robinson reported that performance retrofits employing exterior insulation to be significantly lower than predicted. Though both supposed that this result was a simple function of the wall area insulated (exterior retrofits did not extend to full depth) the impression remains that it is not effective to apply foundation insulation to the exterior.

Purpose

The goal of this study, sponsored by the State of Wyoming's Energy Programs Office, was to re-examine the thermal performance of exterior crawlspace insulation relative to an uninsulated foundation. In contrast to previous studies, which measured whole-house energy consumption of occupied homes, the emphasis of this effort was placed on measurement of the temperature profile along the conduction paths to the outside air and soil, with controlled, constant input temperature.

Previous studies identified in the literature were performed in significantly milder and more humid climates than that of Wyoming. Therefore, though economic considerations were secondary to the study, energy savings were estimated for a average new Wyoming home.

Experimental Method

A heated, insulated box was constructed along one wall of an existing, unheated building to simulate the living space of a home. For simplicity's sake, no moisture load was introduced for this phase. The "living space" dimensions were approximately 24 ft. long, by 12 ft. wide, by 4 ft. tall. The low height reduced construction and heating costs without affecting on the measurements of interest.

The crawl space beneath the living space was divided into two sections approximately 12 feet square. One half featured external foundation insulation installed as recommended by the EEBA Builder's Guide, and the Builder's Foundation Handbook (Carmody et al, 1991) while the other side had no foundation insulation. The divider between the two sides was insulated to prevent thermal communication between them. The ceiling and walls of the living space/ crawl space unit were insulated to minimize heat loss and maintain a constant temperature of 22°C (72 °F) within the living space.

36 temperature and heat flux sensors were installed at predetermined locations to measure the temperature profile and heat flow out of the living space. Detailed temperature and heat flux data in the crawlspace and through the foundation provided information necessary to directly compare the heat flow between the insulated and uninsulated sides. These energy loss differences were then extrapolated to the foundation of a full-size home to predict the energy savings associated with the exterior foundation insulation.

Facility

The experiment was conducted at the INEEL's Severe Weather Test Site, near Arlington, Wyoming. This test site is ideal for evaluations of the structural and energy performance of housing structures due to its naturally occurring high winds (in excess of 90 mph annually), and temperature extremes (-34° to +32°C). Although remote, the site has been outfitted with electrical power and propane, telecommunications for voice and data transmission, and a 10 m meteorological tower monitoring wind, temperature, barometric pressure, and relative humidity. 160 channels of data are available to measure meteorological, structural and energy flow parameters on the two currently installed test structures. Figure 1 is a photograph of the site.

Figure 1. The INEEL Severe Weather Test Site

This test was performed in the Simpson Strong-Tie Building, an uninsulated, unheated wood structure 24 ft wide by 24 ft. deep. The building rests on a 2.5 ft. deep foundation, with a gravel floor.

Test Space Layout

Figure 2 shows the concept of the test layout, which is divided into 6 thermal spaces as follows:

Area 1. Crawl space, insulated, unheated
Area 2. Crawl space, uninsulated, unheated
Area 3. Living space, insulated, heated
Area 4. Building balance, uninsulated, unheated
Area 5. Outside air
Area 6. Outside soil

Heat flows from Area 3, the heated living space, through parallel paths through the other enclosed spaces, to the sinks of the outside air and soil. The outside air and soil are considered separate sinks since the air temperature experiences large magnitude daily variations, while the soil temperature is more stable. Sensors were placed along each heat flow path from Area 3 to Areas 5 and 6 in an attempt to monitor the overall heat balance.

Three distinct thermal conditions were measured over the course of the experiment. First, the system was monitored with no heat input into the system. This provided a baseline to which the other cases may be compared, and allowed for compensation of the temperature sensors, if necessary. Second, the living space was heated to a constant 22 °C (72 °F) with 6 inch batt insulation in the floor between the living space and crawl space. Finally, the floor insulation was removed, providing a relatively high conductivity path from the living space to the crawl space.

Sensors

The sensor suite included 34 temperature transducers and 2 heat flux sensors to monitor the heat flow and temperature gradients in and around the test space, with detailed measurement through the foundation and into the surrounding soil.

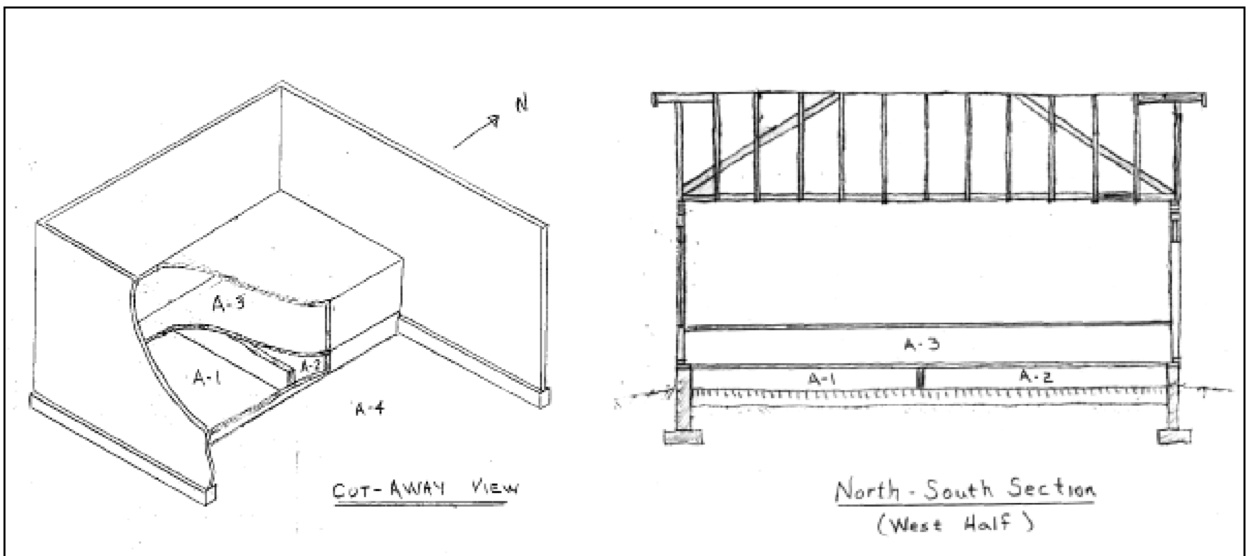

Figure 2. Schematic of Test Space Layout

Sensors were located in the test structure as illustrated in Figure 3. This sensor layout was developed to

- Reduce or remove uncontrolled variables. Given the orientation of the test space in the building, a layout was chosen to minimize the variability of solar heating, wind, and snow accumulation on the different sensor lines.
- Reduce susceptibility to single-point failures. Because the experiment spanned a complete winter, the likelihood of failure of individual sensors was an issue for consideration. Given the location of the test site, failed sensors could not have been repaired once winter set in. The layout employed provided some redundancy in the case of one or more sensor failures.
- Measure 2-dimensional cross-flow effects. A single sensor line perpendicular to the surface of interest assumes, by default, the surface to be infinite, with no component of heat flow orthogonal to the sensor line. With multiple parallel lines of sensors, cross flow such as that caused by differential solar heating could be identified.
- Measure heat flow through all paths. Sensors were placed such that heat flow through the ceiling, walls, and earth could be accounted for in the total energy balance of the test space, if desired.

In addition to the sensors installed in the Simpson Strong-Tie building, the experiment had access to a full suite of local meteorological data (wind, temperature, barometric pressure) being gathered continuously at the site.

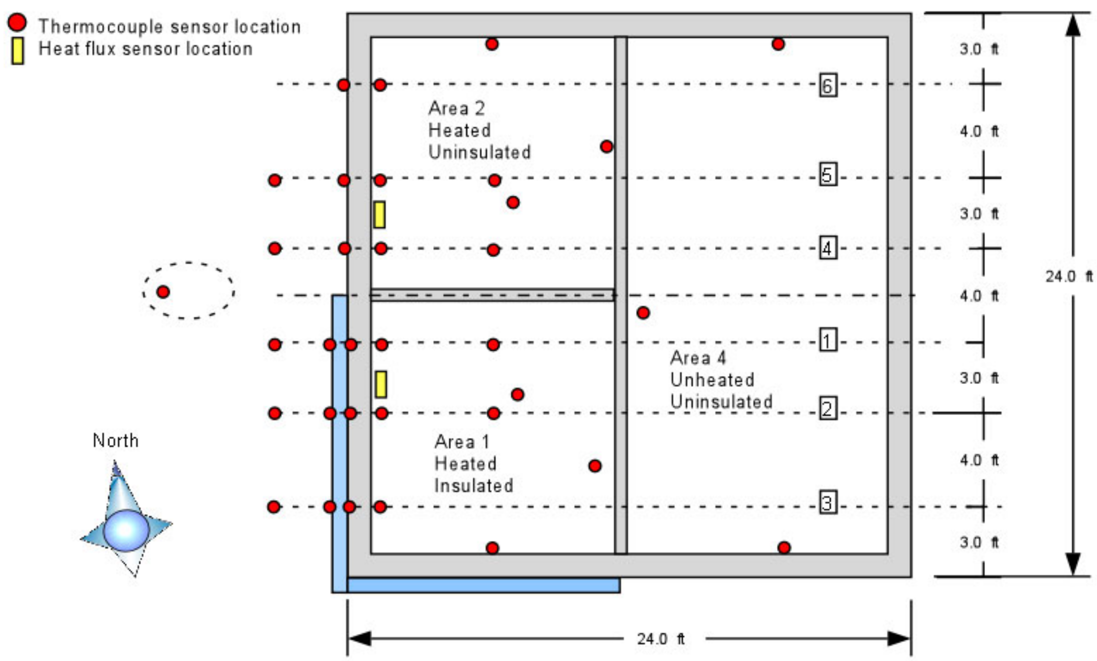

Figure 3. Sensor Layout

Calculation of Energy Flow Through the Foundation

Conductive heat flux through a given medium may be given by the equation

$$q = \frac{k}{t}(T_1 - T_2) \qquad (1)$$

where q is the heat flux in watt/meter^2 (or BTU/ft^{2}hr); t is the distance between two points of measurement 1 and 2; k is the thermal conductivity of the material in watt/m*K (or BTU/hr*ft*°F); and T_1 and T_2 are the temperatures at the two points 1 and 2.

Then for materials with well-characterized thermal conductivities, such as insulation board, the heat flux may be directly determined from the representative surface temperatures. Total heat flow through a wall is then the heat flux q times the area of the wall.

Because sensors were installed on both surfaces of the concrete, as well as both surfaces of the insulation and in the soil, it was possible to compare the computed fluxes along each line of sensors to determine the actual conductivity of the concrete, insulation, and soil. Evaluation of thermal gradients in the soil along the length of the foundation showed that 2-dimensional effects outside the foundation could be neglected.

Results

The test space was constructed with all sensors in place and taking data by mid-December. With a month of baseline unheated data recorded, we began heating the system on January 20. On February 19, the floor insulation was removed to record the heat flow in the third condition (no insulation between floor and crawl space). Only one temperature sensor failed over the course of the experiment, and that occurred within weeks of initial installation, before heat was applied to the living space. That sensor was replaced without affecting the quality of the subsequent data.

The system was monitored and recorded continuously from December 20, 2002, through May 19, 2003. Of that time, the 3 months between February 16 and May 19 were of the primary thermal condition of interest. During that period, the system was set up to most closely reflect the heat flow through a typical inhabited home. The following sections present data gathered and its interpretation.

Temperature Histories

Figure 4 traces the temperature of the outside air 2 inches away from the west wall of the test building, above the sensor lines on the foundation. The figure shows daily temperature swings as large as 30 °C. This large cycle amplitude is due to solar heating of the west wall in the late afternoons. High temperatures due to insolation are of short duration, spanning approximately 2 hours from heat up to cool-down. Therefore the lower edge of the trace more accurately reflects the average air temperature experienced by the soil and foundation wall, though heating of the system in those few hours per day cannot be ignored. Including the effect of solar heating on the wall surface, the air temperature ranged from a minimum of –29 °C on 27 February, to a maximum of 35°C on 10 April.

The temperature of the ground was naturally much more stable, as may be seen in Figure 5. This figure shows the temperature of the soil 24 in. below the ground surface and 12 in. away from the foundation, averaged over 5 stations along the length of the foundation wall. Individual ground temperature traces are tightly clustered, and do not show any significant influence from the foundation. Nor was there a significant thermal gradient along the length of the wall. This fact allows us to approximate the heat transfer through the foundation system as 1-dimensional in our analysis. The ground temperature reached a minimum of -1°C in mid-February, climbing to 9°C by mid-May.

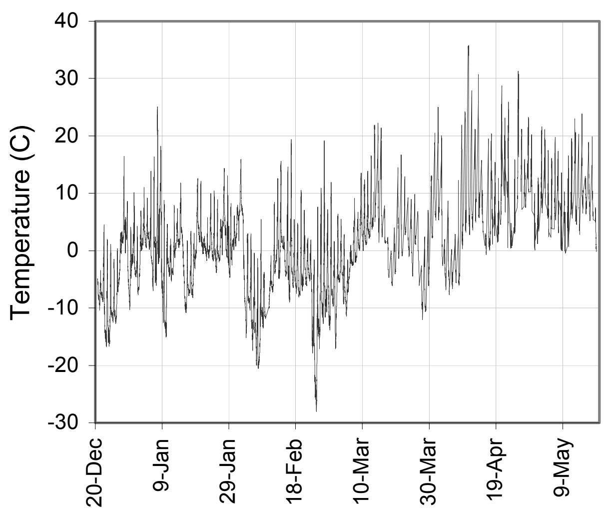

Figure 4. Air Temperature History, West Wall

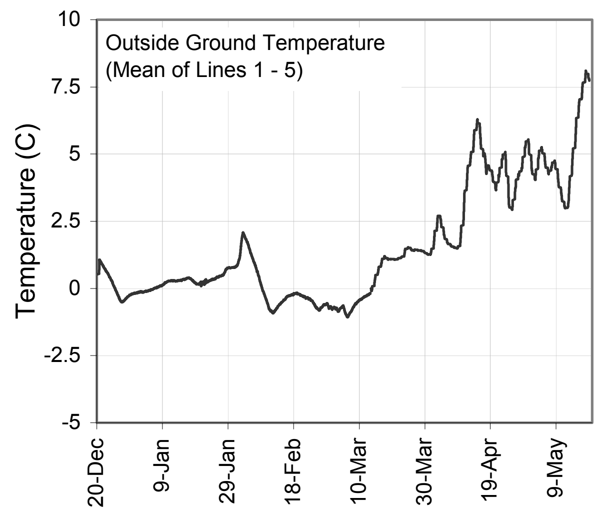

Figure 5. Outside Ground Temperature History

The next two Figures, 6 and 7, trace the temperature of the inner and outer faces of the concrete foundation wall 24 in. below the soil surface. The effect of the insulation is apparent here, especially on the outer foundation face where the insulated side stayed as much as 2°C warmer than the non-insulated side.

The final temperature trace, in Figure 8, is of the soil temperature in the crawlspace 18 in. below the surface, in each of the two halves. It would be expected that the insulated crawlspace soil would be warmer than the non-insulated side, which is indeed the case for most of the record. However, for a period of approximately a month between 10 March and 10 April, the non-insulated half was the warmer of the two. A satisfactory explanation of this switch has not been determined.

Temperature Profile

Figure 9 is a snapshot of the temperatures along the conduction path from the living space to the outside air and soil. The plot represents the 24-hour mean temperature from 11:00 am February 27 to 11:00 am February 28. Each bar cluster represents a location along the conduction path, with the individual bars the temperature on one of the lines described in Figure 3. Not all lines are represented at every point because lines were not fully instrumented at every location. As an example, only one sensor was employed in each of the two crawlspace areas to measure the temperature below the surface. Thus only two bars display the crawlspace soil temperature. Similarly, as there can't be a data point on the outside surface of insulation on the non-insulated side.

The thermal conductivity of concrete is dependent upon its constituent materials, void fraction, and moisture content. Because the thermal properties of rigid foam insulation board are constant and have been well characterized, we may use the thermal profile information to refine

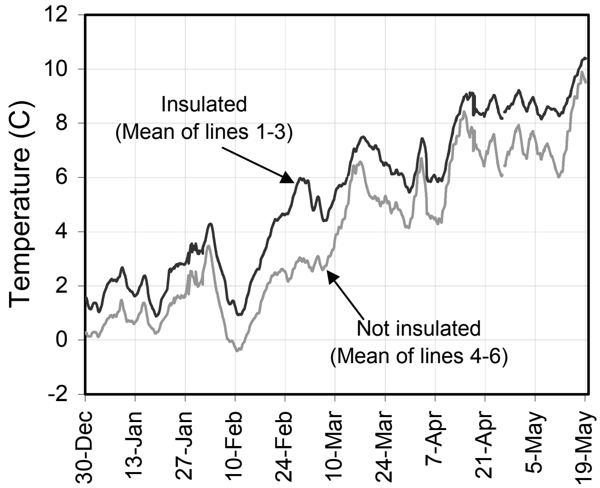

Figure 6. Temperature History of the Foundation Interior Surface

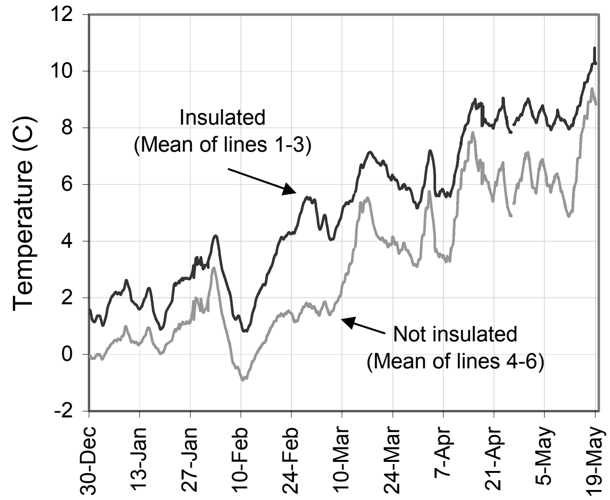

Figure 7. Temperature History of the Foundation Exterior Surface

our estimate of the thermal conductivity of the concrete foundation wall. This value will be utilized for our subsequent heat flux analysis.

Given a 1-dimensional heat flow assumption (validated by the temperature profiles as discussed previously), the flux through the insulated foundation concrete must equal that through the insulation, or

$$q = \frac{k_{concrete}}{t_{concrete}} * \Delta T_{concrete} = \frac{k_{insulation}}{t_{insulation}} * \Delta T_{insulation} \qquad (2)$$

rearranging, we solve for the concrete's conductivity

$$k_{concrete} = k_{insulation} * \frac{t_{concrete}}{t_{insulation}} * \frac{\Delta T_{insulation}}{\Delta T_{concrete}} \qquad (3)$$

If we wish to use R-value notation, we note that R-value is simply material thickness divided by conductivity. Substituting the insulation board R-value of 10, concrete thickness of 8 in. (0.67 ft.)., and averaged temperature differentials across the concrete and insulation of .47°C (0.85°F) and 4.57°C (8.23°F) respectively, we find

$$k_{concrete} = \frac{t_{concrete}(ft)}{R_{insulation}} * \frac{\Delta T_{insulation}}{\Delta T_{concrete}} = 0.652 \frac{BTU}{\circ F \cdot Ft \cdot Hr} \quad (4)$$

This value agrees well with the range of 0.54 (dry) to 0.70 (10% moisture) for concrete published by Kreith (1965).

Foundation Heat Loss

Flux

Figure 10 shows the time history of the heat flow through the foundation wall over the course of the winter. These values were calculated via equation (1), employing the conductivity of the concrete foundation calculated via equation (4), with the difference between the temperatures of the inner and outer concrete surfaces. The two curves represent the mean of the inner and outer foundation wall sensor groups as shown in Figure 3.

Two vertical lines on the heat flux traces demarcate the three thermal conditions we monitored—first, unheated; second, heated with the living space floor insulated; and third, heated with no insulation between the floor and crawlspace. This state was of primary interest as it drove the most heat through the foundation wall. The three conditions are clearly distinct from one another in the figure. In phase one, where no heat is added to the system, only a very small heat flux is apparent. This is caused by solar heating of the enclosed building system relative to the exposed ground. After heat was applied to the living space, the gap between the insulated and non-insulated lines increased somewhat, but the presence of the floor insulation kept the flow of heat into the crawlspace and foundation to a minimum.

When the floor insulation was removed in late February, the difference in heat flux through the two sides became quite distinct. In the 14 days after the floor insulation was removed, the heat flow out of the non-insulated foundation wall climbed from 2.5 watt/m^2 to 7 watt/m^2, while the insulated side climbed from 0.5 watt/m^2 to as much as 3 watt/m^2.

In general, the flux through the non-insulated foundation is approximately 3 times greater than that on the insulated side.

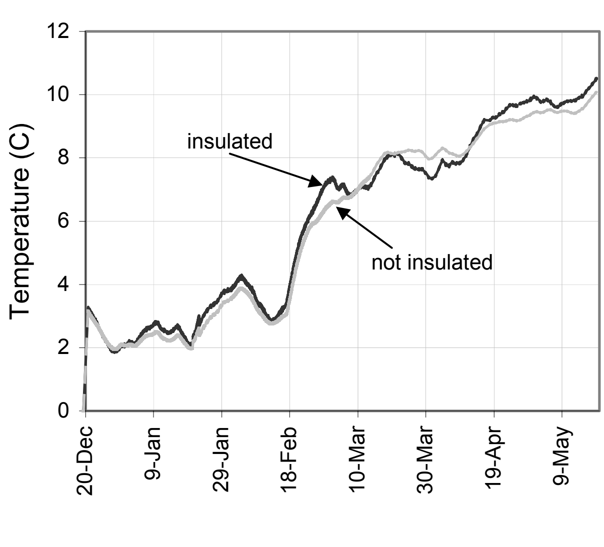

Figure 8. Crawlspace Soil Temperature History at 18in. Depth

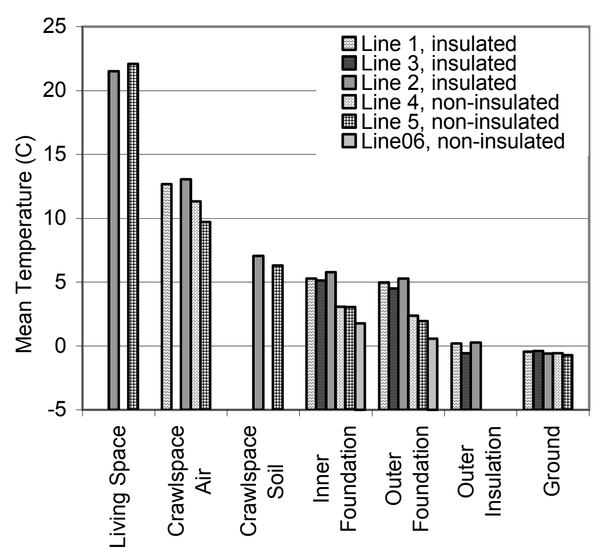

Figure 9. Temperature Profile through the System, February 27

Cumulative Effects

The cumulative energy flow through the foundation wall over the course of the season is presented in Figure 11, showing the cumulative energy loss expressed in terms of kilowatt-hours/square foot of foundation wall. This value was obtained by integrating the heat flux over time.

By the time the data recording system was turned off in mid-May, the difference in heat loss between the two sides was 1.24 kilowatt-hours per square foot of foundation wall, for a ratio of 2.97:1. To relate this value to home use, we postulate a single-story, 2200 sq. ft home. It includes some architectural features such as reentrant corners, and thus its 4-ft. deep foundation encompasses a perimeter 200 ft. in length. For such a home, the calculated foundation heat flow differential would amount to a savings of 990 kW-hrs over just the 3 months that the living space was heated, or 330 kW-hrs per month.

Conclusions

This experiment stepped back from whole-house energy measurement to compare the heat flux through insulated and uninsulated crawlspaces, and verify the fundamental efficacy of exterior foundation insulation for the cold climate of Wyoming. The temperature profile data presented herein is consistent with expectations, showing heat flux through the foundation wall with 2-inch thick (R-10) rigid insulation board to be approximately one-third that of a bare concrete wall. This translated to a savings of 1.24 kW-hrs per square foot of crawlspace wall per month. No additional information to explain lower-than-expected performance of exterior insulation retrofits reported previously was identified.

Recommendations for Further Study

This study is only the first of several appropriate comparisons. The thermal characteristics of other insulation schemes, including floor insulation without foundation insulation and interior foundation insulation should be evaluated. In addition, the moisture and

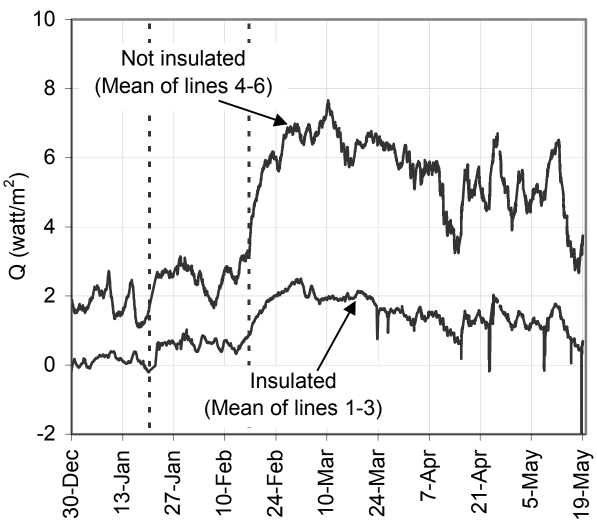

Figure 10. Seasonal Heat Flux Through the Foundation Wall

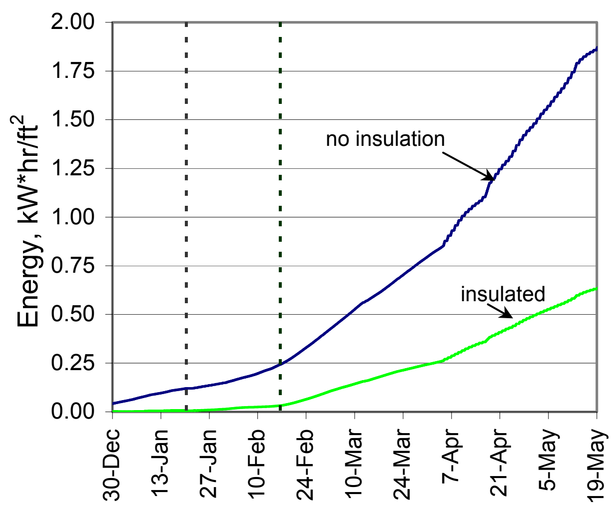

Figure 11. Cumulative Energy Flow Through Foundation, per Square Foot of Foundation Surface

air transport properties of the different schemes should be quantified and evaluated with respect to the requirements imposed by the climate of Wyoming. A comprehensive crawlspace performance study, such as that described by Davis and Warren (2002) in North Carolina, but specific to the cold climate of the intermountain west, would be most instructive.

Acknowledgements

The authors would like thank the staff of the Wyoming Business Council's State Energy Program for their support, along with W. D. Richins, T. K. Larson, J. E. Blakely, and A. L. Crawford of the INEEL Severe Weather Test Site for their invaluable assistance at all phases of this project. We would also like to thank Simpson Strong-Tie Company, Inc., whose generous donation of the test building made this effort possible.

References

Carmody, J., J. Christian, and K. Labs. 1991. *Builder's Foundation Handbook*, ORNL/CON-295, Oak Ridge National Laboratory.

Davis, B, W. E. Warren, S. Fitzpatrick, C. Maurer, and T Brennan, 2002. *A Field Study Comparison of the Energy and Moisture Performance Characteristics of Ventilated Versus Sealed Crawl Spaces in the South*. Advanced Energy, Raleigh, NC. Feb. 28.

Kreith, F., 1965. *Principles of Heat Transfer, 2nd Ed.*, International Textbook Company, Scranton, PA,.

Lstiburek, J. 2001. *Builder's Guide, Cold Climates*, Energy and Environmental Building Association, January.

Moody, T. L., C. W. Jennings, and D. Lamb. 1983. "Effect of Insulating Crawlspace Walls in Residential Structures," *Thermal Performance of the Exterior Envelopes of Buildings II*, Atlanta, ASHRAE.

Moody, T. L, C. W. Jennings, and W. C. Whisenant. 1985. "Heat Loss and Gain through Floors above Crawlspace Walls," *ASHRAE Transactions*, Vol. 91, pt 2B, pp 623-639.

Robinson, D. A., L. S. Shen, G. D. Nelson, M. J. Hewett, M. T. Noble, and L. F. Goldberg. 1990, "Cold Climate Foundation Insulation Retrofit Performance," *ASHRAE Transactions*, Vol. 96, pt. 2, pp. 573-579.

Quaid, M. A., and M. O. Anderson, Jr., 1988, "Measured Savings for Foundation Insulation of Minneapolis Single Family Homes," *ACEEE 1988 Summer Study on Energy Efficiency in Buildings*, Vol 1., p. 118.

Yost, N., and J. Lstiburek. 2003. *Basement Insulation Systems*, www.buildingscience.com.