

Real-time measurement of building envelopes to improve U-value characterization

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Abstract

Approximately 40% of total US energy consumption in 2016 was attributed to commercial and residential buildings. In comparison with other building systems, energy is most heavily consumed by systems regulating thermal comfort. Thus, building energy consumption is strongly related to the thermal performance of building envelopes. Architects, engineers and owners have utilized energy modeling and simulations as a way to predict future energy consumption for new and existing buildings. Energy models are also used to evaluate the change in potential energy consumption when comparing multiple design options. Most building energy modeling software utilizes material properties databases for individual envelope components and calculates an assembly overall heat transfer coefficient, known as the U-value. For historic buildings the use of materials from existing databases may be inaccurate, since the actual assembly and materials may be unknown or may not have been previously tested. Low-cost non-destructive in-situ testing can be performed to determine actual U-values for existing building envelopes. Heat flux sensors, thermocouples and air temperature sensors can be used to measure real-time heat flow through building envelopes. These measurements can be used to calculate the transient U-value of the envelope assembly. Although most databases provide a static U-value for an assembly, the actual U-value of assemblies can vary over time in relation to indoor and outdoor temperatures. When measuring in-situ U-values, time averaging can be used to develop a baseline for energy modeling purposes. This paper presents research regarding the determination of in-situ U-values for two historic buildings using heat-flux sensors and time-averaging methods. The results of the study are compared with typical database U-values and show that there is a significant range and difference between the in-situ values and those that might be typically used in energy models. Energy simulations were performed for both the typical and in-situ cases to understand the difference and impact on predicted energy consumption.

Keywords: energy modeling, simulation, in-situ testing, heat flux, U-value

1.0 Introduction

Building energy consumption and indoor environmental comfort are often closely related to the material properties and assembly configurations of building envelopes (Echenagucia et al. 2015). Approximately 40% of total US energy consumption in 2016 was attributed by the US Energy Information Agency (2016) to commercial and residential sectors (mostly building related). In comparison with other building energy uses, site energy is most heavily consumed by systems regulating thermal comfort (space cooling 10% and space heating 37%) (Energy 2010). The building envelope is usually designed to provide protection and separation of indoor spaces from the exterior climate. Heat gain and heat loss between in the indoor and outdoor environments is directly influenced by the thermal resistance of the materials in the envelope assemblies. The thermal resistance of building materials is commonly referred to as the R-value (IP units: $\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$, SI units: $\text{m}^2\cdot^\circ\text{K}/\text{W}$). Generally a material with a higher R-value has greater resistance to heat flow. Building envelope insulation is typically installed in envelope assemblies to increase the resistance to heat flow, improve thermal comfort and reduce energy consumption. The reciprocal of resistance is conductance. The U-value for an envelope assembly is known as the overall heat transfer coefficient and provides a metric for the overall conductance of the envelope (IP units: $\text{Btu}/(\text{h}\cdot\text{ft}^2\cdot^\circ\text{F})$, SI units: $\text{W}/(\text{m}^2\cdot^\circ\text{K})$). Generally a high R-value, low U-value assembly is desirable to reduce heat flow through the building envelope.

Architects, engineers and owners often select materials for building envelopes based on expected thermal properties. To estimate the impact of envelope material choices on energy consumption, energy models have been used to simulated annual outcomes. When developing the models for the simulations, most commercially available energy modeling software will require the user to either input the thermal properties of the envelope materials or ask the user to select known materials from a database. There are at least two known issues with this practice. First, is that the resistance values for most building materials may change

depending on moisture content and temperature (Kumaran 2002a). Second, is that the resistance values that are often quoted in databases typically do not provide characterization of statistical variation due to installation quality, material non-uniformity, and degradation. For historic buildings there also may be the difficulty that the precise assembly materials may not be known and/or that the materials used in the assembly do not have published material properties for thermal analysis. Many historic building envelopes lack modern insulation materials and as such have lower overall thermal resistance. Energy models of envelopes that have lower thermal resistance values can have greater sensitivity to error since small absolute value changes in thermal properties can have a large proportional impact on the calculated heat flow and energy consumption results. For instance, if a modern wall assembly with insulation has an estimated R-value of 20 h·ft²·°F/Btu, then a mischaracterization of 0.5 h·ft²·°F/Btu will only change the R-value by 2.5%. For a historic envelope assembly with an estimate R-value of 3 h·ft²·°F/Btu, a 0.5 h·ft²·°F/Btu error would represent a change of 16.7%. Since heat transfer through building materials is directly related to conductivity (thus inversely related to R-value), mischaracterization of the thermal properties can have a significant impact on estimated results.

1.1 Testing Methods

Most modern commercially available building envelope materials that have published thermal properties have been tested in a laboratory using ASTM C1363 (*Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*) (C1363 2011) and ASTM C177 (*Steady-State Heat Flux Measurement and Thermal Transmission Properties by means of the Guarded-Hot-Plate Apparatus*) (C177 2013). Both of these tests are primarily focused on determining properties under steady state conditions meaning that the simulated indoor and outdoor climate conditions are held steady and are not intended to represent fluctuating environmental conditions. Both of these test also require that the material and/or assembly can be isolated in a controlled chamber so that the heat energy input to the testing apparatus is precisely known and can be used to calculate the heat flow rate through the material(s). Figures 1 and 2 show schematics of the testing apparatus used in ASTM C1363 and C177.

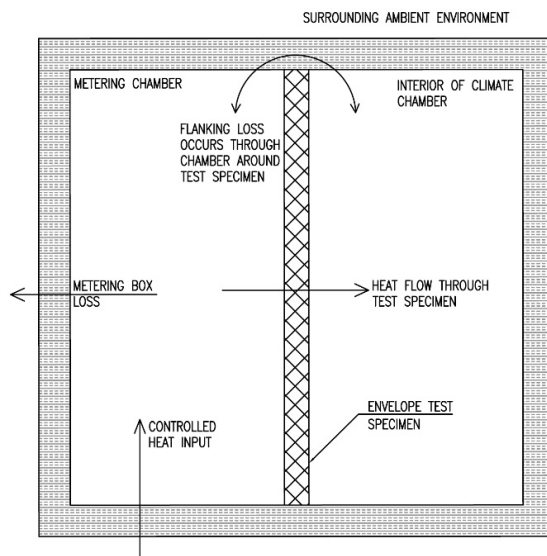


Figure 1. Schematic of Hot Box (C1363 2011) (C177 2013)

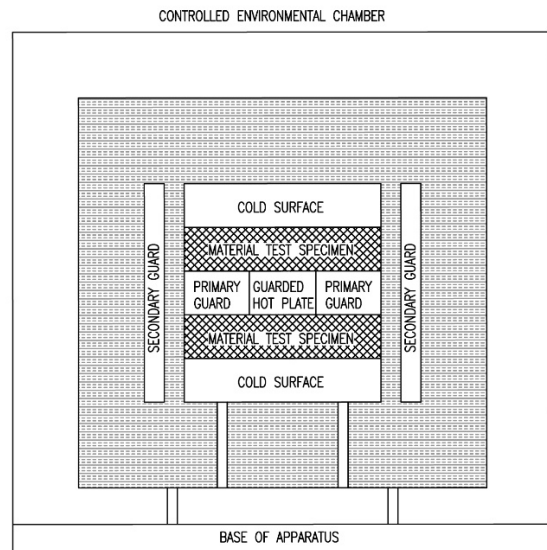


Figure 2. Schematic of Guarded Hot Plate

The basic equation that relates the heat flow rate (due to conduction) to a material's thermal conductivity is based on Fourier's law of heat conduction. This can be expressed as:

$$q = -\lambda A \frac{\partial T}{\partial x} \quad (1)$$

q is the total heat transfer (W)
 λ is the material conductivity (W·m⁻¹·K⁻¹)
 A is the surface area (m²)
 T is the temperature (°C)
 x is the thickness (m)

And since the conductance of the material, $U = -\lambda / \partial x$ then equation 2 can be rewritten as:

$$q = -UA\partial T \quad (2)$$

U is the overall heat transfer coefficient ($\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$)

This can also be rewritten in terms of the heat flux which is the heat transfer over the surface area:

$$U = \frac{Q}{|T_1 - T_2|} \quad (3)$$

Q is the heat flux ($\text{W}\cdot\text{m}^{-2}$)
 T_1 is the surface temperature on side 1 ($^{\circ}\text{C}$)
 T_2 is the surface temperature on side 2 ($^{\circ}\text{C}$)

Temperature transducers are used in these tests methods to determine the surface temperatures and in combination with the known heat inputs (thus also the heat flux) the U-values for the material or assembly can be determined.

Some of the reason these tests are not used for in-situ analysis is that it is extremely difficult to recreate the scenario of precise steady state conditions, known heat input to the system, and an isolation chamber. To evaluate the in-situ thermal properties a heat flux transducer can be employed to directly measure the heat flow rate through a small area of the envelope. ASTM C1046 Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components provides a method to observe the real-time heat flow and surface temperature values needed in equation 3. Although ASTM C1046 provides a method for measuring the heat flow, transient environmental conditions will create fluctuations in the heat flux measured. This fluctuation will be due to the change in temperatures and due to the thermal storage capacity of the envelope materials that influence the materials' thermal time constants. By definition, the thermal time constant for a material is the time necessary for a change in temperature on one side of the material to cause a change in heat flux on the other side of the material. Many lightweight building materials have short time constants, whereas heavy and denser materials often have longer time constants. While precisely controlled steady state conditions may not be achievable, near steady state conditions should provide a reduced amount of fluctuations from temperature fluctuations. Also the largest possible steady state temperature difference between the indoor and outdoor environments should reduce the magnitude of noise and error in the heat flux and temperature readings. Since heat flux is measured over a small area, spatial variation can also create errors and inconsistency. Thus ideally heat flux should be spatially and temporally sampled for in-situ applications.

In an attempt to improve building envelope thermal property characterization of existing historic buildings a research project was devised to build upon ASTM C1046, augmenting the in-situ method with thermographic imaging and near steady state environmental conditions. The project examined two historic buildings located in Philadelphia, Pennsylvania and compared typical material thermal properties used in energy modeling of the two buildings with the thermal properties derived from in-situ testing.

2.0 Methodology

2.1 Buildings and Environmental conditions

The two buildings that were studied in this research project are Roxboro House on Philadelphia University's campus and the RittenhouseTown Homestead in Fairmount Park (both in Philadelphia, PA). These two buildings are registered historic buildings and either they have a substantial portion of their original building envelope assemblies intact or they have been recently restored to their original conditions. RittenhouseTown Homestead has load bearing stone masonry walls that were originally constructed in 1707. Roxboro House is a Georgian period house constructed of wood frame and clapboard that was at least partially constructed in 1779. Both buildings lack modern insulation in their wall assemblies. Since both buildings have original construction materials within their assemblies that have not been previously tested for thermal properties and have elements of non-uniform construction they were identified as good candidates for this project.

Since changing environmental conditions can alter the flow of heat through the envelope, near steady state conditions with large temperature differences between the indoor and outdoor areas were considered desirable. To achieve near steady state outdoor conditions with the least impact due to latent heat, wind and radiation, the north side of the buildings were used during a calm winter weather period. Further since the outdoor temperature fluctuates with higher temperatures during the day and lower temperatures during the night, surface and air temperatures were monitored to determine the time period with the lowest amount of

temperature change. Typically after midnight and before sunrise, the radiation of the sun and the longwave radiation from the sky have the least amount of impact on heat gain to the envelope. Winter climate conditions in Philadelphia are favorable for this study's near steady state conditions for three reasons: (1) the greatest amount of temperature difference between in the indoor and outdoor air typically occurs in the winter and thus represents the conditions where the most heat flow will occur, (2) winter climate often has less absolute moisture in the air, thus potential latent heat and moisture transport issues are minimized, and (3) the night time period is longer, thus reducing outdoor radiation impact.

2.2 Material Properties within Energy Models

Based on field survey and/or existing drawings the dimensions and material assemblies for the two buildings were approximated and used in the creation of energy models using IES Virtual Environment 2014 as the simulation software. Using the material database available within the IES program the nominal U-value for the 23 inch thick stone masonry wall at RittenhouseTown was 0.3756 Btu/h·ft²·°F (R-value of 2.66 h·ft²·°F/Btu). The nominal U-value for the Wood framed wall with wood clapboard was 0.2779 Btu/h·ft²·°F (R-value of 3.60 h·ft²·°F/Btu). These were used to create baseline models that represented energy models based on best-practice assumptions without in-situ testing. Further details of the energy modeling parameters such as air exchange rates, mechanical systems, user schedules, indoor set points, and micro climate conditions although outside of the scope of this paper are available in the research project's final report (Chung 2016).

2.3 Experiment Set-up

This research was funded by a grant from the National Center for Preservation Technology and Training. The following equipment was purchased through these funds and used for collecting thermal data.

- FLIR E6 thermal IR camera with 160x120 resolution, \$1,262.00
- Hukseflux HFP01-05 heat flux plate (used with the Omega datalogger), \$640.00
- (8) Standard k-type thermocouples (used with the Omega and Amprobe dataloggers)
- Omega Engineering, OM-DAQLINK-TEMPRH hand held datalogger, \$506.00
- (2) Amprobe TMD-56 Multi-logger Thermometer, \$109.84
- REED Temperature & Humidity Datalogger model ST-171, \$77.42
- Extech RHT10 Humidity and Temperature Datalogger, \$70.84
- Davis Instruments 6250 Vantage Vue Wireless Station, \$665

The in-situ tests were performed over approximately a twenty-four-hour period at each building. During the tests, thermocouples were connected to a temperature datalogger as seen in figure 3. Thermocouples and a heat flux sensor were arranged on the inside wall surface as shown in figure 4. The heat flux plate was connected to a handheld datalogger that also recorded ambient air temperatures. Additional thermocouples were located in the same configuration on the corresponding outside surface of the wall as seen in Figures 6 and 7. At least three thermocouples were used on each surface to provide spatial averaging and redundancy. Thermal imaging was used to help locate an appropriate location for the tests. Areas with strong contrast and brightness changes in the thermal images indicate locations of large surface temperature changes and generally would not be appropriate for using the heat flux plate for this test. Figures 5 and 8 are images taken with the thermal IR camera at RittenhouseTown Homestead. Ideally the areas selected should be relatively uniform and not in an area of strong air currents to reduce the influence of surface irregularities and convective heat transfer. With the thermocouples in place on the inside and outside surfaces along with the heat flux plate on the interior, the U-value of the wall assembly at the location of the sensors can be determined using equation 3. Sensor readings were recorded in 60 second intervals.



Figure 3. Temperature datalogger

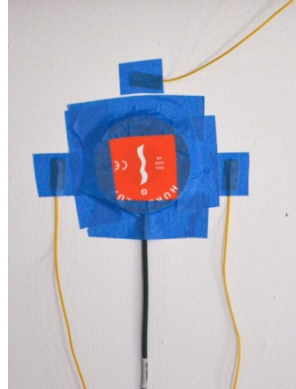


Figure 4. Heat flux plate on inside wall at RittenhouseTown



Figure 5. Full 160x120 pixel image, North wall at 6:59 AM



Figure 6. N.wall at thermocouples, RittenhouseTown

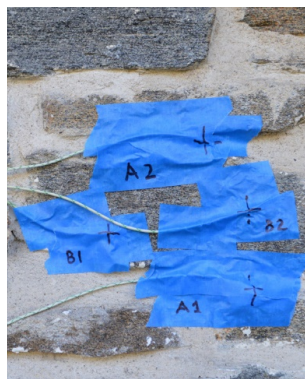


Figure 7. Thermocouple

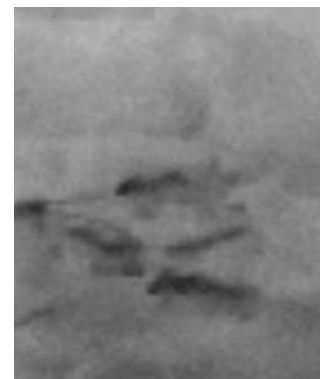


Figure 8. Thermal image at sensors

The thermal IR camera was also used to detect variation and non-uniformity so that a spatially averaged thermal resistance value could be calculated when used in conjunction with the heat flux plate and thermocouples. Although the experimental details and methods of calculation related to the use of the thermal IR camera for determining a spatially averaged resistance value are outside the scope of this paper, the full details were previously published (Chung 2015).

3.0 Results and Discussion

Figures 9 and 10 show the recorded temperatures, heat flux and calculated thermal resistance values for the two historic buildings. These are dual vertical axes graphs with temperature units on the left side. Heat flux and R-values units are on the right side. Over a 24-hour period the envelope at RittenhouseTown Homestead had an averaged calculated resistance value of $5.74 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$. During the six-hour period of near steady state conditions (from midnight to 6AM) the calculated thermal resistance of the wall at RittenhouseTown Homestead is $7.83 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$. These resistance values are much higher than the nominal value used for sandstone $2.66 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$ and appears to reflect the uncertainty that exists due to material variations that occur in a naturally forming sedimentary rock. Thermal storage of the masonry wall most likely influenced the heat flux readings. This can be inferred since although the air temperature was relatively steady from midnight to 6AM, the surface temperature on the masonry continued to decrease until approximately 9AM when both the sun was visible and the air temperature began to rise. At 23 inches thick, the masonry wall has considerable thermal storage capacity. Sandstone is often estimated to have a heat capacity of $0.203 \text{ Btu}/\text{lb}\cdot^\circ\text{F}$ ($850 \text{ J}/\text{kg}\cdot\text{K}$) and a density of about $125 \text{ lb}/\text{ft}^3$ ($2000 \text{ kg}/\text{m}^3$) (Krus 1996). This leads to a thermal capacity of approximately $25.375 \text{ Btu}/\text{ft}^3\cdot^\circ\text{F}$ ($1,700,000 \text{ J}/\text{m}^3\cdot\text{K}$).

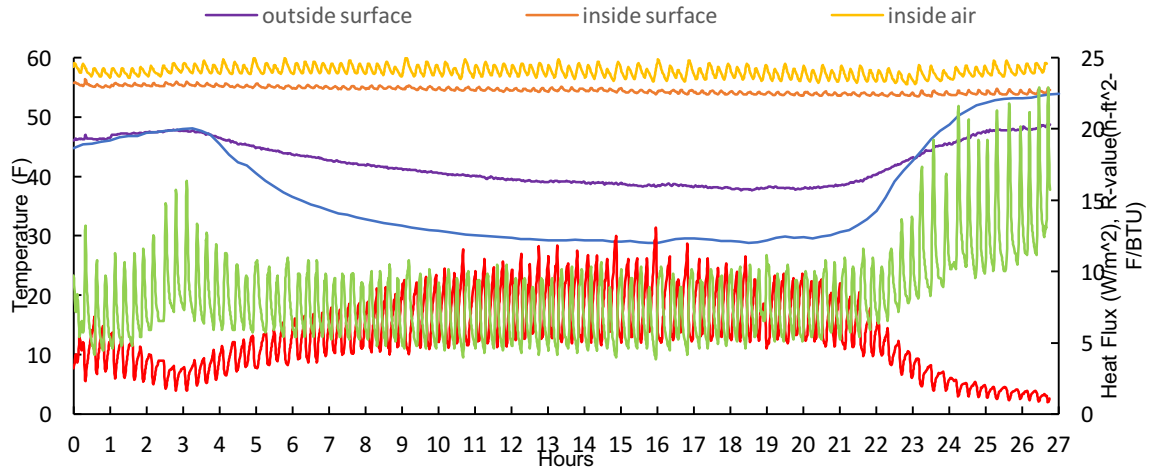


Figure 9. Transient temperature and thermal behavior of a masonry wall over 27 hours at RittenhouseTown Homestead, Philadelphia, PA. Time = 0 at approximately noon on December 26, 2014.

For Roxboro House the time averaged thermal resistance value (over a 23-hour period) was $4.29 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$. During the 4-1/2 hour period (from 4AM to 8:30AM) of near steady state conditions, the calculated thermal resistance of the wall at Roxboro House was $3.92 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$. These resistance values are higher than the nominal value of $3.60 \text{ h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$, yet much closer to the nominal values than the resistances for RittenhouseTown Homestead. This may be due to the fact that the construction of Roxboro House is more thoroughly documented and comprised of manufactured materials that have more consistency in terms of thermal properties. It also may be related to the weight and thermal storage capacity of the assembly. While wood is often estimated to have a relatively high heat capacity $0.449 \text{ Btu}/\text{lb}\cdot^\circ\text{F}$ ($1880 \text{ J}/\text{kg}\cdot\text{K}$), its density is about $25 \text{ lb}/\text{ft}^3$ ($400 \text{ kg}/\text{m}^3$) (Kumaran 2002b) which is much lower than masonry. This leads to a thermal capacity of approximately $11.225 \text{ Btu}/\text{ft}^3\cdot^\circ\text{F}$ ($752,000 \text{ J}/\text{m}^3\cdot\text{K}$). The wood framed wall has an air cavity and is much thinner than the masonry wall. Thus the thermal lag due to thermal mass of the wood framed wall should have less impact on the Roxboro House measurements.

Indoor temperature fluctuations can be observed in both graphs. Since both of these buildings have integrated modern ducted forced air heating systems, the indoor temperature is controlled via a thermostat with set points that allow for some range before the heating system turns on or off. The automated and regular time intervals of the indoor air systems produces corresponding fluctuations in the observed heat flux and calculated R-values. From the oscillations in the graph for RittenhouseTown Homestead the thermostat appears to have operated in 16 minute cycles. For Roxboro House the thermostat appears to have operated in 10 minute cycles. The shorter interval should produce more steady state conditions and reduce the amplitude of the oscillations. Future work using this in-situ method should try to minimize the thermostat cycling time and also limit any other heat gains both indoor and outdoor to improve the near steady state conditions.

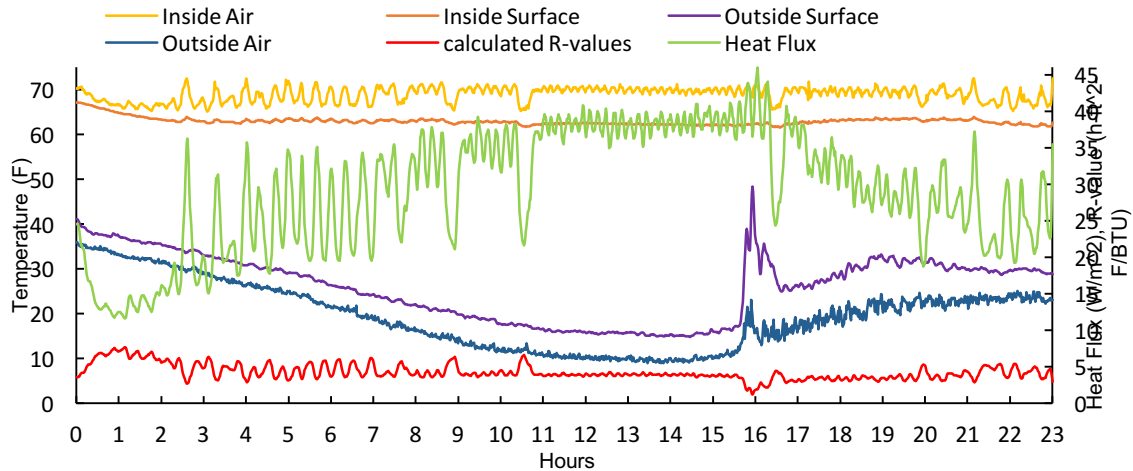


Figure 10. Transient temperature and thermal behavior of a wood framed clapboard siding wall at Roxboro House, Philadelphia, PA. Time = 0 at approximately 5PM on February 12, 2015.

Using the thermal properties of the baseline models and the in-situ models, both buildings were simulated over a typical meteorological year. These results are shown in tables 1 and 2. Looking at the results one can see that in both buildings their simulations with baseline models predicted a higher amount of energy use when compared to the simulations with in-situ models. This was primarily due to the fact of having much lower thermal resistance values for the walls than what was measured in the field tests. The calculated total annual energy costs for RittenhouseTown Homestead in the simulation with the in-situ model is approximately 10% less than the simulation with the baseline model. The calculated total annual energy costs for Roxboro House the simulation with the in-situ model is approximately 14% less than the simulation with the baseline model. Historical energy consumption records for Roxboro House were not available. Some recent energy use records for RittenhouseTown Homestead were available. Natural gas consumption in 2014 was 1344 CCF. Electricity consumption in 2012 was 4381 kWh. These historical data points suggest that the energy models may be overestimating the future energy use. This may be due to the difference between the simulated and actual indoor temperature set points and occupancy schedules.

Table 1: RittenhouseTown Homestead Building Energy Simulation Annual Energy Consumption Results

	Baseline Existing	In-situ Model Existing
electricity (kWh)	9,025	6,030
natural gas (CCF)	1,876	1,988
electricity cost	\$1,367.27	\$913.53
natural gas cost	\$1,899.89	\$2,013.78
Total annual cost	\$3,267.16	\$2,927.31

Table 2: Roxboro House Building Energy Simulation Annual Energy Consumption Results

	Baseline Existing	In-situ Model Existing
electricity (kWh)	66,491	57,397
electricity cost	\$10,073.40	\$8,695.63

4.0 Conclusions

This paper provides a brief background, context, methodology and results of an experimental study in using in-situ testing to improve building envelope thermal properties. The benefits of the methods are that historic building envelopes can be assessed using non-destructive methods, in the field with relatively low cost equipment and a short time frame. The method allows for observation of the thermal time lag due to thermal mass and requires user judgement in selecting appropriate envelope sites and time periods for testing. This method is sensitive to fluctuations in heat gains/losses and as such requires near steady state conditions which may limit its application both in regards to location and times during the year when it can be performed.

Although the method provides improvement over using nominal values, further study is needed to better understand the magnitude of impact regarding thermal mass.

5.0 Acknowledgements

Portions of the work contributed to this project were performed by two graduate research assistants, Katie Herber and Anastasiia Savchenko. Both were graduate students in the M.S. in Sustainable Design program at Philadelphia University. Their participation was directly funded by Philadelphia University and were provided to the project as an in-kind match. This research was funded by the NCPTT Grants Program. Their financial contribution allowed for the purchase of testing equipment and research time that was essential to the success of this project. This research was made possible by the generous access to RittenhouseTown Homestead provided by Chris Owens, the Executive Director of Historic RittenhouseTown. This research was also made possible by the generous access to Roxboro House provided by Philadelphia University's Physical Plant. Special thanks go to Thomas Becker the Associate Vice President for Operations and Karl Pettit who was the project manager for the restoration of Roxboro House.

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