IMPROVING ENERGY MODELING TECHNIQUES FOR HISTORIC BUILDINGS USING PRELIMINARY VERIFICATION METHODS

Daniel Chung[1]

[1]Drexel University, Philadelphia, Pennsylvania

ABSTRACT: Often for historic buildings air infiltration and thermal resistance values for the envelope are not well known and can significantly influence accuracy of building energy simulations as well as the actual energy performance of a building. This paper will detail some of the methods used in a funded research project to improve energy modeling for historic buildings using low cost preliminary verification methods. By using in-situ non-destructive testing methods to measure heat flux and surface temperatures more accurate thermal resistance values were determined for two buildings. By using door blower pressurization tests the air tightness of both buildings were measured allowing for a more accurate understanding of air infiltration rates. By using these field derived parameters building energy simulations with calibrated input parameters were created and compared with baselines (using standard assumptions for materials and air infiltration) to study the significance of preliminary verification methods on the predictive nature and accuracy of building energy simulations for historic buildings. Using this method of modeling coupled with field testing should improve confidence and accuracy in future building energy simulations for historic buildings and ultimately help provide more meaningful energy data in the decision-making process for owners and operators of historic buildings.

KEYWORDS: historic buildings, energy modeling, heat flux, in-situ testing, air tightness

1.0 INTRODUCTION

1.1 Modeling and Simulation

The nouns modeling and simulation are often used interchangeably in architectural discussions regarding the analysis of energy flows of buildings. In this paper, modeling activities and simulation processes will be divided into two separate categories related to energy analysis of buildings. Modeling will refer to the activity of gathering building characterization and other input parameters used in building energy analysis. Modeling often includes the definition of geometry, orientation, material properties and climate data. The term simulation will refer to the physics-based analysis of past or future energy flows for buildings. Energy simulation is usually governed by numerical techniques regarding mass and energy balances. Energy consumption in buildings is often dominated by energy used by mechanical systems to condition the interior space for thermal comfort. This research focused on improving understanding and accuracy of modeling parameters that impact energy consumption for heating, ventilation and air conditioning (HVAC) systems by improving characterization of the building envelope used in building energy simulations. While the research project involved the creation of detailed building energy simulations including internal gains, occupancy schedules, HVAC systems and local microclimate parameters, this paper focuses on the preliminary verification techniques used to improve input parameters for building energy simulations of historic buildings.

1.2 Unique Considerations for Historic Buildings

The analysis methods and building physics equations that are used in most building energy simulation software are generally based on one-dimensional heat transfer analysis (IESVE, eQuest and DOE 2.2 all are based on 1-D heat transfer) and the same analytical techniques are used in both existing and new construction. The simulation process however is heavily dependent on the modeling inputs. For historic buildings, a significant concern is collecting meaningfully accurate characterization data. Although characterization is an important issue for all building energy simulations, it often is more of an issue for historic buildings due to two issues. The first is that historic buildings that were built before modern insulation materials tend to have low thermal resistance values (such as R-values less than 5 $h \cdot ft^2 \cdot °F/Btu$) and consequently small absolute inaccuracies in characterization can have a large relative influence in simulated performance. For example, if a wall assembly has a relatively high resistance value of 20 $h \cdot ft^2 \cdot °F/Btu$ and the amount of inaccuracy is ± 1 $h \cdot ft^2 \cdot °F/Btu$. This is within 5% and most likely will have only a small impact on the overall energy simulation results. For a wall assembly with a relatively low resistance value of 3 $h \cdot ft^2 \cdot °F/Btu$, an inaccuracy of ± 1 $h \cdot ft^2 \cdot °F/Btu$ would be an inaccuracy of ± 33% and could have a large impact on the overall energy simulation results. The second issue is that many historic buildings utilize envelope material assemblies that are non-uniform or have been significantly altered over time. This is of concern because assembly and material uniformity are often assumed when performing building energy simulations.

2.0 Methodology

2.1 Equipment

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.

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

2.2 Energy Models

The equipment was used to perform in-situ non-destructive testing of building envelopes to measure thermal properties. 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 were selected for the research since they are both historically registered buildings and either have their original envelope assemblies or have been reconstructed and restored to the original assemblies. Energy models were developed for Roxboro House and RittenhouseTown Homestead using IES Virtual Environment 2014. Baseline and in-situ energy models were created for each building. The baseline model is composed of building properties based on physical surveys and existing drawings. The in-situ model uses properties derived from in-situ testing.

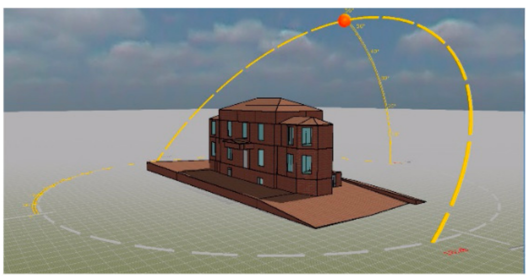

Figure 1: Virtual representation of Roxboro House in IESVE

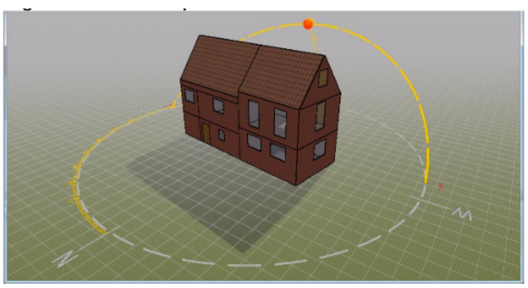

Figure 2: Virtual representation of RittenhouseTown Homestead in IESVE

2.3 Basic Parameters

In building energy simulation, the basic information to collect for input are (1) the material thermal properties (conductance and resistance) of the building envelope, (2) the air exchange rate, (3) the internal gains and (4) the climate conditions. Existing drawings, field surveys and readily available visual information of the two buildings were used to create baseline models. Baseline models were developed using local weather station inputs and standard materials assumptions using thermal properties published in existing literature and databases. This baseline model attempts to represent the typical professional practice that normally precludes in-situ building testing. The heat transfer coefficients used in the baseline model are listed in Tables 1 and 2. The outdoor climate is modeled by using a weather file that attempts to represent a typical meteorological year (TMY). The Northeast Philadelphia Airport weather station is the closest weather station to both sites and has TMY3 weather data available. The weather station is located at coordinates of 40.08°N, 75.02°W and is approximately 10 miles away from the two building sites.

Table 1: Overall heat transfer coefficients (Btu/h·ft²·°F) for RittenhouseTown Homestead Envelope Assemblies

U-value	Description
0.9502	Single-glazed windows (frame occupies 33% of area)
0.3756	Stone masonry exterior walls 23 inches thick (sandstone)
0.4408	Stone masonry exterior walls 18 inches thick (sandstone)
0.2466	Wood floors over wood joist and plaster ceiling
0.0445	Sloping roof, wood shingle, exposed wood framing + glass fiber insulation
0.3658	Wood framed wall partition plaster both sides
0.3195	Stone masonry load bearing internal wall 18 inches thick with plaster both sides
0.4750	Solid hardwood door (oak)

Table 2: Overall heat transfer coefficients (Btu/h·ft²·°F) for Roxboro House Envelope Assemblies (historic portions only)

U-value	Description
0.7032	Large single-glazed windows (frame occupies 10% of area)
0.9502	Single-glazed windows (frame occupies 33% of area)
0.2779	Wood framed, plaster on wood lath, wood clapboard on plywood exterior walls
0.2466	Wood floors over wood joist and plaster ceiling
0.0445	Sloping roof, wood shingle, exposed wood framing + glass fiber insulation
0.3658	Wood framed wall partition plaster both sides
0.4750	Solid hardwood door (oak)

2.4 Air exchange rate

Air exchange rates used in building energy simulation typically represent the rate at which outdoor and indoor air are being exchanged within the volume of the building being studied. As air is a fluid with heat carrying capacity, the exchange of air between the inside and outside is a source of heat gain/loss for the building interior. In some cases the heat loss/gain from air infiltration can exceed the loss/gain related to conductance and radiation and thus is an important building energy simulation variable. The air exchange rate is typically expressed as Air Changes per Hour (ACH) which is the number of times that the total volume of air inside the building has been exchanged with the outside air. In developing energy models for modern buildings of similar scale to the two buildings in this project air exchange rates can range between 0.33 to 1.47 ACH depending on the outdoor temperature, wind speed and tightness of construction (Grondzik et al. 2011). 0.33 ACH represents a relatively well-sealed building while 1.47 ACH represents a building with relatively poor air-tightness. A building with medium air-tightness is expected to have a range of 0.46 ACH to 1.05 ACH depending on wind speed and outdoor temperature.

Using wind speed and seasonal design temperature values, the expected medium air-tightness values could be estimated to be 0.46 ACH in the summer and 0.85 ACH in the winter (Grondzik et al. 2011). Since building energy simulation software typically require the input parameter of a baseline ACH for the entire year this would be typically the average of the summer and winter ACH values. In the case of developing energy models in Philadelphia this leads to an expected average medium air-tight building with a value of 0.66 ACH. This is a reasonable air exchange rate value if one does not actually know the air-tightness condition of a building via testing. This is the rate that is used in the baseline models for this research project.

2.5 Verification & Testing

Air infiltration rates can be tested by using door blower tests and material uniformity can be studied via thermocouples, hygrometers, thermographic photography and heat flux sensors. This research utilized each of these relatively low cost techniques to enhance the building characterization process with the goal of increasing accuracy of the associated building energy simulations.

2.6 Testing Methodology for Thermal Resistance

To determine the in-situ thermal performance and resistance values of the wall assemblies a day long test was conducted at both sites. ASTM C1046-95 and C1155-95 both provide detailed methods for collecting in-situ data of building envelopes performance parameters and were used as starting points for the testing performed in this research project (ASTM 2013a, b). Using the equipment listed in section 2.1, thermocouples were placed on both inside and outside surfaces of an exterior wall. A heat flux plate was attached to the inside surface and temperature data loggers were also used for the room and outdoor air temperatures. The dataloggers recorded readings at 30 second intervals over a 23-hour or 24-hour period. Using these readings along with thermal images of the walls taken with the IR camera the thermal resistance of the wall and air films were calculated. This procedure is detailed in the article titled "*Historic Building Facades: Simulation, Testing and Verification for Improved Energy Modeling*" (Chung 2015). This article covers step-by-step calculations using a method derived from EN ISO 6946-2007 using the collected in-situ data to calculate thermal resistance and transmittance (ISO 2007). Heat transfer through the building envelope varies spatially and over time. Although the resistance value of the envelope can be measured over a short time interval at a single point, this research collected data to determine the resistance value over a broad area of the envelope and over many hours. To use this data in the software simulations, the sum of the resistance values over time and area are divided by the area and time to determine a time and spatially average resistance value. This is denoted as "$R_{env\_av\_tav}$" in the results section. Additional information and requirements of this testing methodology are discussed in the article and are available online at: http://digital.journalofthenationalinstituteofbuildingsciences.com/nibs/february_2015?pg=17#pg17.

2.7 Testing Methodology for Air Infiltration

To test for the air exchange rate due to air infiltration for a building one can use a door blower test to determine the amount of air flow through the building envelope at a specific pressure. The standard for testing airtightness of buildings using a door blower sets the target pressure at 50 pascals (Standard 2011). By placing a fan within a sealed collar at an exterior doorway and using a pressure and flow gauge the flow rate of air in cubic feet per minute (CFM) can be determined at the target pressure. This is typically known as the CFM@50 Pa or CFM_{50}. If the building interior air volume (in cubic feet) is known then the air exchange rate can be calculated at the target pressure. This air exchange rate is known as ACH@50 Pa or ACH_{50} and is calculated as $ACH_{50} = CFM_{50}$ / building volume. See ASTM Standard E1827-11 for more information on this testing method. Both RittenhouseTown Homestead and Roxboro House are buildings that are approximately 2-1/2 stories tall with a normal exposure to wind. Using ASHRAE Standard 136 for such buildings in Philadelphia provides an N-factor = 17.6 (Standard 1993). The conversion from ACH@50 Pa to an estimated naturally occurring ACH is calculated by: $ACH_{natural} = ACH_{50}$/N-factor. See figure 4 for images of the door blower test at RittenhouseTown Homestead.

3.0 Results and Discussion

3.1 In-Situ Thermal Resistance Rittenhouse Town Homestead

On December 26-27, 2014 RittenhouseTown Homestead had a measured thermal resistance time averaged value (over a 24 hour period) of 5.74 h·ft²·°F/ Btu at the location of the heat flux sensor. Using the thermal images and sensor readings taken at 5:59 AM at RittenhouseTown Homestead on December 27, 2014 the following resistance values were estimated:

<u>2nd Floor, 18 inch thick masonry stone wall:</u>

- Resistance area averaged instant value, $R_{env\_av\_inst}$ = 4.672 h·ft²·°F/ Btu
- Resistance 24 hour time average spot value, $R_{env\_spt\_tave}$ = 5.74 h·ft²·°F/ Btu
- Resistance instant spot value, $R_{env\_spt\_inst}$ = 4.636 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, $R_{env\_av\_tav} = R_{env\_av\_inst} \times R_{env\_spt\_tave} / R_{env\_spt\_inst}$ = 5.78 h·ft²·°F/ Btu

<u>1st Floor, 23 inch thick masonry stone wall:</u>

- Resistance area averaged instant value, $R_{env\_av\_inst}$ = 4.888 h·ft²·°F/ Btu
- Resistance 24 hour time average spot value, $R_{env\_spt\_tave}$ = 5.74 h·ft²·°F/ Btu
- Resistance instant spot value, $R_{env\_spt\_inst}$ = 4.636 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, $R_{env\_av\_tav} = R_{env\_av\_inst} \times R_{env\_spt\_tave} / R_{env\_spt\_inst}$ = 6.05 h·ft²·°F/ Btu

The in-situ determined thermal resistance of the 23 inch thick masonry wall of R_{env} = 6.05 h·ft²·°F/ Btu is approximately 204% the default value used in the baseline model of 2.96 h·ft²·°F/ Btu. The in-situ determined thermal resistance of the 18 inch thick masonry wall of R_{env} = 5.78 h·ft²·°F/ Btu is approximately 255% the default value used in the baseline model of 2.27 h·ft²·°F/ Btu. See figure 3 for a thermal image of RittenhouseTown Homestead. These in-situ values appear to reflect the uncertainty and range that exists in the assumed values for sandstone masonry walls. Since sandstone is a naturally formed sedimentary rock, variations in composition, density and homogeneity may exist that can lead to variations in thermal properties.

3.2 In-Situ Thermal Resistance Roxboro House

On February 12-13, 2015 Roxboro House had a measured thermal resistance time averaged value (over a 23 hour period) of 4.29 h·ft²·°F/ Btu (which corresponds to a U-value of 0.2331 Btu/h·ft²·°F) at the location of the heat flux sensor. Using the thermal images and sensor readings taken at 6:39 AM at Roxboro House on February 13, 2015 the following resistance values were estimated:

- Resistance area averaged instant value, $R_{env\_av\_inst}$ = 4.322 h·ft²·°F/ Btu
- Resistance 23 hour time average spot value, $R_{env\_spt\_tave}$ = 4.29 h·ft²·°F/ Btu
- Resistance instant spot value, $R_{env\_spt\_inst}$ = 4.070 h·ft²·°F/ Btu
- Resistance area averaged time ave. value, $R_{env\_av\_tav} = R_{env\_av\_inst} \times R_{env\_spt\_tave} / R_{env\_spt\_inst}$ = 4.56 h·ft²·°F/ Btu

The in-situ determined thermal resistance of the wood framed wall of R_{env} = 4.56 h·ft²·°F/ Btu is approximately 27% higher than the default value used in the baseline model of 3.60 h·ft²·°F/ Btu.

Figure 3: Full 160x120 pixel image, North wall at 6:59 AM

Figure 4: Door blower at RittenhouseTown

3.3 In-Situ Air Infiltration

A door blower test for RittenhouseTown Homestead was performed on May 14, 2014 (see figure 4). The test was performed by a Building Performance Institute (BPI) certified technician from the Energy Coordinating Agency (106 W Clearfield Street, Philadelphia, PA 19133). This service was provided at a cost of $125. The test measured 6002 CFM@50 Pa. With the building volume modeled at 12,270 cubic feet of interior volume this results in an air exchange rate of 29.35 ACH@50 Pa. This the door blower tests results can be used to estimate a natural air exchange rate of 1.67 ACH for RittenhouseTown Homestead.

A door blower test for Roxboro House was performed on August 14, 2014. The test was performed by a Building Performance Institute (BPI) certified technician from the Energy Coordinating Agency. This service was provided at a cost of $250. The test used two door blower fans and two pressure and flow gauges with a combined measurement of 9410 CFM@50 Pa. Two door blower fans were needed due to the larger volume of Roxboro House. With the building volume modeled at 38,570 cubic feet of interior volume this results in an air exchange rate of 14.63 ACH@50 Pa. Thus door blower tests results can be used to estimate a natural air exchange rate of 0.83 ACH for Roxboro House.

When comparing these air infiltration rates derived from the door blower tests to the baseline value of 0.66 ACH one can see that for both of these historic buildings air infiltration rates are higher than might be normally predicted without testing. For RittenhouseTown Homestead the air exchange rate determined from testing increased significantly by a factor of 2.55. For Roxboro House the air exchange rate determined from testing increased by a factor of 1.27.

3.4 Weather comparison

At the RittenhouseTown Homestead site a small lab grade weather station (Davis Instruments 6250 Vantage Vue Wireless Station) was installed to help monitor differences between local/regional climate (from local weather stations) and micro-climate at the target building site. Figure 5 shows a comparison of the monthly average weather data from June 2014 through March 2015 between the local airport weather station and the onsite weather station at RittenhouseTown Homestead. The Northeast Philadelphia Airport weather station data was downloaded from the National Oceanic and Atmospheric Administration website. The on-site weather station was located approximately 30 feet north of the building in a clearing on the building property. This allowed the on-site weather station to be out of any direct shadows cast by the building but still within the range of experiencing similar climate effects. The graph shows that the airport weather station is consistently higher in terms of both high and low temperatures throughout the year. The difference in rainfall appears to be minimal to non-existent. When comparing all the values during the 10 months the average air temperature daily high is 2.92°F greater and the average daily low is 2.94°F greater at the airport. This will have some impact on the building energy simulation accuracy since cooler months will require less air conditioning (thus less electricity) in the summer and greater heating (thus more natural gas) in the winter. One way to include this micro-climate information would be to edit the airport weather file to reduce the outdoor air temperature values to produce a customized weather input file for building energy simulation. An alternative to editing the weather file is to increase the indoor thermal set points by the average offset of 2.93°F. The second method is what was employed in this research and should provide some compensation for the difference in airport and site weather conditions.

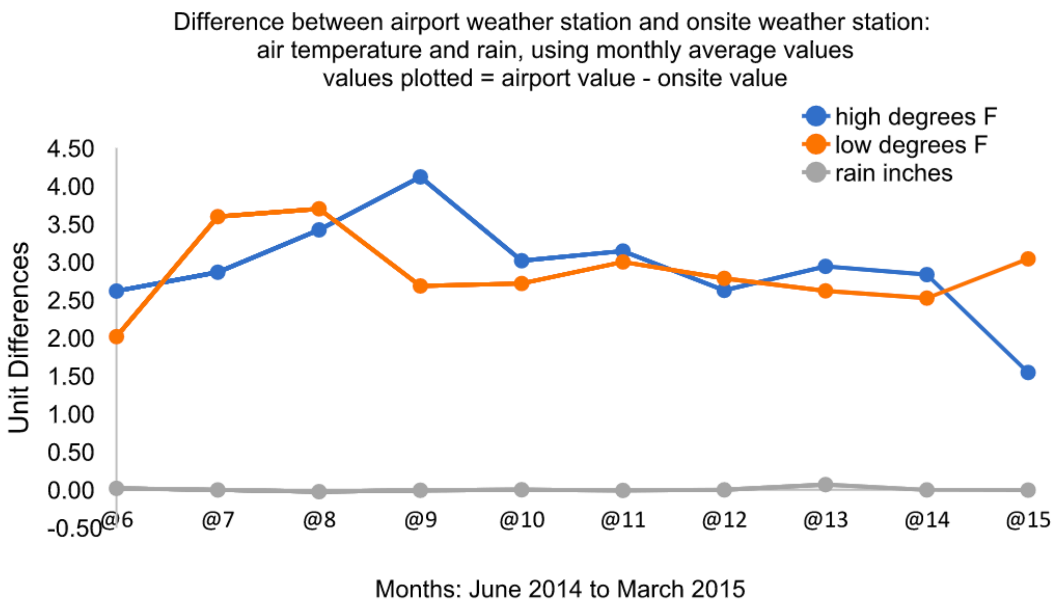

Figure 5: Comparison of weather station data between the RittenhouseTown Homestead site and the NE Phila. Airport

3.5 Building Energy Simulation Results

The results of the building energy simulations for RittenhouseTown Homestead are shown in table 3. The results for Roxboro House are shown in table 4. These include simulations with the baseline models using typical assumptions and the in-situ models using thermal resistance and air infiltration test data. For each of the simulations the total energy due to lighting loads, heat gain from occupants and thermal conditioning were calculated. The total cost of annual energy was calculated by using 15.15 cents per kWh to represent the cost of the base rate plus transmission and delivery charges charged by PECO Energy Company, the local utility. The cost for natural gas used was 1.013 per CCF (100 cubic feet) with a heat value of 1040.5 Btu/CF. These values were listed for Pennsylvania on the Energy Information Agency's website for commercial properties. The cost of natural gas was the average value for 2014 and the heat value used was the average value for the 6-year period from 2009-2014. 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 3: 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 4: 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

CONCLUSION

By using in-situ non-destructive testing methods to measure heat flux and surface temperatures more accurate thermal resistance values were determined for both buildings. By using a simple door blower pressurization test the air tightness of both buildings were measured allowing for a more accurate understanding of air infiltration rates. By using these field derived parameters, the building energy simulations should provide a better approximation of future energy use when compared to simulations with baseline models. Using this method of energy modeling coupled with field testing should improve confidence and accuracy in input parameters used in building energy simulations for historic buildings and ultimately help provide more meaningful energy data in the decision-making process for owners and operators of historic buildings. It should be noted though that variations in occupancy schedules and building use can highly influence energy simulation outcomes. Also, building energy simulations for future use are predictions based on a multitude of assumptions and thus should not be interpreted as precise estimates but a quantitative method to help make more informed decisions.

ACKNOWLEDGMENTS

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.

REFERENCES

ASTM. 2013a. "ASTM C1046-95(2013), Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components." ASTM International, West Conshohocken, PA.

ASTM. 2013b. "ASTM C1155-95(2013), Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data." ASTM International, West Conshohocken, PA.

Chung, Daniel. 2015. “Historic Building Facades: Simulation, Testing and Verification for Improved Energy Modeling.” Journal of the National Institute of Building Sciences 3 (1):5.

Grondzik, Walter T, Alison G Kwok, Benjamin Stein, and John S Reynolds. 2011. Mechanical and electrical equipment for buildings: John wiley & sons.

ISO. 2007. “EN ISO 6946-2007, Building components and building elements - Thermal resistance and thermal transmittance - Calculation Method.” International Organization for Standardization.

Standard, ASHRAE. 1993. “136, A Method of Determining Air Change Rates in Detached Dwellings.” American Society of Heating, Refrigerating and Air conditioning Engineers.

Standard, ASTM. 2011. “Standard test methods for determining airtightness of buildings using an orifice blower door.” ASTM International, West Conshohocken, PA.