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Energy Modeling of Historic Buildings, Improving Simulation and Verification Techniques | 2016-01

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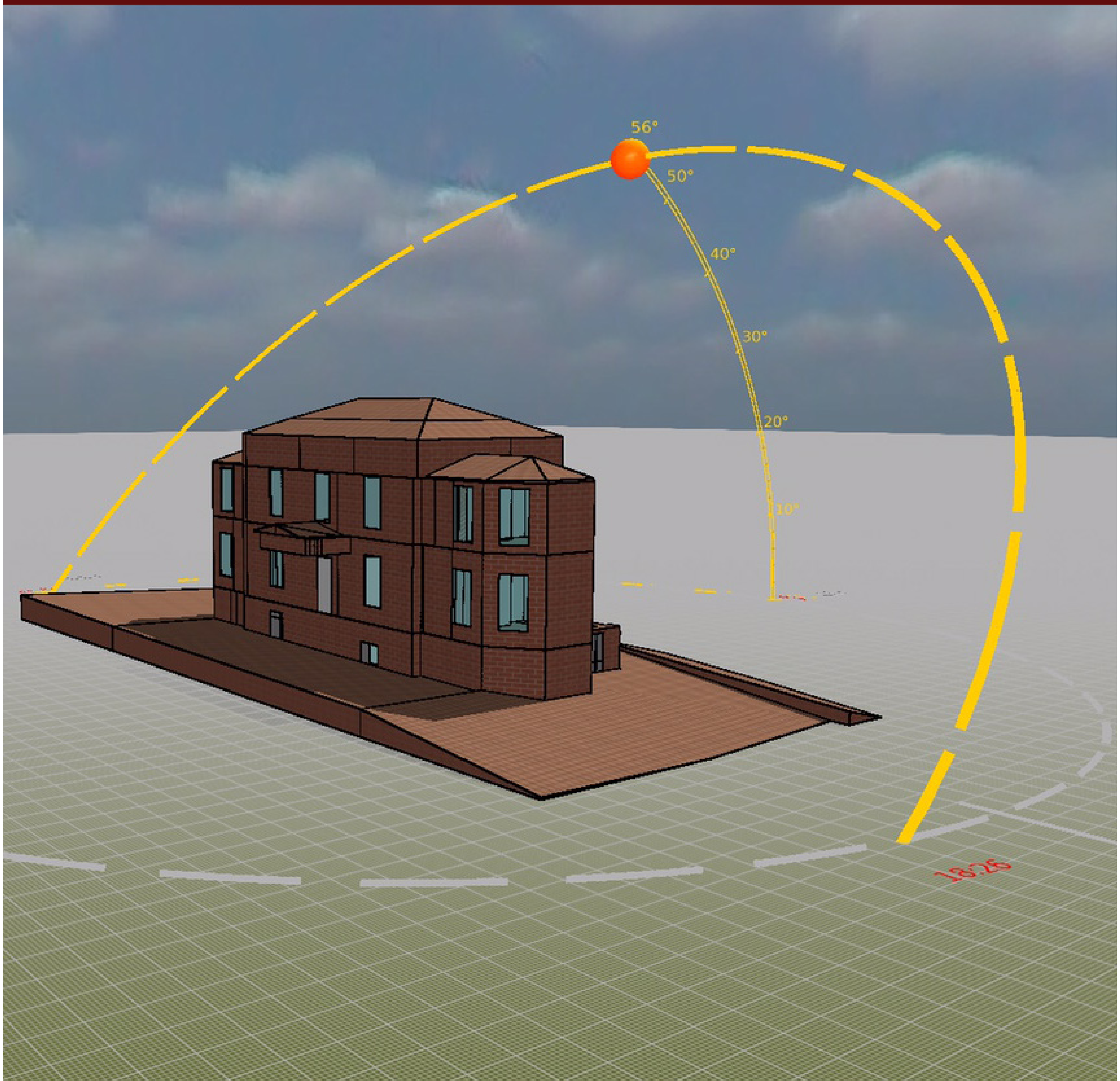

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Energy Modeling of Historic Buildings, Improving Simulation and Verification Techniques

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Executive Summary

This research project, titled *Energy Modeling of Historic Buildings, Improving Simulation and Verification Techniques*, was formulated to address two energy modeling objectives.

- *Improving Methods of Energy Modeling Historic Buildings*: to develop and implement energy modeling methods that are sensitive to the unique situation of historic buildings and
- *Low-cost Verification Techniques for Building Characterization*: to investigate the use of preliminary verification techniques using low cost testing equipment and sensors to provide more reliable building characterization data for energy modeling use.

These two objectives were researched through three primary tasks.

- Task 1, *Preliminary Verification and Building Evaluation* was investigated through in-situ verification techniques using air infiltration tests (via door blower tests) and thermal transfer tests (via thermal infrared photography and heat flux sensors) to ascertain existing properties of two registered historic buildings in Philadelphia, Pennsylvania. The research focused on two buildings of different size and construction so that the work might have broad reaching impact and be more readily applied to other historic buildings. RittenhouseTown Homestead built in 1707 is a load bearing masonry building and Roxboro House originally built in 1779 is of frame and clapboard construction.
- Task 2 – *Energy Modeling* was performed using data determine in task 1 to develop field calibrated energy models. These models were developed to serve as virtual test beds for potential retrofits to improve energy efficiency.
- Task 3 – *Monitoring* research activities involving regular periodic site visits and energy monitoring of the two buildings through a calendar year was performed to help validate the energy models in task 2 by comparing predicted performance with actual measured performance.

Often for historic buildings air infiltration and thermal resistance values for the envelope are not well known and can significantly influence accuracy of energy modeling simulations as well as the actual energy performance of a building. 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 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 the energy models and proposed retrofits provided a better approximation of the potential energy cost savings and payback period when evaluating different retrofit options. Using this method of energy modeling coupled with field testing should improve confidence and accuracy in future energy modeling activities for historic buildings and ultimately help provide more meaningful energy data in the decision making process for owners and operators of historic buildings.

Introduction

This document presents the final report for the *Energy Modeling of Historic Buildings, Improving Simulation and Verification Techniques*. This research project was formulated to address two energy modeling objectives:

1. *Improving Methods of Energy Modeling Historic Buildings*: to develop and implement energy modeling methods that are sensitive to the unique situation of historic buildings and
2. *Low-cost Verification Techniques for Building Characterization*: to investigate the use of preliminary verification techniques using low cost testing equipment and sensors to provide more reliable building characterization data for energy modeling use.

Methods

Overview of Tasks

Three main task areas were proposed to achieve these objectives and have been completed with a modified schedule due to the delayed time of the grant award.

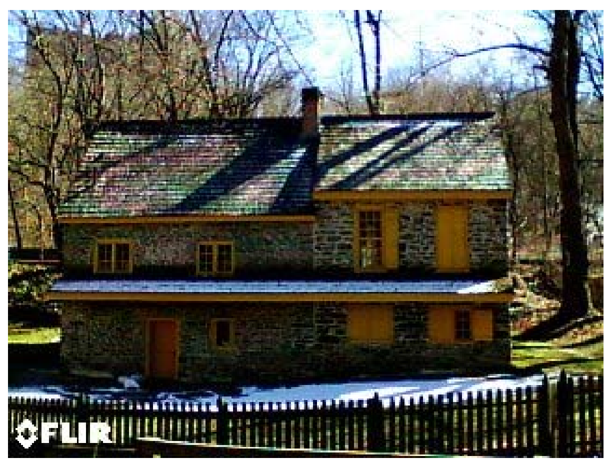
- Task 1, *Preliminary Verification and Building Evaluation* was investigated through in-situ verification techniques using air infiltration tests (via door blower tests) and thermal transfer tests (via thermal infrared photography and heat flux sensors) to ascertain existing properties of two registered historic buildings in Philadelphia, Pennsylvania. The research focused on two buildings of different size and construction so that the work might have broad reaching impact and be more readily applied to other historic buildings. RittenhouseTown Homestead built in 1707 is a load bearing masonry building and Roxboro House originally built in 1779 is of frame and clapboard construction.
- Task 2 – *Energy Modeling* was performed using data determine in task 1 to develop field calibrated energy models. These models were developed to serve as virtual test beds for potential retrofits to improve energy efficiency.
- Task 3 – *Monitoring* research activities involving regular periodic site visits and energy monitoring of the two buildings through a calendar year was performed to help validate the energy models in task 2 by comparing predicted performance with actual measured performance.

Task 1 – *Preliminary Verification and Building Evaluation*: Literature reviews were performed to better understand the implementation of technical equipment used for testing and verification in the context of historic buildings and to learn from related published research. A summary of literature reviewed along with notes on their pertinence to this project is provided in appendix A. Two key equipment purchases were made with grant funds for repeated use in this project. They are the FLIR E6 thermographic camera and the Hukseflux HFP01 heat flux sensor. These two essential pieces of equipment have been used to perform in-situ non-destructive testing of building envelopes to measure thermal properties for the purpose of more accurately characterizing building envelope assemblies for energy modeling purposes. See figures 1 & 2 for an example of photographic data collected using the FLIR E6. The two buildings that have been chosen after visual surveys of six historic buildings are Roxboro House on Philadelphia University's campus and the RittenhouseTown Homestead in Fairmount Park (both in

Philadelphia, PA). RittenhouseTown Homestead's physical address is 207 Lincoln Dr., Philadelphia, PA 19144. Roxboro House's physical address is 3240 West School House Lane, Philadelphia, PA 19144. These two buildings were selected as good candidates for the research because they are both historically registered buildings and either have their original envelope assemblies intact or they have been restored to their original assemblies. Additionally they were selected because:

1) They represent two different (typical) primary material assembly types. RittenhouseTown Homestead has load bearing stone masonry walls. Roxboro House is a wood framed, wood clad building.
2) They represent two different building sizes. Roxboro House has an interior area of approximately 6,045 square feet. RittenhouseTown Homestead has an interior area of approximately 1,735 square feet.
3) They both lack modern insulation in their original wall assemblies.
4) They were both originally constructed in the 18th century. Roxboro House is a Georgian period house constructed of frame and clapboard and was at least partially constructed in 1779 (University 1998). The RittenhouseTown Homestead was originally constructed in 1707 (Architects 1989).

By targeting these two buildings the work in this research should be relevant to a large number of historic buildings that may need to use energy modeling in future building assessments. The section of this document titled "Verification and Testing" provides more detailed reporting of Task 1.



Figures 1 & 2. Thermographic (embedded) and regular photograph of RittenhouseTown Homestead.

Task 2 – Energy Modeling: Literature reviews were performed to better understand the known issues of energy modeling in the context of historic buildings and to learn from related published research. As with Task 1 the pertinent sources and summaries are provided in appendix A. Primary issues identified with modeling historic buildings generally focus on high levels of air infiltration and non-uniform or undocumented envelope assemblies. Dynamic simulation computer energy models have been developed for Roxboro House and RittenhouseTown Homestead. Although initially EnergyPlus and eQuest were considered for use for energy modeling, the research was performed using IES Virtual Environment 2014 due to its more popular use by professional architecture and engineering firms engaged in energy modeling (AIA 2014). See figures 3, 4, 5 & 6 below for images related to the energy model for Roxboro House. See figures 7 & 8 for images of the RittenhouseTown Homestead energy model.

Three types of models were produced for each building. All three types share the same building geometry and climate data. The materials, air infiltration rates, mechanical systems and envelope assemblies are the variables that change between the three types. The first type is the baseline model and is composed of building properties based on visual survey and or existing drawings. The second type is the in-situ model and uses properties derived from in-situ testing. The third type is the retrofit model which includes proposed enhancements to reduce energy consumption in comparison to the in-situ model. The section of this document titled “Energy Modeling” provides more detailed reporting of Task 2.

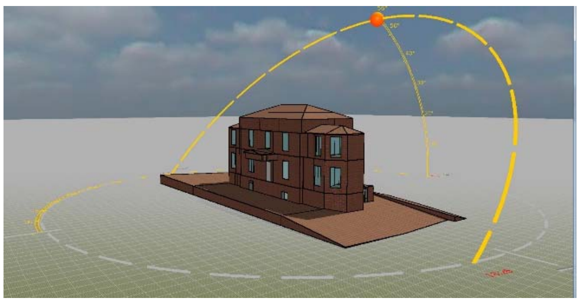


Figure 3. Model of Roxboro House in IESVE

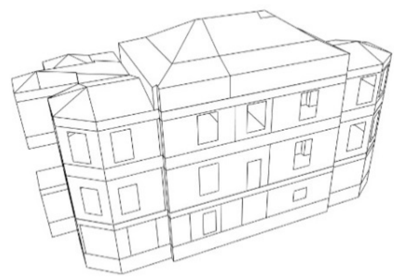


Figure 4. Massing for energy model of Roxboro House

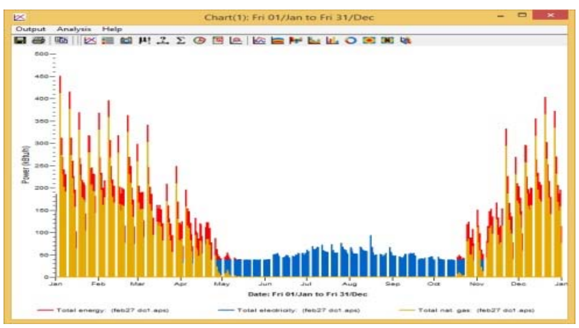


Figure 5. Predicted Energy Consmuption Graph for Roxboro House

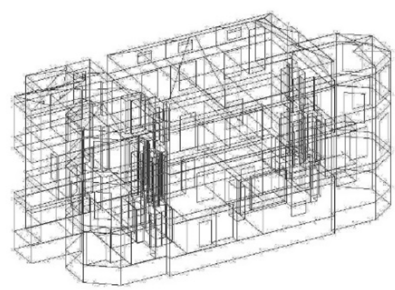


Figure 6. Wireframe showing zones in energy model

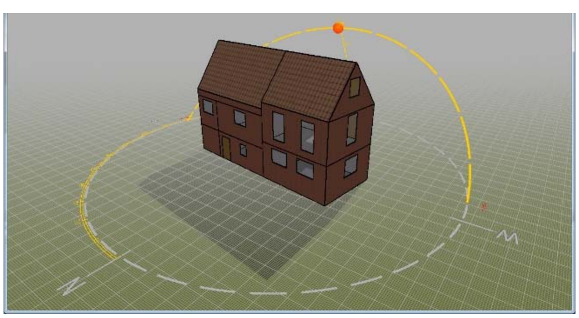


Figure 7. Model of RittenhouseTown Homestead in IESVE

Figure 8. Wireframe of RittenhouseTown Homestead

Task 3 – Monitoring: This research acquired regular monthly building energy consumption data for RittenhouseTown Homestead. Along with periodic site testing using thermography and heat flux sensors this provided data to calibrate and validate the energy models. At the

RittenhouseTown Homestead site a small lab grade weather station was installed to help monitor differences between regional climate (from local weather stations) and micro-climate at the target building site. This was important to help evaluate the impact of the climate input files used in running energy model simulations. During a majority of the research duration Roxboro House was under a significant restoration effort. Due to construction delays Roxboro House was not occupied or environmentally conditioned under a regular schedule to provide useful energy consumption data for verification purposes. The section of this document titled "Monitoring" provides more detailed reporting of Task 3.

Energy Modeling (Task 2)

In this report and in the context of this research a distinction is made between modeling and simulation. Although these terms are often used interchangeably, for the remainder of this report modeling will refer to information gathered regarding building characterization that will be input to a computerized energy model or used to define the input parameters used in energy simulation. The term simulation will refer to the analysis of simulated energy flows (typical in determining energy consumption) of buildings. These two parts are the basis of building energy modeling. Energy consumption in buildings is often dominated by energy used by mechanical systems to condition the interior space for thermal comfort. Although, lighting, electronics, water heating, cooking and refrigeration are significant primary energy end-uses it is the combination of space cooling, space heating and ventilation that is often most strongly related to building envelope design (DoE 2008) and climate conditions. As such 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 in energy modeling.

Unique Considerations for Historic Buildings

For historic buildings the issue of concern in the modeling portion is collecting relevant and accurate building characterization information. Although characterization data is an important aspect of all energy models, it tends to be even more influential for historic buildings due to two factors. The first factor is that historic buildings that predate modern insulation products tend to have low thermal resistance values (such as R-values less than 5 $h \cdot ft^2 \cdot °F/$ Btu) and thus small absolute inaccuracies in characterization data can have a large relative impact in simulated performance. For instance if a wall assembly has a relatively high resistance value of 20 $h\text{-}ft^2\text{-}F$/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 factor is that many historic buildings utilize envelope material assemblies that are non-uniform or have been significantly altered over time. This second issue is of concern because assembly and material uniformity are often implicitly assumed when performing energy modeling. Thus even if a historic envelope assembly has been documented in databases or literature the true thermal properties of the building could be considerably different due to non-uniformity of construction or misidentification of the materials.

Basic Parameters

In energy modeling, the basic elements of information to collect and 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. This includes spatial geometry, surface materials and occupancy schedules (which can be highly related to internal gains/losses). Climate data and air exchange rates require more specialized databases and field measurements. Local weather data although available from local weather stations, should be compared to field measurements to see if there are strong correlations to the buildings' microclimates. If site conditions vary greatly compared to the local weather station climate data using a local weather station could be misleading.

In this research, 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.

Material Thermal Properties

Typical material assembly properties that are used in whole building energy modeling are thickness, density, conductivity, permeability, emissivity, reflectance and transmittance. Some of these parameters (such as conductivity, density and thickness) are often used to calculate an overall heat transfer coefficient of material assemblies referred to as the U-value (also U-factor) measured in Btu/h·ft^2·°F. This parameter essentially characterizes the rate of energy (Btu) transferred through one square foot of material assembly per degree of temperature difference between the two sides of the assembly. This research explored nominal and field tested values for the assembly U-values to study their impact on improving energy modeling. The inverse of the U-value is commonly referred to as the R-value or thermal resistance of the assembly (h·ft^2·°F/ Btu).

The material assemblies used in the baseline model for RittenhouseTown Homestead are shown in table 1. The material assemblies used in the baseline model for Roxboro House are shown in table 2. These values are the nominal values using existing data available within the modeling software which are generally derived from published values such as those listed in the 2013 ASHRAE Handbook Fundamentals (ASHRAE 2013). In the case of Roxboro House the recently completed renovation and restoration project also included a portion of new construction using modern materials to provide a new vertical elevator system on the rear (southeast) portion of the project to meet accessibility requirements. The thermal properties of these modern portions of the project are included in the models for relevant areas but are excluded from the table of values for Roxboro House.

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)

Air Exchange Rate

Air exchange rates used in energy modeling typically represent the rate at which outdoor and indoor air are being exchanged within the volume of the building being modeled. This could be through air infiltration/exfiltration which is the air that is brought in or exits the building through cracks and porous envelope assemblies. Alternatively it could be air exchange through openings such as open windows and doors (a.k.a. natural ventilation). This also could be through ventilation equipment such as mechanically driven fresh air and exhaust systems (a.k.a. forced mechanical ventilation). As air is a fluid with heat carrying capacity, the exchange of air between in 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 energy modeling parameter. 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. For RittenhouseTown Homestead the sole means of air exchange is through air infiltration/exfiltration. 1 ACH for RittenhouseTown Homestead (with an interior volume of approximately 12,270 cubic feet) would denote that a volume of air equal to the building's interior volume (12,270 cubic feet) of air per hour would enter and exit the building through infiltration and exfiltration.

A difficultly in modeling historic buildings is to determine an appropriate air exchange rate. 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 energy modeling 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 0.655 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. It should be noted that since air exchange rates due to infiltration and exfiltration are heavily influenced by pressure differentials due to outdoor air temperature and winds the actual infiltration rate varies throughout the day and year.

Internal Gains

In energy modeling the thermal conditioning of spaces is not only dependent on the exterior climate but also on the internal gains. Internal gains are the heat gains due to occupants, lighting, equipment and all other interior sources that produces heat (excluding HVAC systems). For example in an average office space in the United States sensible heat gain due to occupants ranges from 1.3 Btu/h-ft^2 to 2.3 Btu/h-ft^2 and heat gains for equipment ranges from 0.4 Btu/h-ft^2 to 1.1 Btu/h-ft^2. Heat gains for electric lighting in offices ranges from approximately 1.6 Btu/h-ft^2 to 5.1 Btu/h-ft^2 depending on how much daylighting is utilized (Grondzik et al. 2011).

For RittenhouseTown Homestead the building is only physically occupied occasionally for tours and short duration gatherings and is estimated to be occupied less than 4% of the total hours in a year. A typical office building that is occupied for 10-12 hours on weekdays might be closer to being occupied 30% to 40% of the total hours in a year. Since internal gains due to occupant activity, equipment and lighting are often tied to hours when people are expected to be inside the modeled buildings, occupancy schedules are typically used in energy modeling to simulate heat gains and indoor air temperature set points.

For RittenhouseTown Homestead the occupancy schedule was set for 2 hours on a single weekday morning (Friday from 10 AM to 12 PM) and 4 hours on a weekend day (Saturday morning from 10 AM to 2 PM) with an expected number of occupants of 15 people. Roxboro House is intended to be used as an academic facility housing specialty community outreach programs and student group activities. At the time of writing this report this facility was not intended for large class use but rather for smaller to medium sized classroom gatherings. The building has one permanent faculty office and a few meeting rooms. As such the occupancy schedule for this building was estimated to be 2 hours each weekday (from 10 AM to 12 PM) for the meeting rooms with 10 people in each meeting room and 5 hours a weekday for the faculty office with one person (12 PM to 5 PM).

In each of the occupancy cases each person was modeled as being seated doing very light work and generating 245 Btu/h of sensible heat and 155 Btu/h of latent heat (ASHRAE 2013). These heat gain values can be found in chapter 18 of the 2013 ASHRAE Handbook – Fundamentals. Electric lighting can also play a role in creating internal heat gains. For the RittenhouseTown Homestead only a few electric light fixtures are actually used within the building. During the times of expected occupancy these fixtures are generally not needed due to adequate daylighting in the main spaces. Thus for the RittenhouseTown Homestead energy model internal gains from lighting are excluded. For the Roxboro House energy model internal gains from newly installed electric lighting are expected from fluorescent ceiling fixtures. The building is estimated to have a lighting power density of 1.0 W/ft^2 and are generally controlled with occupancy sensors and thus follow the same schedule as the occupancy schedule.

Solar radiation through glazing can also be a significant source of heat gain. This however is typically calculated by the energy modeling software once the appropriate weather and glazing information has been entered into the model.

Climate Conditions: Weather

When running energy simulations the outdoor climate is modeled by using weather files that attempt to represent a typical meteorological year (TMY). The latest generation of these files are known as TMY3 files and use weather data collected between 1976 and 2005 (Wilcox and Marion 2008). These files are available through the U.S. Department of Energy's EnergyPlus website (energyplus.net/weather). 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. The airport weather station is approximately 10 miles away from the two building sites.

Environmental Systems

In energy modeling there are generally two approaches to determining the energy consumed annually for a building. The first approach is to determine the thermal loads of the building without specifying the actual environmental systems. This basically calculates how much energy (BTUs) would need to be added or removed in the form of heat to or from the interior environment over a year to reach target comfort levels. The second approach is to model the actual environmental systems equipment such as heating and air conditioning units to take into account their mechanical efficiency and fuel used when producing or removing heat. In the second approach the thermal loads are first calculated and then the amount of fuel (gas, oil, electricity, etc.) needed to power the HVAC equipment to add or remove heat is calculated. Using publically available fuel price databases or using user provided fuel prices the energy modeling software can then convert thermal loads into fuel used and finally the annual energy costs. The first approach is helpful when trying to evaluate alternatives to building designs without having to define the building's environmental systems and can be quite effective in evaluating and comparing multiple design alternatives. The second approach is helpful in determining the type, size and cost of the equipment needed as well as estimating future operating costs of that equipment. In many retrofit cases, the second approach is used to help determine the time it will take to get a return on an investment when purchasing new mechanical equipment.

For RittenhouseTown Homestead the existing HVAC system was manufactured by Carrier Corporation and consists of a natural gas furnace (model number 58STA110---14116) and is rated at 80% Annual Fuel Utilization Efficiency (AFUE) with 110,000 Btu/h input and 89,000 Btu/h output. It is listed as having 1,515 cubic feet per minute (CFM) of heating airflow and 1680 CFM of cooling airflow. The air conditioning system uses R410A refrigerant and is split between an indoor section for the evaporator coil (model number CNPVP4221ATAACAA) and an outdoor section for the condenser (model number 24ABC636A0030010). The air conditioning system is listed as having a seasonal energy efficiency ratio (SEER) of 15.5 with a nominal cooling capacity of 36,000 Btu/h. The duct system in RittenhouseTown is estimated to have a delivery efficiency of 75% based on typical duct losses for residential sized systems. The HVAC system is controlled via a single thermostat located in the western most room on the second floor. The thermostat is a simple heating or cooling, single set point device and does not accommodate schedules. Given the simplicity of the existing HVAC system and the likelihood of achieving cost effective energy efficiency through equipment upgrades the RittenhouseTown Homestead energy model includes the buildings HVAC systems and is able to calculate fuel consumption and estimate energy costs.

For Roxboro House the recently installed HVAC system is much more complex with six air source heat pumps, a gas fired boiler for fin tube convectors, a ductless split system and two surface mounted electric heaters. The primary thermal conditioning systems are the air source heat pumps which range in capacity from 19.2 MBH to 57.4 MBH for heating and 18 MBH to 60 MBH for cooling using R410A refrigerant with a SEER of 13. This building's environmental systems has the ability to have multiple set points for various zones, occupancy sensors, building use schedules and communication with a facilities management computer system. The HVAC systems for this building were completely redesigned by professional engineers to be as efficient as possible for the intended institutional use and as such are unlikely targets for exploring additional cost effective energy savings via equipment upgrades or retrofits. For simplicity the Roxboro House energy model includes the heat pumps as the only building HVAC system and calculates the thermal loads and costs based on the use of electricity to power the heat pumps. Comparisons between baseline and alternative building retrofits (such as envelope insulation or air tightness improvements) are evaluated on electrical costs savings.

Set Points and Thermostat Schedules

Energy modeling simulations use indoor air temperature set points as targets for controlling HVAC equipment to meet thermal comfort. HVAC equipment in these two buildings is controlled by thermostats. RittenhouseTown Homestead uses a digital thermostat but lacks any scheduling ability and is set at 70°F all year, which is the set point used in the baseline energy model. Roxboro House uses environmental control systems that are capable of implementing a schedule. The baseline model uses a set point of 70°F from 8 AM to 6 PM Monday through Friday. During the cooling season the Roxboro House energy model uses a setback temperature of 80°F from 6 PM to 8 AM Monday through Friday and all weekend. During the heating season the Roxboro House energy model uses a setback temperature of 60°F from 6 PM to 8 AM Monday through Friday and all weekend.

1-D Simulation

Traditionally energy modeling of buildings requires a large degree of generalization and approximation due to the scale of the energy flows being simulated. Heat transfer through the building can be highly non-linear with a great deal of spatial variation due to the non-uniformity of building construction and time related inputs. Thus even though 3-dimensional geometry models are created for simulations, the inherent analysis is mathematically considered to be a series of 1-dimensional heat transfer analyses (IESVE, eQuest and DOE 2.2 all are based on 1-D heat transfer). This means that for each thermal zone (for instance a room) and for each surface (for instance a wall) the entire element/zone is approximate as 1-dimensional element/zone. This means that even though the surface may have surface changes, non-uniformity or even different measured temperatures, the simulation will calculate the element as a single point, with a single resistance value. In the case of a zone, even if the room has a large thermal variation in the space, the simulation will approximate this as a single point value. Thus for the sake of simulation a room will be calculated to have a uniform temperature for the entire volume. Now this is done for the most part due to computational necessity and analytical pragmatism. The purpose of most energy models is not to determine the temperature gradient within a space or the detailed variation of heat flows through a wall but to determine building scale heat flows and to calculate annual energy consumption. Thus for many buildings 1-D heat transfer simulations are entirely appropriate to determine bulk heat flows and their related energy consumption.

Although most energy modeling software use 1-D heat transfer analysis this still takes into account a complex set of thermal interactions between rooms (zones), surfaces, solar radiation, climate and internal activity. Most energy modeling programs also take into account time effects, dynamic climate and internal conditions and typically calculate these at least at hourly or sub-hourly time intervals across an entire calendar year. This project used a 6 minute time interval for dynamic simulations. The primary thermal analyses in energy modeling are conduction, convection and radiation heat transfer. These are used to determine the amount of energy needed to environmentally condition the building and the resulting predicted energy use calculated in an energy model. This can usually be determined daily, monthly or annually to help one understand the magnitude and estimated costs associated with energy use and design decisions.

Retrofits

While occupant behavior and user equipment (known as plug loads) can have a significant impact on energy consumption in buildings, they are generally not considered target areas for building energy savings. Therefore the most significant energy savings studied in energy models typically will come from (1) improving environmental systems equipment efficiency, (2) improving air tightness of the building envelope including doors and windows, (3) improving the efficiency and controls of lighting fixtures while maximizing daylighting, and (4) improving the insulation and thermal resistance of the building envelope. In this research project methods 1, 2 and 4 were studied for potentially improving the energy efficiency of each building. Improving the indoor electrical lighting fixtures and daylighting was not studied for two reasons. The first reason is that since both of these buildings are registered historic buildings it would be undesirable to modify or alter the existing glazed openings. The second reason is that RittenhouseTown Homestead already has minimal electrical lighting in use and Roxboro House has already installed highly efficient lighting fixtures, occupancy sensors and controls such that there would be little to no energy efficiency improvement gained from attempting to upgrade the lighting in either building.

For RittenhouseTown Homestead the following retrofits were studied:

1) Improving the energy efficiency of the HVAC equipment from 80% AFUE to 98% AFUE for the natural gas furnace, increasing the Air Conditioning equipment from 15.5 SEER to 24 SEER and reducing the duct losses from 25% to 15%. This would require all new HVAC equipment with an improved thermostat at an estimated installed cost of $8,000. The improved thermostat will allow for programming of set points and the use of a schedule of setbacks similar to Roxboro House. Insulating the ductwork and sealing all seams, joints and transitions of ductwork is estimated to cost $1,500. These estimates and those in the proposed retrofits below were provided via verbal conversations with local HVAC and building renovation contractors during July of 2015.
2) Improving the air sealing via caulking, taping, repairs to openings (doors and windows), and patching cracks and cracks in the building envelope to achieve an air infiltration rate of 0.55 ACH has an estimated cost of $2,000.
3) Improving the insulation of the walls of this building is generally not viable as the walls are load bearing masonry, exposed stone on the outside and a plaster finish on the inside without any internal cavity spaces. Thus adding insulation would require adding thickness to the assembly. Therefore improving building envelope insulation was only considered in the attic roof area. Since this area already has fiberglass batt insulation between the roof rafters the retrofit would be to replace the existing batts with higher R-value (6.5 $h \cdot ft^2 \cdot °F$/ Btu per inch) spray foam insulation providing approximately R40 between the rafters and then also adding approximately 16 inches of R3.8/inch insulation (providing approximately R60) on the floor to help improve thermal isolation of the unoccupied attic from the rest of the building. This insulation installation is estimated at a cost of $4,000.

For Roxboro House the following retrofits were studied:

1) Improving the air sealing via caulking, taping, repairs to openings (doors and windows), and patching cracks and gaps in the building envelope to achieve an air infiltration rate of 0.55 ACH has an estimated cost of $1,500. Although this building is larger than the RittenhouseTown Homestead, it has been very recently reconstructed with all new glazed openings and restored exterior walls.
2) Improving the insulation of this building would most likely require closed cell foam (6.5 $h \cdot ft^2 \cdot °F$/ Btu per inch) injected in the wood framed air spaces in the exterior walls. The attic spaces already have modern high quality insulation and thus are not a target for improvement. The insulation installation is estimated at a cost of $10,000.

The energy modeling results are provided and discussed in the Results and Discussion section of this report.

Verification & Testing (Task 1)

Historic buildings and existing buildings in general have the benefit of being able to be surveyed for building characterization information. Many energy modeling efforts collect geometric data (size, shape, dimensions) and surface materials for modeling input but often do not utilize techniques to verify material uniformity and air infiltration rates. These two can be readily examined by established onsite non-destructive testing techniques. 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 models. On site sensor readings and tests were taken at regular intervals throughout the project to obtain data for comparison and analysis. These data points also helped in calibrating the energy model with the goal of increasing accuracy in predicting future thermal transfer behavior.

Testing Equipment

The following equipment were purchased 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

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 above 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 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*" which is included in appendix B (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). Additional information and requirements of this testing methodology are discussed in the article.

The thermal images taken with the FLIR E6 camera the digital files can be processed to find spot and average surface temperature values. Adobe Photoshop CS5 was used to process the files by using the Histogram window while selecting regions for analysis. The Histogram window provides mean and standard deviation information in the range of 1 to 255 for luminosity intensity. Using a grayscale thermal image the luminosity range can be correlated with surface temperatures. For instance the recorded range of a sample image (figure 12) is 21.2°F to 42.1°F. When selecting only the region of the wall a total of 9,294 pixels are selected (figure 14). The Histogram window provides the average luminosity value as 137.38 out of 255. The range size is calculated as 42.1°F

-21.2°F=20.9°F. Thus each increment between 1 and 255 has an incremental value of 20.9°F /255=0.08196°F. The average luminosity value is then multiplied by the incremental value and added to the lower limit of the range. Thus the average surface temperature (in figure 14) is 137.38 x 0.08196°F + 21.2°F = 32.46°F.

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. This test was conducted on the north exterior wall in a location that is shaded by the building. The six hour steady state time averaged thermal resistance value (observed between 12 AM to 6 AM) was 7.83 h·ft²·°F/ Btu (which corresponds to a U-value of 0.1277 Btu/h·ft²·°F). Recall that the baseline model input for the exterior 23 inch thick masonry wall is 2.66 h·ft²·°F/ Btu (which corresponds to a U-value of 0.3756Btu/h·ft²·°F).

Using the thermal images and sensor readings taken at 5:59 AM at RittenhouseTown Homestead on December 27, 2014 the following data was collected:

- heat flux, Q_i = 3.5198 Btu/h·ft²
- temperature of air inside, T_{in} = 57.3°F
- temperature of the inside surface, T_{is} = 54.086°F
- temperature of the outside surface T_{os} = 37.769°F
- temperature of air outside, T_{out} = 29.2°F

This can be used to calculate the thermal resistance of the air films:

- inside air film resistance, $R_{ai} = (T_{in}-T_{is})/Q_i$ = 0.913 h·ft²·°F/ Btu
- outside air film resistance, $R_{ao} = (T_{os}-T_{out})/Q_i$ = 0.2.435 h·ft²·°F/ Btu

Then using the air film resistances along with the sensor readings the envelope resistance is:

$R_{env} = R_{ao}(T_{in}-T_{os})/(T_{os}-T_{out}) - R_{ai}$ = 4.636 h·ft²·°F/ Btu

The thermal image of the north wall of RittenhouseTown Homestead has an average surface temperature reading of 37.60°F as can be seen in figure 15. By replacing the spot reading of T_{os} = 37.769°F with the average surface reading of T_{os} = 37.64°F for the 2nd floor walls and 36.88°F for the first floor walls this updates the calculated thermal resistance of the outside air and envelope. Thus R_{ao_2ndFl} = 2.398 h·ft²·°F/ Btu and R_{env_2ndFl} = 4.672 h·ft²·°F/ Btu for the area isolated in the image that corresponds to the 2nd floor masonry walls (excluding openings and visual obstructions). Likewise R_{ao_1stFl} = 2.182 h·ft²·°F/ Btu and R_{env_1stFl} = 4.888 h·ft²·°F/ Btu for the area isolated in the image that corresponds to the 1st floor masonry. By using a ratio of instant/time averaged values the area & time averaged value can be estimated for the masonry walls' thermal resistance values:

<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

1st Floor, 23 inch thick masonry stone wall:

- 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.

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. This test was conducted on the south exterior wall in an area in permanent shade by a porch roof. The four hour steady state time averaged thermal resistance value (observed between 4 AM to 8 AM) was 3.93 h·ft²·°F/ Btu (which corresponds to a U-value of 0.2545 Btu/h·ft²·°F). Recall that the baseline model input for the exterior wood framed wall is 3.60 h·ft²·°F/ Btu (which corresponds to a U-value of 0.2779 Btu/h·ft²·°F).

Using the thermal images and sensor readings taken at 6:39 AM at Roxboro House on February 13, 2015 the following data was collected:

- heat flux, Q_i = 11.694 Btu/h·ft²
- temperature of air inside, T_{in} = 69.85°F
- temperature of the inside surface, T_{is} = 62.73°F
- temperature of the outside surface T_{os} = 15.13°F
- temperature of air outside, T_{out} = 9°F

This can be used to calculate the thermal resistance of the air films:

- inside air film resistance, $R_{ai} = (T_{in}-T_{is})/Q_i$ = 0.609 h·ft²·°F/ Btu
- outside air film resistance, $R_{ao} = (T_{os}-T_{out})/Q_i$ = 0.524 h·ft²·°F/ Btu

Then using the air film resistances along with the sensor readings the envelope resistance is:

$R_{env} = R_{ao}(T_{in}-T_{os})/(T_{os}-T_{out}) - R_{ai}$ = 4.070 h·ft²·°F/ Btu

The thermal image of the south wall of Roxboro House has an average surface temperature reading of 12.186°F as can be seen in figure 21. By replacing the spot reading of T_{os} = 15.13°F with the average surface reading of T_{os} = 12.186°F this updates the calculated thermal resistance of the outside air and envelope to R_{ao} = 0.272 h·ft²·°F/ Btu and R_{env} = 4.322 h·ft²·°F/ Btu for the area isolated in the image that corresponds to the wood framed wall (excluding openings and visual obstructions). By using a ratio of instant/time averaged values the area & time averaged value can be estimated for the wood framed wall's thermal resistance value:

- 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. See figures 9-17 for images related to the testing for RittenhouseTown Homestead and figures 18-22 for images related to testing for Roxboro House.

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.


Figure 9. N.wall at thermocouples, RittenhouseTown

Figure 10. Thermocouples

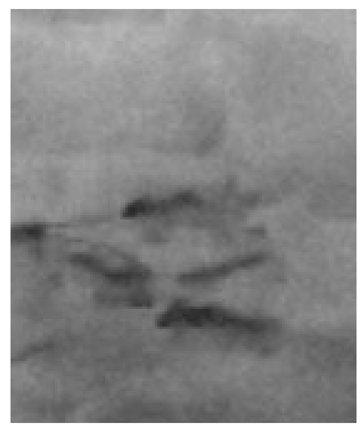


Figure 11. Thermal image at sensors

Figure 12. Full 160x120 pixel image, close up taken at 6:58 AM

Figure 13. Full 160x120 pixel image, North wall at 6:59 AM

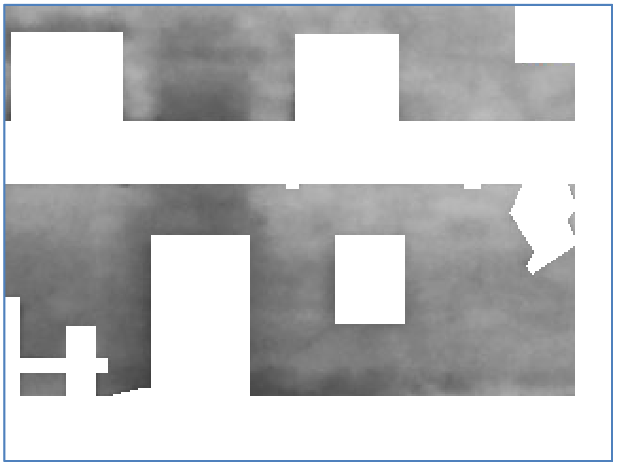


Figure 14. Cropped image of wall area only
Average temperature = 32.46°F
9,294 Pixel Sensor Readings

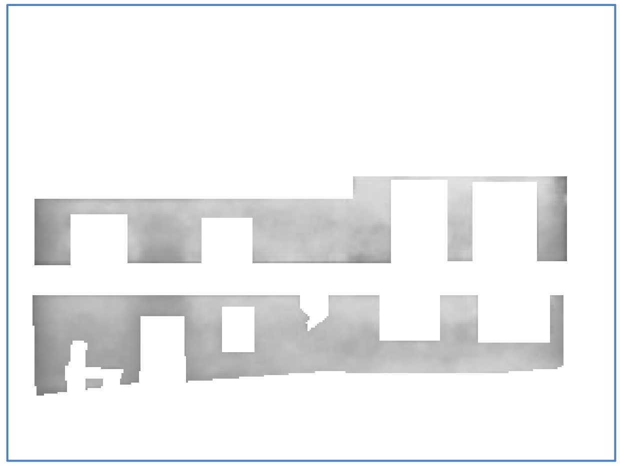


Figure 15. Cropped image of wall area only
Ave. temp. = 37.60°F, 2nd fl. = 37.64°F, 1st fl. = 36.88°F
3,818 Pixel Sensor Readings

Figure 16. Thermal datalogger

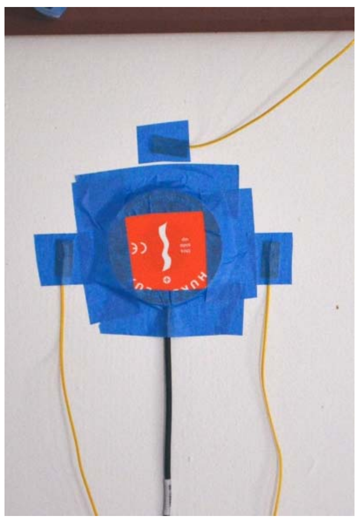


Figure 17. Heat flux plate on inside wall

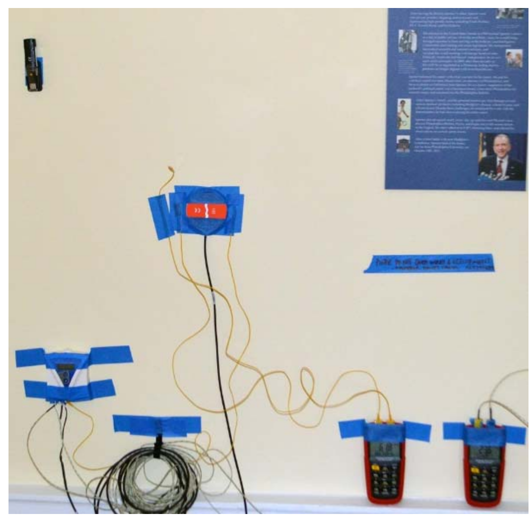


Figure 18. Dataloggers and heat flux plate at Roxboro

Figure 19. Thermal image, South wall at 6:35 AM

Figure 20. Photograph, North wall at 6:35 AM

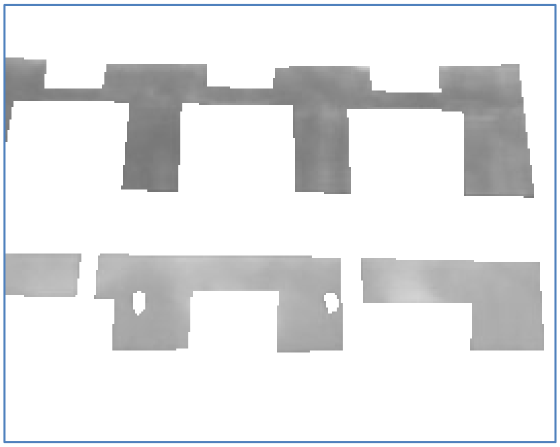


Figure 21. Cropped image of wall area only
Average temperature = 12.186°F
9,294 Pixel Sensor Readings

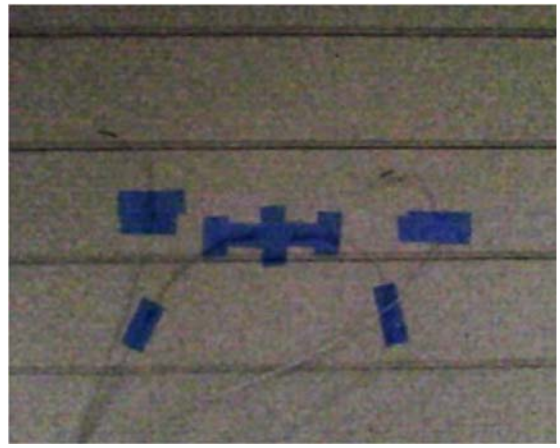


Figure 22. Photograph of wall at exterior sensors

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 figures 23-26 for images of the door blower tests.

In-Situ Air Infiltration

A door blower test for RittenhouseTown Homestead was performed on May 14, 2014. 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. Thus the door blower tests results can be used to estimate a natural air exchange rate of 1.668 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 0.831 ACH for Roxboro House.

When comparing these air infiltration rates derived from the door blower tests to the baseline value of 0.655 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.

Figure 23, 24. Door blower at RittenhouseTown

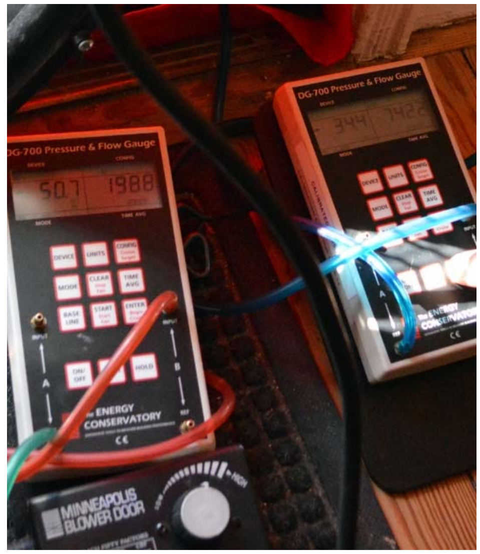


Figure 25, 26. Door blower at Roxboro House

Monitoring (Task 3)

To improve accuracy of the energy models and the energy modeling process this research conducted regularly schedule site readings for actual metered building energy consumption, indoor and outdoor air temperature, humidity and rainfall. These were used to calibrate and improve the energy models. At the RittenhouseTown Homestead site a small lab grade weather station (Davis Instruments 6250 Vantage Vue Wireless Station, purchased for $665) was installed to help monitor differences between local/regional climate (from local weather stations) and micro-climate at the target building site.

Weather comparison

Figure 27 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 grpah 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 energy model's 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 energy modeling. 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.

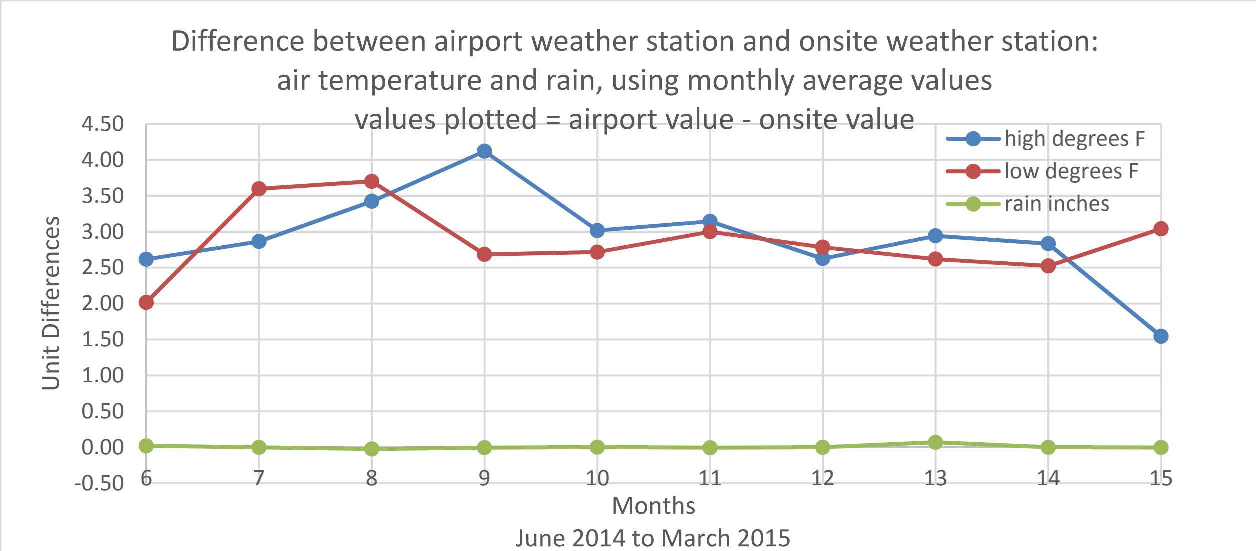


Figure 27. Comparison of weather station data between the RittenhouseTown Homestead site and the NE Phila. Airport

Site Energy Use

For RittenhouseTown Homestead the monthly site energy use for natural gas and electricity were both available for years 2009 through 2014. These values are listed in table 3 for natural gas and table 4 for electricity. Plots of these values are shown in figure 28 and 29. A two-year average using 2013 & 2014 electricity consumption was calculated (shown in table 4 and figure 29) due to the fact that the current air conditioning equipment (modeled in the energy model) has only been active since 2013. These past values help provide a comparison to the results calculated by the energy models. Looking at table 3 and figure 28 the natural gas use appears to be relatively consistent across multiple years. When looking at table 4 and figure 29 however the electrical use appears to be less consistent with some significant variation in the summer months. This is likely due to user interaction with the thermostat to change set points during the summer months.

Table 3
Actual Natural Gas Consumption for RittenhouseTown Homestead in CCF

		Year						2009-2014
		2009	2010	2011	2012	2013	2014	6 year ave
Month	1	269	282	275	174	305	306	268.5
	2	197	188	180	111	176	279	188.5
	3	126	98	151	41	176	159	125.2
	4	28	55	19	17	56	53	38.0
	5	7	9	3	3	11	4	6.2
	6	5	4	3	3	0	4	3.2
	7	4	4	3	0	0	4	2.5
	8	5	5	3	0	0	3	2.7
	9	7	34	7	30	0	5	13.8
	10	7	97	97	106	88	76	78.5
	11	64	183	133	165	290	204	173.2
	12	315	348	169	231	172	247	247.0

Table 4

Actual Electricity Consumption for RittenhouseTown Homestead in kWh

		Year						2013-2014
		2009	2010	2011	2012	2013	2014	2 year ave
Month	1	36	154	177	380	231	195	213
	2	32	243	145	404	220	213	216.5
	3	30	72	98	113	175	135	155
	4	26	27	24	70	132	54	93
	5	27	12	14	18	66	132	99
	6	7	15	228	10	73	482	277.5
	7	7	19	717	1893	459	270	364.5
	8	7	30	240	437	460	285	372.5
	9	17	31	595	429	35	219	127
	10	6	57	383	286	88	164	126
	11	4	104	353	135	201	178	189.5
	12	209	201	383	206	233	140	186.5

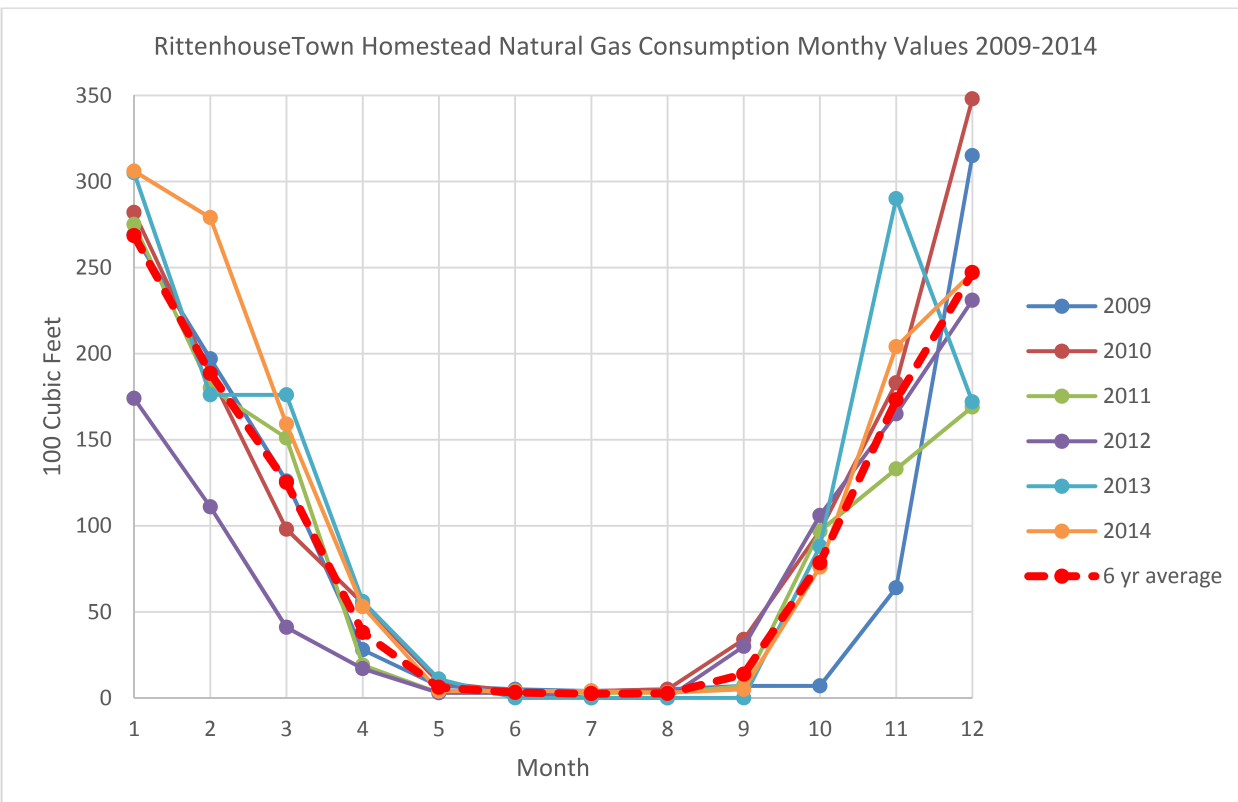


Figure 28. RittenhouseTown Homestead Actual Natural Consumption

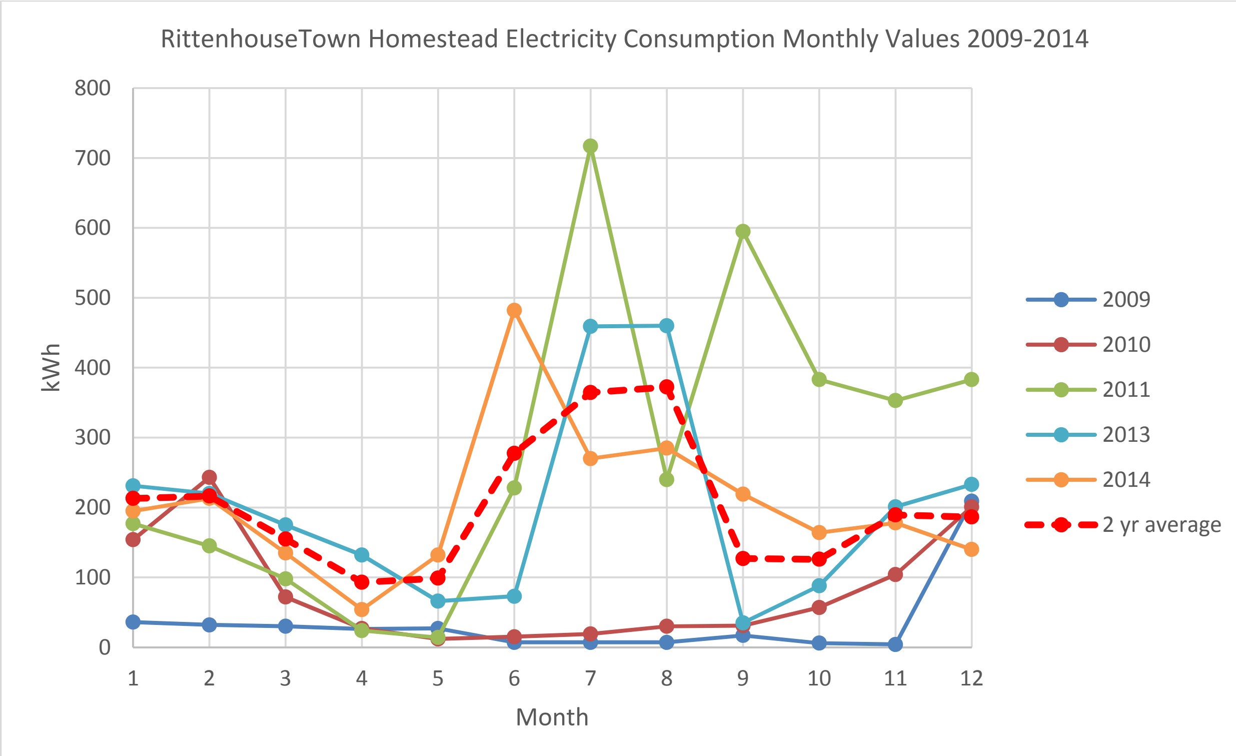


Figure 29. RittenhouseTown Homestead Actual Electricity Consumption

Results and Discussion

The results of the energy models for RittenhouseTown Homestead are shown in table 5. The results for Roxboro House are shown in table 6. These include the baseline models using typical assumptions, the in-situ models using thermal resistance and air infiltration test data, and the retrofit models as described earlier (in the Energy Modeling – Retrofits section of the report). For each of the models the total energy due to lighting loads, heat gain from occupants and thermal conditioning were calculated. For RittenhouseTown Homestead this was summarized as the annual energy in electricity and natural gas and then converted to costs. For Roxboro House the building's primary HVAC system are six air-source heat pumps and thus operate on electricity. 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 Agencies 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 baseline models predicted a higher amount of energy use when compared to the 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. In regards to the potential of finding cost effective retrofits, both buildings appear to have the ability to save approximately $1,700 per year by implementing improvements to the building with capital costs that are recouped within approximately 6 to 7 years.

Table 5
RittenhouseTown Homestead Energy Modeling Annual Energy Consumption Results

	Baseline Existing	In-situ Model Existing	Retrofit 1 HVAC & Ductwork	Retrofit 2 Air Sealing	Retrofit 3 Attic & Roof Insul.	Retrofit 1a Thermostat Only	Retrofits 1,2,3 (all)	Retrofits 1&2
electricity (kWh)	9,025	6,030	2,902	5,770	5,980	4,503	2,786	2,822
natural gas (CCF)	1,876	1,988	1,128	1,387	1,953	1,566	763	784
electricity cost	$1,367.27	$913.53	$439.61	$874.10	$905.94	$682.13	$422.13	$427.59
natural gas cost	$1,899.89	$2,013.78	$1,142.78	$1,404.53	$1,978.66	$1,586.55	$773.34	$793.83
Total annual cost	$3,267.16	$2,927.31	$1,582.39	$2,278.62	$2,884.61	$2,268.68	$1,195.47	$1,221.42

	Retrofit 1 HVAC & Ductwork	Retrofit 2 Air Sealing	Retrofit 3 Attic & Roof Insul.	Retrofit 1a Thermostat Only	Retrofits 1,2,3 (all)	Retrofits 1&2
Reduction vs In-situ =	45.94%	22.16%	1.46%	22.50%	59.16%	58.27%
Saved each year =	$1,344.92	$648.69	$42.71	$658.63	$1,731.84	$1,705.89
Estimated capital cost =	$9,500	$2,000	$4,000	$200	$15,500	$11,500
Years for ROI =	7.06	3.08	93.67	0.30	8.95	6.74

Table 6
Roxboro House Energy Modeling Annual Energy Consumption Results

	Baseline Existing	In-situ Model Existing	Retrofit 1 Air Sealing	Retrofit 2 Wall Insulation	Retrofits 1&2
electricity (kWh)	66,491	57,397	55,129	47,893	45,782
electricity cost	$10,073.40	$8,695.63	$8,351.99	$7,255.74	$6,935.99

	Retrofit 1 Air Sealing	Retrofit 2 Wall Insulation	Retrofits 1&2
Reduction vs In-situ =	3.95%	16.56%	20.24%
Saved each year =	$343.64	$1,439.89	$1,759.64
Estimated capital cost =	$1,500	$10,000	$11,500
Years for ROI =	4.36	6.94	6.54

When comparing the various retrofit combinations and predicted energy cost savings it becomes clear that for RittenhouseTown Homestead performing the proposed attic and roof insulation improvements have little value since the model predicts a less than 2% reduction in annual energy costs and a payback period of nearly 94 years. Interestingly the cheapest improvement of just replacing the single set point thermostat with a programmable thermostat with setbacks had a significant savings for RittenhouseTown Homestead of nearly 23% and a payback period of 0.3 years. Because the Homestead was measured to have a natural air exchange rate of 1.668 ACH the air sealing retrofit to achieve 0.55 ACH is predicted to reduce energy costs by approximately 22% with a payback period of 3 years. By performing the HVAC, ductwork and air sealing retrofits the energy model predicted an annual savings of $1,705.89 which represents a 58.27% reduction in the estimated current energy costs (as predicted by the in-situ model).

For Roxboro House the air sealing retrofit provides only a savings of approximately 4% per year compared to the existing in-situ model. This project's capital cost however is relatively low and thus the payback period is approximately 4 years and may still be worth considering. The wall insulation improvement using foam injected into the air cavity reduced predicted annual energy costs by approximately 17%. By performing both the air sealing and wall insulation the energy model predicted an annual savings of $1,759.64 which represents a 20.24% reduction in the estimated current energy costs (as predicted by the in-situ model).

Considerations regarding results and retrofits

The results regarding energy modeling and predict energy use should be considered as a way to help inform those making operating and design decisions. The actual energy use can and will vary from predicted use from energy modeling especially due to occupant behavior, schedules and weather events that cannot be easily predicted and included within an energy model. For instance the models used in this project did not include plug loads such as kitchen and office equipment since these were not considered targets for building design improvement. Also the schedules used are estimated and may not represent actual use. Thus the benefit of energy model often is first in helping create an order of magnitude study that becomes a baseline or framework to evaluate alterative designs and operations that impact energy consumption. Once that baseline is created alternatives can be explored in comparison with the estimated baseline. The simple analysis in regards to capital costs and expected payback period presented in this report does not take into account any lost time, access or use of the building during retrofit installations. These and other factors would most likely need to be weighed in a decision making process.

When looking at the annual energy use predicted by the RittenhouseTown Homestead models and comparing them to the actual energy use the magnitude of results although similar show that the existing in-situ model currently over predicts energy consumption by about 40-50% versus peak historic energy use in the last 6 years. Given the high degree of variation in the electrical energy use in the past 6 years it may be that the occupancy and schedules used in the energy models do not well represent the more intermittent actual use of the building.

In both buildings adding insulation and air sealing are considered as potential retrofit strategies. It should however be noted that air sealing and/or adding insulation to an existing historic envelope assembly is somewhat controversial due to the potential of interlayer moisture accumulation. To responsibly consider installing new insulation to existing historic assemblies and or significantly air sealing an envelope, heat, air and moisture (H.A.M.) analysis should be performed to determine whether or not there is a significant risk of mold or moisture damage. Although the use of H.A.M. analysis was outside of the time and scope of this research project it should be noted that Oak Ridge National Laboratory provides a free version of the software WUFI which can be used to model and perform H.A.M. analysis using a personal computer.

Conclusion

This research project sought to improve energy modeling methods of historic buildings by considering modeling methods and retrofit proposals targeted at improving energy efficiency without negatively impacting the historic character of the buildings being studied. This was done by both traditional energy modeling techniques along with low-cost verification techniques to improve building characterization parameters used in energy modeling. 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 energy models and proposed retrofits provided a better approximation of the potential energy cost savings and payback period when employing different retrofit options. Using this method of energy modeling coupled with field testing should improve confidence and accuracy in energy modeling activities for historic buildings and ultimately help provide more meaningful energy data in the decision making process for owners and operators of historic buildings.

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Appendix A: Summary of Pertinent Literature Reviewed with Brief Descriptions of the Relevance to the Research Project.

Five key topics were researched via literature in preparation for and concurrently with research activities. These topics are:

A. Historic Building Energy Modeling and Energy Modeling Accuracy
B. Non-Destructive Techniques for the Evaluation of Historic Buildings
C. Other Studies Using Similar Technologies
D. Importance of Accurate Weather Data and Local Micro-climate
E. Review and Comparison of Commercially Available Energy Modeling Software

The following sections provide information on twenty-four articles/papers that were reviewed and found to be pertinent to this research project.

A. Historic Building Energy Modeling and Energy Modeling Accuracy

Energy modeling is commonly used to determine energy use and energy saving strategies for historic buildings. However, building an energy model of a historic building often requires many assumptions, as it can be difficult to determine exact construction techniques and materials. Many historic buildings have undergone multiple renovations or additions, which may or may not be documented in construction documents. Early construction techniques can lead to variation in thickness and insulation level throughout a single façade. Property owners are typically reluctant to allow intrusive investigations into the building structure and therefore nondestructive techniques must be used. It is important to determine the impact these factors have on the accuracy of the energy model. The following references investigate these issues and other issues related to creating energy models for historic buildings.

1. Widström, Torun. "Enhanced Energy Efficiency and Preservation of Historic Buildings: Methods and Tools for Modeling." PhD diss., KTH, 2012. <http://www.diva-portal.org/smash/get/diva2:555391/FULLTEXT03>.

This thesis provides an overview of issues related to improving the energy efficiency of historic buildings using energy modeling techniques.

The paper discusses potential problems and concerns related to energy evaluation of historic buildings. Concerns include: complexity of geometry, lack of insulation or moisture barrier, need for nondestructive or invasive measures, lack of heterogeneity, and ventilation. The author also looks at the danger of using a single reference point for analysis.

The paper also discusses issues related to using energy simulation software to evaluate historic buildings. One of the challenges is the balance between complexity and simplification. The author outlines a system to determine how complex an energy model should be based on the components of the project and also discusses model uncertainty in terms of availability, variability, complexity, unreliability, and insufficiency.

This paper provides an overview of the issues and concerns our research is attempting to address. The paper addresses the issues involved with collecting data that accurately represents the building façade that have led us to explore using thermography to provide a reading of the variation of the façade. This article provides support for the need for more accurate energy modeling of historic buildings.

2. Ascione, F., F. de Rossi, and G.P. Vanoli. "Energy retrofit of historical buildings: theoretical and experimental investigations for the modeling of reliable performance scenarios." *Energy & Buildings* 43, no. 8 (2011): 1925-1936.

This article uses an Italian historic building, Palazzo dell'Aquila Bosco-Lucarelli, to analyze ways to improve the accuracy of a historic building energy model. The building was analyzed with site surveys that included core sampling, endoscopies and in situ monitoring in order to create the energy model. The model was then compared and calibrated using monthly bills as energy historical consumptions.

Once the model is completed, six proposed retrofits are evaluated, first independently and second with the most promising coupled. It is proposed that improving the building envelope will reduce the heating load and the cooling load be reduced by increasing the set point temperature. The proposed improvements offer a 22% decrease in overall energy use.

This article represents a standard method for improving and measuring the accuracy of historic building energy models. Calibrating an energy model using historical consumption is a widely accepted method of verifying energy model results. This research relies on invasive techniques such as core sampling to gather information about the building structure. Since invasive methods are not desirable for historic structures and often prohibited, the proposed research is attempting to find ways to accurately gather information about the building structure using entirely non-invasive techniques.

3. Cluver, John H., and Brad Randall. "Saving Energy in Historic Buildings: Balancing Efficiency and Value." *Planning for Higher Education* 40, no. 2 (2012): 13-24.

This article looks at using energy modeling and life-cycle costing to find the most effective ways to save energy in a historic building. Once an energy model is constructed and verified based on existing energy bills and documentation, scenarios should be constructed to analyze the effects of various improvements. Improvements should be run in combinations in addition to individually in order to properly determine the impacts.

The results of the energy simulation are incorporated with a cost analysis to create the life-cycle cost assessment. The life-cycle cost includes the cost of manufacture and installation, operation, maintenance, and replacement. The time of the lifecycle considered will vary based on the use and ownership.

Swift Hall at Vassar College is examined as a case study. It was built in 1902 and little has changed from the original building design. The building has 3 floors, a stone foundation and 12-inch masonry walls. Energy simulation found lighting and heating to be the largest annual energy uses. After various scenarios were modeled and cost assessed, upgrading light fixtures and controls and improving insulation in the attic were the two most cost-effective energy-saving solutions.

This research uses the standard technique of using historic energy bills to verify energy model results. We are looking to improve this standard practice and find a more accurate way to verify building performance.

4. Leigh, Benjamin and Sarah Welniak. "Energy Efficiency in Historic Residences: A Case Study." Report, North Charleston, South Carolina, The Sustainability Institute, May 2010.

This paper is a case study regarding energy efficiency improvements of historic structures in Charleston, South Carolina. The goal of the research is to establish guidelines for improving historic building's energy efficiency without compromising their historic status. Baseline energy models were created and analyzed using the Home Energy Rating System (HERS). Site visits were completed to gather information including blower door testing and duct blaster testing. Energy modeling was done in REM/Rate software and was verified by a third party quality assurance group. The model is then used to assess potential improvements and their cost-benefit. An improvement analysis report is created listing priorities for repair and their cost.

The paper provides a summary of common issues and terminology related to efficiency in historic buildings. Finally, five buildings were analyzed using the previously laid out framework. The buildings are all homes and their ages range from the mid-18th century to the early 20th century. The existing efficiency of the buildings varies with envelope leakage rates from 42% to 149% and duct leakage rates from 3% to 134%. For each building, a 'likely' and a 'best case' improvement scenario was created. The study concludes that reducing air leakage is a very effective improvement and replacing windows was not a cost effective solution in most cases.

This paper discusses standard techniques for evaluating the efficiency of historic buildings such as blower door testing and duct blaster testing. Our research proposes to use standard techniques but to also improve upon them by also investigating the façade to gain a more detailed assessment of the heat transfer of the façade.

5. Jenkins, David. "Energy Modelling in Traditional Scottish Houses: Heriot-Watt University Analysis of Potential CO2 Saving of Building Variants." Report, Historic Scotland Technical Conservation Group, November 2008. Web. 10 December 2013. <http://www.historic-scotland.gov.uk/energy-modelling-scottish-houses.pdf>.

This paper looks at the importance of energy modeling of historic houses in Scotland in order to understand the most effective way to conserve energy in these buildings. 23% of Scotland's dwellings are made of traditional sandstone or granite construction. The project uses the "Tarbase Model" to collect information and assumptions.

Three building variants are examined, the terraced flat, the cottage, and the detached house. Both specific and general improvements are made for each building. Improvements estimated a 24% carbon savings to the terraced flat, a 46% carbon savings to the cottage and a 40% saving to the detached house. The paper also explored the opportunities for onsite generation of renewable energies at each site. The researchers conclude that overall heat loss through walls and roofs is the most universal issue when approaching energy efficiency in historic homes. They also note that moisture content and how the building retains moisture are significantly different than modern buildings. Efficiency factors such as lighting and appliances vary more by individual building and need to be examined on a case by case basis.

This study uses standard practices for energy modeling and the "Tarbase Model" for information and assumptions. We can examine this model to determine how it compares to the collection techniques our research is proposing.

B. Non-Destructive Techniques for the Evaluation of Historic Buildings

In many cases when investigating the structure of a historic building, invasive measures such as core sampling to determine material layers in a façade will not be allowed due to preservation requirements. Therefore, it is necessary to use non-destructive techniques such as thermography, impulse radar, acoustical methods, and fiber optics to gather information regarding the structure. The following articles investigate the applications of various non-destructive techniques and their accuracy.

1. Avdelidis, N. P., and A. Moropoulou. "Applications of infrared thermography for the investigation of historic structures." *Journal of Cultural Heritage* 5, no. 1 (2004): 119-127.

This article looks at thermography as a tool for historic preservation. It discusses the passive and active approaches for infrared thermography. The passive approach is typically used in civil engineering structure inspections and examines qualitative means. In the active approach, a heating or cooling system is used allowing quantitative data to be collected.

The article then discusses various conservation approaches that can benefit from thermography techniques. The article concludes that infrared thermography can be a helpful tool in appraising and conserving historic structures.

This article discusses the standard way that infrared thermography is used in relation to historic buildings. This study uses thermography to collect qualitative data, while we are attempting to match the qualitative analysis to quantitative data.

2. Danese, Maria, Urška Demšar, Nicola Masini, and Martin Charlton. "Investigating material decay of historic buildings using visual analytics with multi-temporal infrared thermographic data." *Archaeometry* 52, no. 3 (2010): 482-501.

This article discusses using thermography and visual analytics to analyze air leaks and moisture in historic buildings. The article looks at a Romanesque church as a case study. As opposed to a thermographer analyzing a single static picture, this article proposes using the visual analytics method, which allows the researcher to look at data from a spatial and temporal perspective simultaneously. The goal of the study is to try to identify patterns in the structure to identify the type of material used and level of decay. The study looks at various thermographs taken at different points in time and compares the change in each pixel over time. This approach seems to be affective for collecting qualitative data, but does not offer any quantitative results.

This article presents an alternative to the standard way that thermographs are analyzed and seeks to look at change overtime. The approach used for comparing pixels over time may be helpful for our research, however unlike this study, we are attempting to gain quantitative data regarding the building structure.

3. Silman, Robert. "Applications of non-destructive evaluation techniques in historic buildings". APT Bulletin 27, no. 1-2 (1996): 69-73.

This article looks at various techniques for nondestructive evaluation of historic buildings. The first technique is impulse radar, which can help to determine hidden building components and help to measure them. The next are acoustical methods, which use vibrations to determine the properties and conditions of building materials. The next technique is infrared thermography to measure heat loss. The last technique is fiber optics, which creates a small hole and inserts a fiber optic device to transmit an image. These techniques are all limited and do not provide concrete qualitative data, but can be useful in determining the condition of existing building materials in a nondestructive manner.

This article discussed various nondestructive analysis techniques, but the most relevant to our research is the infrared thermography technology. The study provides an overview of how the technique is typically used in standard practice in regards to historic buildings.

4. Kandemir-Yucel, A., A. Tavukcuoglu, and E.N. Caner-Saltik. 2007. "In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity." *Infrared Physics & Technology* 49, no. 3 (2007).

This article discusses using a combination of thermography and ultrasonic velocity measurements as a nondestructive technique to assess timber in historic buildings. A 13th century mosque was used as a case study. It has stone masonry walls with timber pillars that support a timber ceiling. The goal of the study was to determine the deterioration of the timber elements. The moisture level of the timber was studied in a laboratory setting, in addition to the in situ studies. The laboratory results were compared to the in situ results to determine that based on the ultrasonic velocity tests, the pillars were sound. The thermography identified the thermal gradation in the timber related to its proximity to stone. The combined techniques were effective for identifying the conditions of the pillars, but did not offer quantitative data.

This study uses standard techniques for thermography, but pairs them with a unique moisture analysis technique. While the moisture analysis technique does not apply to our research, we can learn from the thermography analysis technique used.

5. Hoyano, Akira, Kohichi Asano, and Takehisa Kanamaru. "Analysis of the sensible heat flux from the exterior surface of buildings using time sequential thermography." *Atmospheric Environment* 33, no. 24 (1999): 3941-3951.

Time sequential thermography and sensible heat flux were measured in order to determine the surface temperature distribution and sensible heat flux of a building facade.

This study focuses on heat flux of a building at different times of day. It does not use heat flux sensors to determine heat flux, but rather uses the thermography camera to determine the surface temperature at different times of day and compares that to the air temperature. Then an equation is used to calculate the heat flux from that data. It does not appear that they verified their findings with an actual heat flux meter. The paper acknowledges that the temperature measured from the thermograph is radiant temperature and not surface temperature. Since there is not a formula correlating the two, they are considered to be equivalent except in areas where emissivity is particularly low.

This study uses thermography to analyze the building heat flux by measuring building surfaces. This article suggests a method for determining heat flux without the use of a heat flux sensor, which could be a useful technique for our proposed research.

6. Fokaides, Paris A., and Soteris A. Kalogirou. "Application of infrared thermography for the determination of the overall heat transfer coefficient (U-Value) in building envelopes." *Applied energy* 88, no. 12 (2011): 4358-4365.

In this study infrared thermography is used to determine the U-value of building envelopes. The U-values are then validated with measurements from a thermohygrometer for both winter and summer and heat flux meters. The deviation between the thermography values and measured U-values is found to be between 10-20%. This is considered by the researchers to be an acceptable level. A sensitivity analysis reveals that the reflected apparent temperature and the assumed emissivity of the building surfaces are the most sensitive values for the calculation of the U-value. The authors believe that the infrared thermography method of calculating U-values may be more accurate than other methods and find the duration of the measurement procedure to be advantageously shorter.

This study compared using IR thermography and thermohydrometers to calculate U value. The thermohydrometers were found to be more accurate at calculating U value than the IR thermography, while both were found to be acceptable. The results were then validated by calculating the U value with heat flux sensors.

A FLIR T360 camera with a resolution of 320x240 pixels was used.

Two thermohygrometers were used. The first was used to determine the atmospheric conditions and the second as a validation of the surface temperature captured by the thermal image. The results were validated, approximately a year later, using International Thermal Instrument (ITI) Company,Model No. GHT-1C(801) heat flux sensors to measure heat flux and surface temperature.

The study references other research that suggests taking thermographic images on cloudy days or at night in order to avoid temperature increases form incident solar radiation. It also recommends choosing days with low wind speeds to avoid convection heat losses.

This article looked at the accuracy of infrared thermography versus data gathered from a thermo hygrometer to calculate the resistance of a surface. We are proposing using the techniques in conjunction to gain the most accurate picture of the façade. We can learn from the researcher's recommendations regarding the ideal conditions in which to take thermographic images.

7. Ramos, Luís F., Leandro Marques, Paulo B. Lourenço, Guido De Roeck, A. Campos-Costa, and J. Roque. "Monitoring historical masonry structures with operational modal analysis: Two case studies." *Mechanical Systems and Signal Processing* 24, no. 5 (2010): 1291-1305.

This article discusses the use of networks of vibration, temperature and relative humidity sensors installed in two historic monuments in Portugal. The goal is to analyze the vibration and weather conditions in order to monitor and preserve the structures. Traditionally, historic buildings are monitored by condition surveys or visual inspection. The development of sensor technology allows for the real-time and constant monitoring of building conditions.

The study looks at two case studies, a clock tower in Mogadouro, Portugal and a church in Lisbon. Sensor networks are applied to identify current conditions and act as monitoring systems for potential future damage.

This study looks at a standard technique for monitoring a historic structure using sensor networks and data logging to collect information about multiple variables. This technique may be helpful for our proposed research as we need to collect temperature and relative humidity information overtime.

C. Other Studies Using Similar Technologies

The proposed research is considering using technologies such as thermo hydrometers, a thermography camera, thermocouples, and data loggers. In order to gain information about how these technologies are typically used in practice and to avoid repeating the mistakes of others, case studies that use these tools were collected. Studies of blower door pressurization testing accuracy and repeatability were also examined.

1. Terés-Zubiaga, J., K. Martín, A. Erkoreka, and J. M. Sala. "Field assessment of thermal behaviour of social housing apartments in Bilbao, Northern Spain." *Energy and Buildings* 67 (2013): 118-135.

This study focuses on the evaluating thermal comfort in existing apartment buildings in Spain. The study attempts to evaluate multiple factors that affect building performance and occupant comfort. This study collects temperature and humidity data with Temp-RH Hobo Data loggers (HOBO U12-011) to track indoor environmental conditions. In addition, a thermo hydrometer was installed in the living room of each apartment. Data for outdoor temperature and RH were taken from a government owned meteorological station. The u-value of the facades is estimated based on the construction of the wall. The study uses IR thermography to identify variations in the u-value of the façade. The temperature and RH were noted when the images were taken to use in analysis of the images. The thermographs were performed at night to avoid solar gain and used a FLIR PS60 camera. The study notes that the affect of thermal bridges on heat consumption can vary from 5% to 39%. The point furthest away from a potential thermal bridge is considered the minimum temperature. The difference between the minimum and maximum temperature indicates the level of impact of the thermal bridges. The study also notes that the fact that the buildings were occupied during the data collection makes it difficult to accurately quantify the effect of thermal bridging.

This study uses standard methods for collecting temperature and humidity data, as well as thermography to determine surface variations. Our proposed research uses both of these techniques and we can learn from the recommended procedures.

2. Santamouris, M., C. Pavlou, P. Doukas, G. Mihalakakou, A. Synnefa, A. Hatzibiros, and P. Patargias. "Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece." *Energy* 32, no. 9 (2007): 1781-1788.

This study is attempting to identify the energy performance of a roof in Athens with and without a green roof system installed. The experiment is done in two phases. The first phase collects actual data from inside and outside the building. Temperature and humidity information was collected inside and outside the building. Indoor air temperature was measured with miniature temperature data loggers, indoor humidity was measured with an EBRO 200 hydrometer and outdoor temperature was measured with an electric thermo hygrometer. A thermography camera was used to illustrate the surface temperature. When the data is analyzed there is found to be a correlation coefficient of 0.79 between the indoor air temperature and the ambient temperature.
The second phase of investigation used TRNSYS software for building energy simulation to look at the heating and cooling load of the building with and without the green roof. The modeled data and the experimental data were found to match up very well, with a difference of less than 1 degree C in most cases. The roof was found to significantly reduce the cooling load and have an insignificant affect on the heating load.

3. Dall'O, Giuliano, Luca Sarto, and Angela Panza. "Infrared Screening of Residential Buildings for Energy Audit Purposes: Results of a Field Test." *Energies* 6, no. 8 (2013): 3859-3878.

The goal of this research is to determine if it is possible to determine the u-value of a wall using thermography. This article includes a literary review of several articles that use thermography to provide quantitative data about a building's performance. It notes that the Fokaides and Kalogirou article was completed from the interior of the building, limiting the affects of weather on the measurements.
In this study, u-values obtained through thermography were compared with known actual u-values to identify sensitivity and margin of error. The calculation used to determine U-value is described on p6 in the Theoretical Basis for Calculating U-value section. Sensitivity analysis is performed to determine the impact of factors like wind speed. The study used a FLIR T640bx camera and 14 test buildings were identified. The study was carried out on days where conditions were as close to ideal as possible: average low temperature, little wind, overcast, stable weather. The deviation between measured u-value and actual u-value was found to be acceptable for solid mass buildings but not for buildings with exterior insulation.

The study identified the following problems with their technique and proposed the following solutions:

1. *"The temperature differences are small values and difficult to monitor with accuracy;*
2. *The infrared camera has large absolute errors compared to the values of temperature to be measured;*
3. *It is often impossible to know the compensation parameters (emissivity, reflected temperature, etc.) necessary to obtain the correct value of temperature;*
4. *The convective coefficient to be used in the formula has a significant influence on the result and must therefore be a real and not a standard value;*
5. *The climatic parameters may vary considerably during the execution of the measurement.*

To resolve each of the problems highlighted above we have developed the following solutions:
- A day is chosen which is deemed appropriate for the purposes of our investigation, looking at the weather forecast of the previous 24 h (cold, little wind, cloud cover). The conditions should possibly persist: in any case the conditions set

out in the standard (rain, sun, etc.) must be avoided (this solves point 1);
- The method is limited to high thermal mass walls and it is not valid for externally insulated walls (this solves points 1 and 5);
- We use as reference temperature the external temperature measured with the same thermal camera for a non-dissipating portion of the same masonry (solution for points 2 and 3);
- In any case data to perform the compensation of the measurement were detected, excluding the determination of emissivity, in order to minimize the error in the determination of the temperature difference;
- The convective coefficient h is estimated considering the average wind speed of the previous hours, since it is not important to have the instantaneous value, especially for walls with high thermal inertia. Thus, the h value was calculated in a more sophisticated way than that indicated in the literature which refers almost exclusively to the values given by standard (this solves point 4).”

This study attempts to improve upon the standard method for using thermography to determine U-value and our study can benefit from the recommendations made to improve accuracy.

4. Persily, A. "Repeatability and accuracy of pressurization testing." *Thermal Performance of the Exterior Envelopes of Buildings II, Procedures of ASHRAE/DOE Conference. (ASHRAE SP*, vol. 38, 1982) 380-90.

This study looks at the repeatability of blower door air pressurization tests. The same building, a mid 1960’s two story wood frame home, is tested eighty times in one year to identify the effects of wind and seasonal variation on the results. The localized wind speed was recorded during each test. The study finds that for times with wind speeds below 5.5 mph, there is a standard deviation of about 2% and for periods of stronger winds there were errors as large as 15%. The seasonal variation was shown to be 25% due to the moisture content of the outside air and building materials.

This study looks at the standard technique for blower door testing and offers information about the accuracy and variability of the test, which we are proposing to use in our research.

5. Purdy, Julia, and Ian Beausoleil-Morrison. "The significant factors in modeling residential buildings." *Canmet Center for Technology (7th International IBPSA Conf., Rio de Janiero*. 2001.)

This article looks at significant factors in the energy modeling of residential buildings. The study uses the HOT3000 modeling program. Sensitivity analyses are completed on several factors including zoning, simple versus explicit windows, internal thermal mass, shading, thermal bridging, and solar radiation, among others.

Infiltration assumptions that would be used in lieu of a blower door test are examined. When the airtightness rating was changed from 3.0 to 3.5 ac/h, representing the low end of uncertainty when a blower door test is not used, the heating load increased 6.6%. Many simulation programs assume infiltration at a constant rate, as opposed to a time-variant infiltration rate. When the model replaced the constant rate with a variable rate, the heating load decreased 7%.

This study looks at the standards for energy modeling residential buildings. We can learn from their results regarding the most important factors that can affect model accuracy, specifically the importance of accurate blower door test results.

6. Payne, A. O., & Johnson, J. K. “Firefly: Interactive prototypes for architectural design.” *Architectural Design* 83, no. 2 (2013): 144-147.

This article discusses the uses of the Firefly Plug-in for Grasshopper, a datalogger that allows communication between building models and real world data. The plug-in uses hardware, such as the Arduino Microcontroller, to collect data from various types of sensors to influence the prototyping process. Sensor types can include light, touch, proximity and acceleromotors. The designer has the opportunity to test how systems would function in real world environments. The feedback can also be used to send information from Grasshopper to hard ware devices that can control real-world systems such as lighting, motors and valves.

Applications for this technology include double skin facades and single skin ventilation systems. A façade can respond to passing pedestrians or changes in environmental conditions. It also opens opportunities for advanced physical prototyping.

This research discusses the use of Firefly datalogging, which is an improvement over standard dataloggers. This is helpful as we research datalogging technology in order to select the most appropriate product for our application.

D. Importance of Accurate Weather Data and Local Micro-climate

When creating an energy model, weather data is typically extracted from the closest publically available weather station. These stations are often found at airports, schools or other locations that may be more remote than the building's actual location. Surrounding structures, vegetation, or geographic features can all have effect on the microclimate of a building. It is important to understand the impact that the variation between weather dataset and building microclimate can have on the accuracy of the energy model. The following studies attempt to analyze the variation in and impact of microclimate and weather datasets on energy models and expected building performance.

1. Bhandari, Mahabir, Som Shrestha, and Joshua New. "Evaluation of weather datasets for building energy simulation." *Energy and Buildings* 49 (2012): 109-118.

This paper looks at the variation in typical weather datasets compared to actual, private weather station data. Some dataset vendors use publically available datasets, such as NOAA, and interpolate the results, while others claim to have full datasets with a geospatial resolution of a 15-40 sq.km. grid. The study used weather data collected in Oak Ridge, Tennessee and compared that data to two publically available datasets. After comparing the results, each dataset was used for energy modeling to ascertain the impact of weather data on heating and cooling loads. Overall energy use was found to change +/- 7% based on weather set used, however heating and cooling loads differed by +/- 40%.

This study looks at the standard use of widely available weather datasets used in energy models. This relates to our research by gauging the importance and inherent variability that comes from using localized weather data in our energy models.

2. Radhi, Hassan. "A comparison of the accuracy of building energy analysis in Bahrain using data from different weather periods." *Renewable Energy* 34, no. 3 (2009): 869-875.

This paper looks at the effects of using past weather data versus more current weather data in energy modeling. The research looks at a statistical approach to climate data and a simulation approach. The quality of both of these approaches relies on the sources, the collection location and methods, and the length of the record.

The study uses Bahrain as a case study by creating two weather data sets and then comparing them to assess their impact on building energy analysis. The first data set uses data from pre-1991 and the second from post-1991. The data sets were applied to a building model and compared to the actual building consumption. The study concluded that there is a noticeable difference in climate in Bahrain overtime and therefore it is important to use a more recent weather dataset. The older dataset underestimated the electricity consumption by 14.5% while the newer data set only underestimated consumption by 1.4%.

Similar to the previous study, this paper looks at the affect of weather data set on energy modeling, but this paper focuses on the importance of using recent weather data.

3. Crawley, Drury B. "Which weather data should you use for energy simulations of commercial buildings?." *Transactions-American society of heating refrigerating and air conditioning engineers* 104 (1998): 498-515.

This paper looks at the variation in sets of weather data, why they are different and how they affect energy simulations. The four weather data sets analyzed are WYEC2, TMY2, CWEC, and CTZ2. The variations in the sets are mostly attributed to the weight given to applied weather variables.

The research compares the data sets to actual weather data (SAMSON 30 yrs) through energy simulation results. The same model building was analyzed with all data sets in 8 different locations. The study finds the most variation is between heating-dominated climates, with a range of -48.5% to 3.2% of the design equipment size. In addition, it is shown that annual peak cooling and heating load vary more than the annual energy consumption or annual energy costs. The article concludes that simulation should avoid using single year data sets such as TRY, instead using more variable sets such as TMY2 or WYEC2.

4. de La Flor, F. S., & Domınguez, S. A. "Modelling microclimate in urban environments and assessing its influence on the performance of surrounding buildings." *Energy and buildings 36, no.* 5 (2004): 403-413.

This article looks at the affects of urban context and heat island affect on the microclimate of buildings. In order to have an accurate energy model, it is important to couple the model of the building's thermal performance with an urban model. During the GreenCode project, a program was developed to model the conditions of a building in an urban area. The model started with general climate data, typically from a more rural setting like an airport. It then layered sub-models, such as the Urban Canyon Model, which consider street vegetation, wall and ground convection and solar radiation. Tests of the system show the model to be in relatively good agreement with actual conditions. When the urban canyon model is paired with building thermal simulation programs, it is possible to study the influence of individual climactic variables on the performance of a building.

5. Bouyer, J., Inard, C., & Musy, M. "Microclimatic coupling as a solution to improve building energy simulation in an urban context." *Energy and Buildings 43,* no*.* 7 (2011): 1549-1559.

This paper addresses the lack of a suitable tool for analyzing the affects on microclimate on urban buildings. The article addresses the shortcomings of existing modeling software and the potential of computational fluid dynamics (CFD) systems. While numerical calculations exist, there is no complete tool to evaluate the affects of microclimate on building energy use. The study uses a simulation that couples CFD with thermoradiative simulation tools in order to evaluate a building in a specific urban district.

The results show computational benefits related to the modeling of thermoradiative IR balance evaluation, convective heat flux, and moisture transport. The model allows for the quantitative evaluation of the building energy use in different urban scenarios. The downside to this type of analysis is the high computational cost and time required. The results show that of all considered factors, solar irradiation has the greatest impact on building energy simulation.

This study looks to improve and assess the standard weather data used in energy modeling by measuring localized microclimate. Since our study proposes collecting many of these values, we can gather from this study how to best apply them to the energy modeling process.

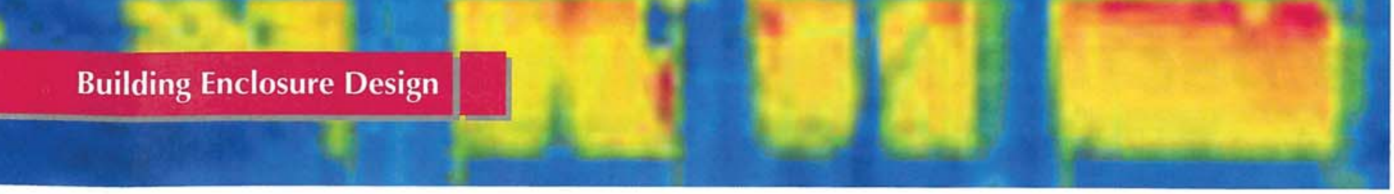
E. Review and Comparison of Commercially Available Energy Modeling Software

1. Crawley, Drury B., Jon W. Hand, Michaël Kummert, and Brent T. Griffith. "Contrasting the capabilities of building energy performance simulation programs." *Building and environment* 43, no. 4 (2008): 661-673.

This article provides a comparison of twenty energy modeling programs based on their capabilities as provided by the manufacturers. The report looks at the following software programs: BLAST, BSim, DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES <VE>, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS. A summary of each software is given, followed by a table that compares the features and abilities of each program.

2. Attia, S., and André De Herde. "Early design simulation tools for net zero energy buildings: a comparison of ten tools." *International building performance simulation association* (2011).

This report looks at energy modeling programs in terms of their general capabilities and how well they assist with the design of net zero buildings. The programs investigated include: HEED, e-Quest, ENERGY-10, Vasari, Solar Shoebox, Open Studio Plug-in, IES-VE- Ware, DesignBuilder, ECOTECT and BEopt. Each program is evaluated on a scale of low-medium-high in the categories of Usability, Intelligence, Interoperability, Process Adaptability, and Accuracy. A table is included which compares the programs' abilities regarding net zero building design. Overall, the programs are lacking features that are necessary for successful net zero design.
IES VE rated high for Usability, medium for Intelligence, medium for Interoperability, medium for Process Adaptability, and high for Accuracy.



Historic Building Façades: Simulation, Testing and Verification for Improved Energy Modeling

By Daniel Chung

Oftentimes, historic building façades have assemblies that are difficult to characterize for energy modeling, due to three primary limitations. First, they often are not uniform in their construction. Second, they may use materials that are not standard in today's materials databases. Third, their construction and assembly may not be well-documented. As a result, when energy modeling these structures, the overall heat-transfer coefficient, known as the U-factor (aka U-value), may be significantly inaccurate and skew results.

However, non-destructive evaluation methods, such as heat flux, thermocouple sensor measurements and thermal imaging, can be used to improve the accuracy of in-situ façade conductance values used in energy models. Current standards exist for heat-flux measurements to derive assembly thermal resistance.[1][2] In contrast, calculations of the conductance from thermal images have not been standardized. Therefore, thermal imaging can be used to augment the heat-flux-sensor measurements to evaluate large areas of a building envelope.

Context of Energy Analysis

Energy analysis for buildings attempts to explore past and/or future energy flows, usually to determine the total amount of energy consumed during a given time period. This can be used to help evaluate the impact of building design and operation decisions most influenced by energy consumption.

Thermal conditioning of indoor air is largely related to heat transfer between indoor and outdoor environments. Therefore, the more accurate heat-transfer coefficients used in modeling should both improve the accuracy of thermal analysis and provide meaningful information about overall energy use.

Overall Heat-Transfer Coefficient

A lot of building characterization for energy modeling involves inputting parameters to describe the physical layout and properties of building materials with regard to their impact on the flow of heat. A significant parameter used in thermal analysis of the building envelope is the overall heat-transfer coefficient. The U-factors used in many energy models are based on databases of experimentally tested materials that are researched and compiled by technical organizations and published, such as the thermal transport database included in the *ASHRAE Handbook—Fundamentals*[3] or the International Organization for Standardization's EN ISO 6946-2007.[4]

When materials or assemblies being modeled are not well-represented in existing literature, energy modelers often use substitutions or assume close approximations to other well-tested approaches from laboratory or field tests. For both this article and recent research (Fokaides and Kalogirou,[5] Dall'O, et. al.[6]), thermal imaging can improve accuracy when evaluating the energy performance of large areas of a building envelope that contain significant U-factor non-uniformity.

In-Situ Techniques

Fokaides and Kalogirou explored using thermal imaging, in conjunction with thermohygrometers, to determine the U-factor in building envelopes—without the need for direct heat-flux measurement. Their method, which considered surface radiation and convection, relied on measuring emissivity, as well as appropriate heat-transfer coefficients for indoor air. Their results showed a deviation of approximately 10 to 20 percent between in-situ measurement and standard database U-factors.

In contrast, the proposed method in this article differs in that it uses heat-flux sensors to derive the heat-transfer coefficients for the air films at spot locations, and then uses them in conjunction with surface temperature readings from thermal images to calculate the U-factor of larger sections of an envelope.

The Methodology

Building envelope heat transfer

Two predominant means of heat transfer exist between outdoor and indoor climates. The first is the heat transfer through the building envelope (q_{env}) via conduction, convection and radiation. The second is the heat transfer through air exchange (q_{air}) via air infiltration/exfiltration and mechanically ventilated exhaust and fresh air intake. Therefore, in building thermal analysis, the total heat transfer, q_{tot} in watts (W, or BTUs per hour), is approximated by **Equation 1**.[7] *(See all Equations on opposite page.)*

U, the overall heat-transfer coefficient that accounts for conductive, convective and radiative heat transfer through the envelope material or assembly, is the reciprocal of its thermal resistance, *R* in units m²•K/W (h•ft²•°F/BTU). Although surface conduction and radiation are modes of heat transfer for the building envelope (above-ground), the more dominant form of heat transfer is via convection, where air is the fluid that is transferring heat by moving across the building surface either through buoyancy forces or forced flow via ventilation and wind. **Equation 2** is the steady-state solution to Fourier's law of heat conduction.[4] *[Author's Note: Though this research project studied the heat-transfer contribution from air exchange, which can be significant (and even dominant) for buildings with high-infiltration rates, it is outside the scope of this article.]*

Heat flux

Because q_{env} is directly proportional to U_i, building energy analysis that includes interior heating and/or cooling is strongly related to a building envelope's overall heat-transfer coefficient. Heat-flux sensors can determine U-factors by measuring the heat flow through a sensing object and passively generate a small output voltage. This voltage is divided by a calibration constant to convert the voltage into units of heat flux (W/m² or BTU/h•ft²). Surface-mounted thermocouples directly adjacent to the heat-flux sensors measure the inside and outside surface temperatures of an envelope assembly. Using the measured heat-flux and surface-temperature values, the heat transfer through an envelope then can be calculated using Fourier's law in the form of $Q = U\,\Delta t$ and rewritten in **Equation 3** to solve for U.[6][7]

If the envelope assembly is relatively uniform, then the U-factor of the assembly can be characterized by taking sensor readings at a few locations. However, if the assembly is highly variable or has unknown characteristics (such as intermittent voids or irregular material or dimensional changes), then multiple readings are needed to accurately characterize the assembly's U-factor. Without physically collecting readings from a large number of uniformly spaced locations on the building envelope, characterizing a façade's thermal properties with heat flux and thermocouple sensors may be inaccurate.

Equation 1: $q_{tot} = q_{env} + q_{air}$

Equation 2: $q_{env} = \Sigma_i\,(U_i \times A_i)\,\Delta T$

U_i = Overall heat transfer coefficient of envelope element, i, W/m²•K (BTU/h•ft²•°F)

A_i = Surface area of envelope element, i, m² (ft²)

ΔT = Temperature differential between the inside and outside air, °K (°F)

Equation 3: $U_i = \dfrac{Q_i}{|T_{is} - T_{os}|}$

Q_i = Heat Flux, W/m² (BTU/h•ft²)

T_{os} = Outside Surface Temperature, °C (°F)

T_{is} = Inside Surface Temperature, °C (°F)

Equation 4a: $T_{os} = T_{in} - \dfrac{(T_{in} - T_{out})\,(R_{ai} + R_{env})}{(R_{ai} + R_{env} + R_{ao})}$

T_{in} = Indoor air temperature, °C (°F)

T_{out} = Outdoor air temperature, °C (°F)

R_{ai} = Resistance of the inside air film, m²•K/W (h•ft²•°F/BTU)

R_{ao} = Resistance of the outside air film, m²•K/W (h•ft²•°F/BTU)

R_{env} = Resistance of the envelope assembly, m²•K/W (h•ft²•°F/BTU)

Equation 4b: $T_{os} = \dfrac{R_{ao}\,\Delta T}{R_{tot}} - T_{out}$

$\Delta T = |T_{in} - T_{out}|$, °C (°F)

$R_{tot} = R_{ai} + R_{ao} + R_{env}$, m²•K/W (h•ft²•°F/BTU)

Equation 4c: $T_{is} = T_{in} - \dfrac{R_{ai}\,\Delta T}{R_{tot}}$

Equation 5: $R_{ai} = \dfrac{|T_{in} - T_{is}|}{Q_i}$ or $R_{ao} = \dfrac{|T_{os} - T_{out}|}{Q_i}$

Equation 6a: $R_{env} = \dfrac{\left(\dfrac{(|T_{in} - T_{os}|)}{|T_{in} - T_{out}|}\right)(R_{ai} + R_{ao}) - R_{ai}}{1 - \left(\dfrac{(|T_{in} - T_{os}|)}{|T_{in} - T_{out}|}\right)}$

Equation 6b: $R_{env} = \dfrac{R_{ao}\,(|T_{in} - T_{os}|)}{|T_{os} - T_{out}|} - R_{ai}$

Equation 6c: $R_{env} = \dfrac{R_{ai}\,(|T_{is} - T_{out}|)}{|T_{in} - T_{is}|} - R_{ao}$

Assumptions and restrictions

Equation 2 assumes a constrained set of steady-state conditions. It also only accounts for surface convection and conduction between the air and the building envelope; as such, solar radiation is not included. Therefore, testing conditions must reflect these limitations. Optimal, real-world conditions would most likely be at night (no solar radiation and less internal activity that might cause interior temperature swings); in winter (longer periods of darkness to minimize re-radiated heat and thermal mass, lower ambient moisture); during a period of dry weather (reduced moisture-related heat transfer) and very little to no winds (more consistent fluid flow), using a geometrically flat envelope surface (frequent geometric variation may change air film parameters).

Throughout the day, the interior air temperature should be consistently higher than the outside air temperature to prevent a reversal of the direction of heat transfer. Indoor air should be mixed thoroughly to minimize thermal variation across the interior.

Thermal gradient

Under such optimal conditions, the thermal resistance of the envelope components can be used to determine the thermal gradient between the interior and exterior climates using the standard simplified numerical method established in EN ISO 6946. This thermal gradient includes an air-film, heat-transfer coefficient to account for convection between the interior and exterior surfaces of an assembly and the adjacent air. These film coefficients contribute to the thermal resistance of a wall assembly and, thus, impact surface temperatures and thermal gradients from interior to exterior surfaces. The interior and exterior film coefficients have relatively low-resistance values (compared to most envelope components); but they can have a significant impact on an envelope's surface temperatures.

The envelope's outside surface temperature (T_{os}) is calculated by using **Equation 4a**, which is an expression

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Assembly	R_i, Resistance		R_{ci}, Cumulative Resistance		T_{ci}, Temperature Change		T_i, Element Temperature	
	°K•m²/W	ft²•°F•h/BTU	°K•m²/W	ft²•°F•h/BTU	°C	°F	°C	°F
Room Air	-	-	-	-	-	-	20.00	68.00
Inside Air Film	0.120	0.680	0.120	0.680	3.09	5.56	16.91	62.44
600mm Stone Wall	0.625	3.549	0.745	4.229	19.23	34.61	0.77	33.39
Outside Air Film	0.030	0.170	0.775	4.399	20.00	36.00	0.00	32.00
Outside Air	-	-	-	-	-	-	0.00	32.00
R_T, Total Resistance	0.775	4.399				Δt, T_{in}-T_{out}	20.00	36.00

Table 1: Example of the steps to determine the thermal gradient through a 600mm stone wall.

based on the manual steps used to calculate the thermal gradient. This can be rewritten in a more simplified notation, as shown in **Equation 4b.** This same procedure can be used to determine the temperature of the inside surface, T_{is}, as shown in **Equation 4c.**

The thermal resistance (and resulting thermal gradient) of the building envelope, due to air films, can be significant for envelope assemblies with high heat-transfer coefficient values, such as load-bearing masonry walls and glazing areas. The example of a thick stone wall in "Table 1" (*see above*) demonstrates that air films can contribute significantly to an envelope's overall resistance and impact the thermal gradient, resulting in noticeably different surface temperatures from indoor and outdoor air temperatures. This example uses published resistance values for air films and materials to predict the temperature gradient through the wall.[8]

Air film properties

The U-factor and resistance of an envelope assembly can be determined using a heat-flux sensor, in combination with two thermocouples for surface temperatures.[7] Similar determinations for indoor and outdoor film coefficients require interior and exterior surface temperatures, in conjunction with indoor and outdoor air temperatures. Since the heat flux (Q_i) moving through the assembly (experimentally measured in-situ by the heat-flux sensor), is the same for the air films as it is for the envelope, Equation 3 can be reused with the same Q_i while changing the denominator to $|T_{in} - T_{is}|$ or $|T_{os} - T_{out}|$ to determine U_{ai} or U_{ao}, respectively. U_{ai} is the heat-transfer coefficient of the inside air film, and U_{ao} is the heat-transfer coefficient of the outside air film. Thus, empirical resistance values of the air films can be derived using the heat-flux and temperature readings by taking the reciprocal of Equation 3, as shown in **Equation 5.**

While computational fluid dynamics (CFD) have been utilized on building components or small-room-size analysis, whole-building energy analysis almost always is a simplified, time-stepped, heat-transfer analysis that does not use CFD. In fact, most whole-building-scale, energy-modeling analyses in commercial applications (such as those using the DOE2.2 engine or EnergyPlus) almost always use one-dimensional, heat-transfer analysis across an envelope and assume non-turbulent airflow. (Some whole-building simulations use two-dimensional analysis for ground conductance models). Instead, they usually apply the assumption of steady-state laminar flow conditions for the air that moves across a building envelope. This greatly reduces the numerical complexity for convective heat transfer and is compatible with the one-dimensional, heat-transfer analysis inherent in these programs. A one-dimensional analysis further imposes uniformity for air films across envelope surfaces. Although, in reality, air speeds and films vary, virtually all whole-building energy analyses impose these restrictions of uniformity.

Envelope resistance

By taking advantage of the assumed air-film uniformity, surface temperatures can be used to determine envelope U-factors by rewriting Equation 4a to solve for $U_{env} = 1/R_{env}$. **Equation 6a** is a rearrangement of Equation 4a that calculates the resistance value of the envelope assembly after determining the air-film resistances, as well as interior-air, exterior-air and exterior-surface temperatures. This can then be rewritten in a more simplified form, as in **Equation 6b.** When using inside surface temperatures, this transforms to **Equation 6c.**

Returning to the example in "Table 1," the calculated T_{os} = 0.77°C (33.39°F) results when using R_{env} = 0.625°K•m²/W (3.55 ft²•°F•h/BTU). If another location on the wall were to be measured to have an outside surface temperature, T_{os} = 1.45°C (34.60°F), then the R_{env} at this alternate location should be calculated to be 0.264°K•m²/W (1.50 ft²•°F•h/BTU) by using the same resistance values for the air film.

Thermal imaging

Each pixel of a thermal image represents the average surface temperature in a given area. By mapping the colors to temperature values, a numeric surface-temperature map can be created for large building-envelope areas. Having already measured Q_i, T_{in}, T_{is}, T_{os} and T_{out}, thermal images of the envelope surface temperatures can be used to determine characteristic heat-transfer values for large areas of an envelope. These conductance values should be verified and calibrated with heat-flux and surface-temperature readings at a few locations. By summing all the temperature values from the thermal images, then normalizing that sum by the area, a single conductance value can be derived. *[Author's Note: If a thermal image is taken directly perpendicular to the envelope surface, divide the sum by the number of readings (assuming the readings are evenly spaced across the envelope area).]*

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Results and discussion

This research used a thermal imaging camera with an infrared resolution of 160 x 120 pixels and a thermal sensitivity <0.06°C, resulting in a theoretical maximum of 19,200 surface-temperature sample points. Commercially available imaging processing tools can be used to read per-pixel color values for most images, as well as provide the mean color value for an area. In "Figure 1" (*see right, top*), the values in the image range from 19.72°C (67.5°F) at the top of the color scale (R:239, G:220, B:188) to 12.67°C (54.8°F) at the bottom of the color scale (R:6, G:3, B:80). Thermal images were first cropped to the areas of consideration, then processed for average thermal values. "Figure 2" (*see right, bottom*) shows a 20-pixel-tall by 90-pixel-wide thermal image, with 1,800 surface-temperature readings.

Figure 1: Thermal image and photograph of the Rittenhouse Homestead, Philadelphia.

Figure 2: Enlarged area of the 20-pixel by 90-pixel building envelope at the Rittenhouse Homestead (thermal, top; normal, bottom).

Heat flux and surface temperatures (inside and outside) using thermocouples were taken on the stone wall. "Table 2" (*see opposite page, top*) compares the typical published value,[9] spot-measured value and calculated thermal-image value for conductance of the stone wall included in "Figure 2."

These readings (heat flux, thermocouples and thermal images) were collected mid-morning on November 14, 2014, and were a trial run of the analysis for future comparison with nighttime winter readings. As such, rising outdoor temperatures and solar heat gain most likely influenced the results of the calculated U-factor. Future tests will examine thermal imaging of small, medium and large areas of the wall and compare them with single, double and multiple spot-value, heat-flux readings at different times (morning, mid-day, evening and night). Additionally, laboratory verification of the method with known assemblies will compare the accuracy of the method.

Conclusions

Using thermal images to determine average envelope conductance values provides a sound method to analyze large variations in a building-envelope assembly. Variations can include changes of materials, density and configuration. This method is limited by assumptions of uniform interior and exterior film coefficients; uniform air temperatures, inside and outside; and steady-state assumptions that may not accurately account for varying weather and climate conditions. Thus, smaller areas with less air-temperature variation most likely will produce more accurate results.

Spot-Measured Heat Flux	Spot-Measured U-Factor	Typical Published U-Factor	Calculated Average U-Factor	Measured Average Surface Temp
13.01 W/m²	1.78 W/°K•m²	1.6 W/°K•m²	2.27 W/°K•m²	5.9 °C
2.29 BTU/h•ft²	0.31 BTU/h•ft²•°F	0.28 BTU/h•ft²•°F	0.40 BTU/h•ft²•°F	42.62 °F

Table 2: In-situ values of a portion of a stone wall on the Rittenhouse Homestead in Philadelphia.

This method may prove inappropriate for building envelopes with low-conductance values, due to the increased sensitivity and variation of results related to air-film resistance values (the relative high resistance would create much smaller thermal changes in air-film layers).

However, for building envelopes with high-conductance values (such as many historic buildings), this method may help provide better results than relying on standard material assumptions. At the present time, further research involving in-situ testing is being conducted to evaluate the methods to improve the use of thermal imaging in characterizing materials and energy flows through historic-envelope assemblies. JNIBS

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