



DEMONSTRATION AND COST ANALYSIS OF A BUILDING RETROFIT USING HIGH- PERFORMANCE INSULATION

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TABLE OF CONTENTS

REPORT DOCUMENTATION PAGE

TABLE OF CONTENTS.....	i
LIST OF FIGURES	iii
LIST OF TABLES.....	vi
EXECUTIVE SUMMARY.....	vii
ACKNOWLEDGMENTS	viii
LIST OF ACRONYMS.....	ix
1.0 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objective of the Demonstration.....	2
1.3 Regulatory Drivers.....	3
2.0 TECHNOLOGY DESCRIPTION.....	4
3.0 TECHNOLOGY DEVELOPMENT	7
3.1 Performance Advantages	7
3.2 Performance Limitations.....	8
3.3 Cost Advantages	9
3.4 Cost Limitations.....	10
3.5 Potential Barriers to Acceptance.....	10
4.0 PERFORMANCE OBJECTIVES.....	11
4.1 Performance Objectives Descriptions.....	12
4.2 Summary of Performance Objectives	13
5.0 FACILITY/SITE DESCRIPTION	18
5.1 General Facility/Site Selection Criteria	19
5.2 Demonstration Facility/Site Location and Operations.....	19
5.3 Site-Related Permits and Regulations.....	20
6.0 TEST DESIGN	21
6.1 Conceptual Test Design	21
6.2 Baseline Characterization	25
6.3 Design and Layout of System Components.....	26
6.4 Operational Testing.....	27
6.5 Sampling Protocol.....	28
6.6 Equipment Calibration and Data Quality Issues.....	29
7.0 PERFORMANCE ASSESSMENT.....	53
7.1 Facility Energy Usage.....	53
7.2 Demand Reduction	55
7.3 Percent of Panels Experiencing Loss of Vacuum (%)	56
7.4 Overall R-Value of Walls with MAI (%)	58

7.5 Coverage of Wall Area with Minimal MAI Panels	58
7.6 Energy Loss through Walls	60
7.7 Economics	62
7.8 Likert Scale Results	62
7.9 Performance Assessment w/out Insulation	62
8.0 COST ASSESSMENT	65
8.1 Cost Model.....	65
8.2 Cost Drivers	65
8.3 Cost Analysis and Comparison	65
8.4 Applicability to Federal Building Portfolio	75
9.0 IMPLEMENTATION ISSUES	80
9.1 Failure Rate of MAI/VIP	80
9.2 Application of MAI for New Facilities	81
10.0 REFERENCES.....	83
11.0 APPENDICES	84
APPENDIX A: POINTS OF CONTACT	84
APPENDIX B: ENERGYPLUS MODELING.....	85
APPENDIX C: BUILDING FASTENERS AND PLANNED MAI PANEL LAYOUT	90
APPENDIX D: LIKERT QUESTIONNAIRE FOR INSTALLERS	94
APPENDIX E: SENSORS.....	97

LIST OF FIGURES

1	R-Values of VIP and Conventional Insulation Materials	4
2	MAI Panels	5
3	Flow Charts of VIP and MAI Production Processes	5
4	Pilot-Scale Unloading (left) and MAI Chamber for Air-Steam Replaces (right)	6
5	Thermal Resistance (R/in.) of MAI Panels, as a Function of Temperature and Pressure, Compared to Conventional Insulation Materials (Foam, Fiberglass and Cellulose)	7
6	Effects of Increasing Insulation on Energy Savings	9
7	Plan View of Building Locations	18
8	Fort Drum Retrofit Facility	19
9	ASHRAE Climate Zones	20
10	Sensor Layout and Locations	23
11	Photographs of a Set of Installed Heat Flux Transducer (HFT) and Temperature/Relative Humidity (T/RH) Sensors	24
12	Planned Solar Tracker and Weather Station Location	24
13	Weather Station Mount Methodology	25
14	Solar Tracker Mounting (Side)	25
15	E+ Model for Calibration against Wall Sensor Data	30
16	Comparison of Global Horizontal Solar Incidence Data from the on-Site Weather Station and from Wheeler-Sack Airfield	30
17	Simulated vs. Measured Outdoor Air Temperatures	31
18	Simulated vs. Measured Indoor Air Temperature Baseline South Wall	31
19	Simulated vs. Measured Indoor Air Temperature Retrofit South Wall	31
20	Simulated vs. Measured Indoor Air Temperature Baseline North Wall	32
21	Simulated vs. Measured Indoor Air Temperature Retrofit North Wall	32
22	Simulated vs. Measured Outdoor Surface Temperature Retrofit North Wall	33
23	Simulated vs. Measured Indoor Air Temperature Retrofit South Wall	33
24	Simulated vs. Measured Indoor Surface Temperature Baseline South Wall	33
25	Simulated vs. Measured Indoor Surface Temperature Retrofit South Wall	34
26	Simulated vs. Measured Outside Surface Temperature Baseline North Wall	34
27	Simulated vs. Measured Outside Surface Temperature Retrofit North Wall	34
28	Simulated vs. Measured Indoor Surface Temperature Baseline North Wall	35
29	Simulated vs. Measured Indoor Surface Temperature Retrofit North Wall	35
30	Simulated vs. Measured Indoor Heat Flux Baseline South Wall	35
31	Simulated vs. Measured Indoor Heat Flux Retrofit South Wall	36
32	Simulated vs. Measured Heat Flux Baseline North Wall	36
33	Simulated vs. Measured Heat Flux Retrofit North Wall	36
34	Summer Outdoor Air Temperature (Both Facilities, Boundary Condition)	37
35	Summer Baseline Indoor Air Temperature	38

36	Summer Retrofit Indoor Air Temperature	38
37	Summer Baseline Electric Energy Use	39
38	Summer Retrofit Electric Energy Use	39
39	Summer Baseline Total Electric Use	40
40	Summer Retrofit Total Electric Use	40
41	Summer Baseline HVAC Electric Use	41
42	Summer Retrofit HVAC Electric Use	41
43	Summer Baseline Natural Gas Use	42
44	Summer Retrofit Natural Gas Use	42
45	Fall Outdoor Air Temperature (Both Facilities, Boundary Condition)	43
46	Fall Baseline Indoor Air Temperature	43
47	Fall Retrofit Indoor Air Temperature	44
48	Fall Baseline Electric Energy Use	44
49	Fall Retrofit Electric Energy Use	45
50	Fall Baseline Electric Measured vs. Simulated Use	45
51	Fall Retrofit Measured vs. Simulated Electric Use	46
52	Fall Baseline Natural Gas Consumption	46
53	Fall Retrofit Natural Gas Consumption	47
54	Winter Outdoor Air Temperature	47
55	Winter Baseline Indoor Air Temperature	48
56	Winter Retrofit Indoor Air Temperature	48
57	Winter Baseline Electric Energy Use	49
58	Winter Retrofit Electric Energy Use	49
59	Winter Baseline Electric Simulation	50
60	Winter Retrofit Electric Simulation	50
61	Winter Baseline Natural Gas Consumption	51
62	Winter Retrofit Natural Gas Consumption	51
63	Normalized Total Electric Energy Use	53
64	Normalized HVAC Electric Energy Use	54
65	Normalized Natural Gas Use	54
66	Normalized Peak Demand (kW)	55
67	IR Image of East Face	56
68	IR Image Showing Failed Panel (top left)	56
69	Failed Panels above Sign (South Face)	57
70	Failed Panels above Sign (North Face)	57
71	Number of Panel Sizes vs. Wall Coverage	59
72	Number of Panel Sizes vs. Area Weighted Coverage	60
73	Normalized Heat Gain through Walls	60
74	Normalized Heat Loss through Walls	61
75	Heat Gain through Opaque Walls Secondary Scenario Analysis	63

76	Heat Loss through Opaque Walls Secondary Scenario Analysis	63
77	Economics with Installation Costs	73
78	Economics without Installation Costs	74
79	Secondary Scenario with Installation Costs	76
80	Secondary Scenario without Installation Costs	77
B1	Information Flow for Modeling	86
B2	E+ Data Flow and Operation Diagram	87
C1	East Elevation	90
C2	North Elevation	90
C3	South Elevation	91
C4	West Elevation	91
C5	East Elevation with MAI panels	92
C6	North Elevation with MAI panels	92
C7	South Elevation with MAI panels	93
C8	West Elevation with MAI panels	93
D1	Likert Questionnaire 2	94
D2	Likert Questionnaire 3	95
D3	Likert Questionnaire 1	96
E1	HH-4000 Humidity Sensor Cut Sheet	97
E2	SR20-T2 Calibration Sheet	98
E3	NR01-05 Calibration Sheet	99
E4	DR02-T1-05 Calibration Sheet	100

LIST OF TABLES

1	Calculated Annual Wall-Generated Heating and Cooling Loads in Residential Buildings	8
2	Summary of Performance Objectives	12
3	Performance Assessment Methodology	28
4	Anticipated Timelines	28
5	Sampling Protocol	28
6	Measured vs. Simulated Annual Data (Calibrated Models)	52
7	Normalized Energy Usage	54
8	Peak Demand by Month	55
9	Calculation of R-Value	58
10	Final MAI Panel Sizes	59
11	Total Heat Loss/Gain through Wall	61
12	Likert Questionnaire Tabulated Responses	62
13	Energy Comparison for Non-Insulated Facility Retrofit	62
14	Secondary Scenario Wall Heat Transfer	64
15	Cost Model	65
16	Data Collection for Each Cost Element	65
17	Operating Parameters for All Three Plant Sizes	66
18	Assumed MAI Panel Sizes	67
19	Raw Material Consumption for All Three Plant Sizes	68
20	Raw Material Costs for All Three Plant Sizes	69
21	Labor Costs with Benefits for All Three Plant Sizes	70
22	Overhead and Total Costs of Goods Sold (COGS) for All Three Plant Sizes	70
23	Capital Equipment Costs for All Three Plant Sizes	71
24	Detailed Labor for Installation	71
25	Normalized Energy Savings	72
26	Secondary Scenario Energy Consumption Analysis	75
27	Total Number of IMCOM Facilities	78
28	ASHRAE Building envelope Requirements for Climate Zone 3	82
29	ASHRAE Building envelope Requirements for Climate Zone 5	82
A1	Points of Contact	84
B1	Data Collection Summary	85

EXECUTIVE SUMMARY

The Department of Energy (DOE) estimates that, in 2010, for all U.S. buildings (including Department of Defense [DOD] Facilities), 15.6 quads of primary energy consumption was attributable to fenestration and opaque building envelope components, of which the wall-related primary energy consumption was about 21%, or 3.3 quads (USDOE 2004). For commercial facilities, primary energy consumption attributed to walls during heating cycles was 1.48 quads, or ~30% of total energy consumption due to building envelope components. Heat loss through walls during a heating cycle is a critical component of overall facility energy use, and mitigation measures are important to reduce total facility energy consumption.

This project demonstrated and validated the use of modified atmosphere insulation (MAI) to reduce wall-related energy consumption in DOD facilities. MAI can significantly increase the thermal resistance of walls with only a marginal increase in wall thickness, thereby reducing wall-related energy consumption. By retrofitting walls and increasing their thermal resistance (R-value) by R10-20 ($\text{h}\cdot\text{ft}^2\cdot^\circ\text{F}/\text{Btu}$), reductions of 30% or more over the baseline wall-generated space conditioning loads are possible. (Greater savings are achievable with buildings of older vintage or those that are poorly insulated.) A combination of facility sensors and modeling activities were used to determine the effectiveness of the MAI.

The Performance Objectives (POs) were met and are as follows:

1. Reduce facility energy usage by 4.0% compared to the building's baseline energy usage. The actual reduction was 6.43%.
2. Reduce electrical demand by 2.0% compared to the baseline demand. The actual reduction was 3.5%.
3. Minimize MAI panel vacuum loss to less than 5%. Only 3.3% of the MAI panels failed.
4. Increase overall R-value of envelope to R-13.8/in. The R-value was increased by R-15.2/in.
5. Achieve 70% coverage of wall area with MAI panels. The project achieved 76%.
6. Reduce energy loss through walls by 20% or more. The project achieved a 31% reduction in energy losses through walls.
7. User satisfaction (qualitative) of 90% or more. The project achieved 100% user satisfaction.

The following PO was not met: Achieve a simple payback of 33.1 years with a Savings to Investment Ratio (SIR) of 0.62. The project demonstrated a simple payback of 198 years with an SIR of 0.13. The high simple payback and low SIR is because the facility already contained insulation. For a facility without existing insulation, the simple payback and SIR would be 28 years and 0.83, respectively. Additional cost reductions in manufacturing and installation are expected improve these economics.

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The following persons and organizations are gratefully acknowledged:

- The ESTCP Program Office for funding and providing guidance and support to this effort.
- Fort Drum Energy Manager Mr. Steve Rowley for his support during the project including assistance with coordination of on-site activities.
- Fort Drum Safety Office for providing facilities to study in this report.
- Fort Drum Carpentry and Electrical Shop staff for supporting the on-site installation and retrofit of the Modified Atmosphere Insulation.

The following members were involved in the demonstration:

- ERDC-CERL: Mr. Tapan Patel, Mr. Lake Lattimore, Ms. Irene Andsager, Ms. Justine Yu, Mr. Sean Wallace, Ms. Megan Kreiger and Mr. Shane Hirschi.
- Oak Ridge National Laboratory: Dr. Kaushik Biswas, Dr. Som Shrestha, and Dr. Andre Desjarlais.
- Nanopore, Inc.: Dr. Doug Smith, and Mr. Ron Esparza.
- Fort Drum: Mr. Stephen Rowley.

LIST OF ACRONYMS

(Insert acronym or abbreviation in first column and definition in second column; insert or delete rows as needed.)

Term	Definition
ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BAS	Building Automation System
BLAST	Building Loads Analysis and System Thermodynamics
BLCC	Building Life Cycle Cost
BTU	British Thermal Unit
CAD	Computer-Aided Design
CERL	Construction Engineering Research Laboratory
CMU	Concrete Masonry Unit
COGS	Cost of Goods Sold
CTF	Conduction Transfer Function
DLA	Defense Logistics Agency
DNI	Direct Normal Incidence
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
ECIP	Energy Conservation Investment Program
EIFS	Exterior Insulation and Finish System
EISA	U.S. Energy Independence and Security Act of 2007
EMPD	Effective Moisture Penetration Depth (model)
EO	Executive Order
ERDC	U.S. Army Engineer Research and Development Center
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
ESTCP	Environmental Security Technology Certification Program
EVOH	Ethylene Vinyl Alcohol
EW	Energy and Water
FY	Fiscal Year
HFMA	Heat Flow Meter Apparatus
HFT	Heat Flux Transducer
HQIIS	[Army] Headquarters Installation Information System
HVAC	Heating, Ventilating, and Air-Conditioning
IECC	International Energy Conservation Code
IMCOM	U.S. Army Installation Management Command
IR	Infrared

Term	Definition
IT	Information Technology
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
LLC	Limited Liability Corporation
LLDPE	Linear Low-Density Polyethylene
LTL	Less Than Load
LW	Long-Wave
MAI	Modified Atmosphere Insulation
MILCON	Military Construction
MMBTU	million BTU
N/A	Not Applicable
NIST	National Institute of Standards and Technology
OMB	Office of Management and Budget
ORNL	Oak Ridge National Laboratory
OSB	Oriented Strand Board
PET	Polyethylene Terephthalate (metallized film)
PO	Performance Objective
QC	Quality Control
RH	Relative Humidity
SAR	Same As Report
SERDP	Strategic Environmental Research and Development Program
SF	Square Feet
SiC	Silicon Carbide
SIOH	Supervision, Inspection, and Overhead
SIR	Savings to Investment Ratio
SMS	Sustainment Management System
SP	Simple Payback
SPB	Spun-Bound Polypropylene
T/RH	Temperature/Relative Humidity
TR	Technical Report
VFSS	
VIP	Vacuum Insulation Panel

1.0 INTRODUCTION

This project, “Demonstration and Cost Analysis of a Building Retrofit using High Performance Insulation,” demonstrates the advantages of modified atmosphere insulation (MAI) as an emerging technology, to mitigate energy loss through walls. Specifically, MAI can significantly increase the thermal resistance of walls with only a marginal increase in wall thickness. The idea of mitigating energy loss in building envelopes has been at the forefront of the U.S. Department of Energy (DOE) and the U.S. Department of Defense (DOD). Successful demonstration of this technology will enable DOD to meet, among others, several executive orders (e.g., Executive Order [EO] 13693), the Energy Security and Independence Act (EISA 2007), the Energy Policy Act of 2005 (EPAct 2005, Sections 102 and 103), and various other mandates.

1.1 Background

The DOE estimates that, in 2010, for all U.S. buildings (including DOD Facilities), 15.6 quads of primary energy consumption was attributable to fenestration and opaque building envelope components, of which the wall-related primary energy consumption was about 21%, or 3.3 quads (USDOE 2004). For commercial facilities, primary energy consumption attributed to walls during heating cycles was 1.48 quads, or ~30% of total energy consumption due to building envelope components. Heat loss through walls during a heating cycle is a critical component of overall facility energy use, and mitigation measures are important to reduce total facility energy consumption.

In Fiscal Year 2012 (FY12), DOD’s annual facility energy consumption was estimated to cost \$4B/year (~20% of total DOD energy cost). Within the U.S. building stock, 37% of primary energy is used for space heating and cooling. By this estimate, DOD spends ~\$1.5B/year for space heating and cooling, split roughly as 45% for heating and 55% for cooling. Hence, during heating cycles alone, it is estimated that heat loss through walls costs DOD about \$200M/year, or about 5% of the total DOD facility energy cost. Mitigating such losses is critical for the reduction of energy consumption by DOD facilities, particularly in cold climates.

This project demonstrates and validates the use of MAI to reduce wall-related energy consumption in DOD facilities. MAI can significantly increase the thermal resistance of walls with only a marginal increase in wall thickness, thereby reducing wall-related energy consumption. By retrofitting walls and increasing their thermal resistance (R-value) by R10-20 (h-ft²-°F/Btu), reductions of 30% or more over the baseline wall-generated space conditioning loads are possible (greater savings are achievable with buildings of older vintage or those that are poorly insulated).

DOD currently uses fiberglass insulation, blown-in cellulose, polystyrene, polyurethane, or polyisocyanurate (polyiso) board for wall insulation. These types of insulation have been used for many years and provide insulation with an “R value per inch” of 3 to 7. Current state of the art technology, Vacuum Insulation Panels (VIPs) is the only technology that promises a step-change in performance (R40/in. compared to conventional insulation materials that achieve up to R6-7/in.). Outside of planned major renovations, insulation is typically not added in DOD buildings. Depending on the building type, traditional insulation retrofits require structural modifications and often do not address issues with thermal bridging. The high performance of this technology and application to the exterior surface of buildings make this technology more readily implementable

while reducing thermal bridging. Installing this technology on the exterior also decreases impact to occupant operations during the retrofit process.

VIPs consist of an evacuated core material (usually fumed silica for building applications) with a microporous structure. The core material is encapsulated within a barrier film and sealed under vacuum. One major hindrance for broad market acceptance of VIPs is their high cost, which is greater than \$0.25/ft²/R. The new insulation technology, MAI, has similar performance to a VIP yet it is processed at ambient pressure using standard vertical form-fill-seal machines, which are the same type as those used to package potato chips, yielding a cost closer to \$0.10-0.15/ft²/R. MAI's high thermal performance is a unique tool for improving building envelope energy efficiency. A thickness of 0.5 to 1 in. of MAI can dramatically improve envelope efficiency without a significant increase in wall thickness. Using conventional insulation materials to achieve a similar thermal performance improvement will require substantially higher thicknesses of the insulation material and hence, the wall assembly with associated costs of structural modifications (extended window and door jambs, longer fasteners, etc.).

For this demonstration, the building under consideration for retrofit already has R-19 fiberglass batts within the wall cavity. This means that any additional insulation has a reduced impact on the energy and cost savings. Nevertheless, this project will demonstrate the retrofit process, and the data can be extrapolated for buildings that lack insulation.

1.2 Objective of the Demonstration

This project retrofitted the exterior walls of a building at Fort Drum (a heating-dominated climate) with MAI panels and quantified the energy benefits. The MAI enhances the effective "R-value" of insulation, thus reducing heat transfer through the walls, while maintaining comfortable temperatures for the building occupants. Two similar buildings were chosen for this study. One building was the baseline, and the second was retrofitted with MAI. Energy monitoring sensors (heat flux, temperature, humidity, etc.) and building electric and natural gas meters were installed to obtain overall energy usage of the building. Once the MAI was installed, energy consumption in both buildings was monitored. Comparisons on overall building energy usage, heat flux through various surfaces, and temperatures were made. Using a complex building energy simulation model, the overall energy usage of both buildings was normalized to account for variations in building factors (occupancy, internal loads, etc.). A comparison of this normalized data is then used to provide performance validation of the technology.

Using the energy savings performance metrics (Btu/ft²), utility rates and the cost of the MAI panels, a detailed cost analysis of the new lower-cost, high performance MAI panels is expected to demonstrate the potential for widespread applications. MAI panels offer a significant cost benefit over traditional VIP. VIPs cost more than \$0.25/ft²/R, whereas the MAI panels cost closer to \$0.10-0.15/ft²/R.

Although the cost of MAI is higher than traditional fiberglass batt insulation, MAI's high thermal performance is a unique tool for improving building envelope energy efficiency. A thickness of 0.5 to 1 in. of MAI can dramatically improve envelope efficiency without a significant increase in wall thickness. Using conventional insulation materials to achieve a similar thermal performance improvement will require substantially higher thicknesses of the insulation material and hence, the

wall assembly with associated costs of structural modifications (extended window and door jambs, longer fasteners, etc.). For retrofit purposes, MAI panels offer a significantly lower cost of structural modifications.

By retrofitting walls and increasing thermal resistance by R10-20 (h-ft²-°F/Btu), reductions of 30% or more over baseline wall-generated space conditioning loads are possible in DOD. Furthermore, with targeted applications for older or more poorly insulated facilities, greater load reductions can be achieved. Financial and environmental benefits will be accompanied by increased occupant comfort.

1.3 Regulatory Drivers

This technology addresses the problem faced by DOD to reduce energy intensity (BTUs per square foot) by 2.5% per year, from the 2015 baseline, as per EO 13693. The Energy Policy Act of 2005, which sets the Federal energy management requirement in several areas including energy reduction, is also addressed by this technology. The project also supports the Energy Security and Independence Act (EISA 2007) for increased energy efficiency in Federal buildings. Secondary drivers include the reduction of greenhouse gases by 40% from 2008 levels (EO13693) and the reduction of fossil fuel use. By reducing heat loss/gain through the walls, building energy consumption will be decreased. This will result in fossil fuel usage reduction and subsequent greenhouse gas reduction. The levels of reduction will depend on site specifics including type of heating fuel (e.g., natural gas, oil, etc.) and the makeup of electric supply (e.g., coal, natural gas, renewable energies, etc.). This technology also supports requirements for Leadership in Energy & Environmental Design (LEED) certifications in major renovations or construction and Net Zero Energy goals.

2.0 TECHNOLOGY DESCRIPTION

NanoPore Inc., working in conjunction with the DOE's Building Technology Program and Oak Ridge National Laboratory (ORNL), is developing a new generation of advanced thermal insulation with the same performance as silica-based VIPs and significantly reduced costs. The new insulation technology is called modified atmosphere insulation (MAI). Vacuum insulation is the only technology that promises a step-change in performance (R40/in. compared to conventional insulation materials that achieve up to R6-7/in. (Figure 1). VIPs consist of an evacuated core material (usually fumed silica) with a microporous structure. The core material is encapsulated within a barrier film and sealed under vacuum. This project will specifically test the cost and performance test of MAIs. Numerous studies related to VIPs in buildings can be found in the literature, but those related to actual building applications are few (Tenpierik, Cauberg, and Thorsell 2007; Brunner and Simmler 2008; Cho, Hong, and Seo 2014). ORNL and industry partners evaluated an exterior insulation and finish system (EIFS) that contained VIPs (Childs et al. 2013). Combined experimental testing and numerical analysis indicated that whole-wall R-values of R30 hr-ft²-°F/Btu or higher were achievable using 3-in.-thick foam-VIP composites.

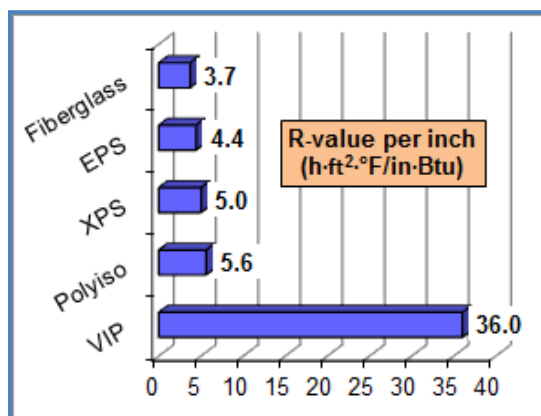


Figure 1. R-Values of VIP and Conventional Insulation Materials.

Heat transfer in insulation occurs via three modes: solid conduction, gas/vapor conduction, and radiation. The microporous structure and low gas pressure within VIPs essentially eliminate the gas/vapor conduction (Childs et al. 2013). Reducing the radiation heat transfer by adding opacifiers, without increasing the solid conduction, can potentially increase the nominal thermal performance of VIPs to R60/in. NanoPore and ORNL are currently working with DOE to evaluate new generations of infrared opacifiers, barrier materials, etc., for improving the performance and durability of VIPs. They have also been awarded funds to design and create foam-VIP composites for incorporation into walls of new and retrofit construction.

The new insulation technology, MAI (Figure 2), demonstrates similar performance to that of VIP, but is processed at ambient pressure using standard vertical form-fill-seal machines, which are the same type as those used to package potato chips. The high-cost of VIPs can be attributed to processing that includes pressing fine powders into a board, cutting, drying, and then evacuating and sealing in a vacuum. MAI avoids these problems by replacing the air in a fluidized powder with a low molecular weight, low conductivity compound, resulting in fewer process steps and lower cost. For comparison, Figure 3 shows both VIP and MAI process flow diagrams.

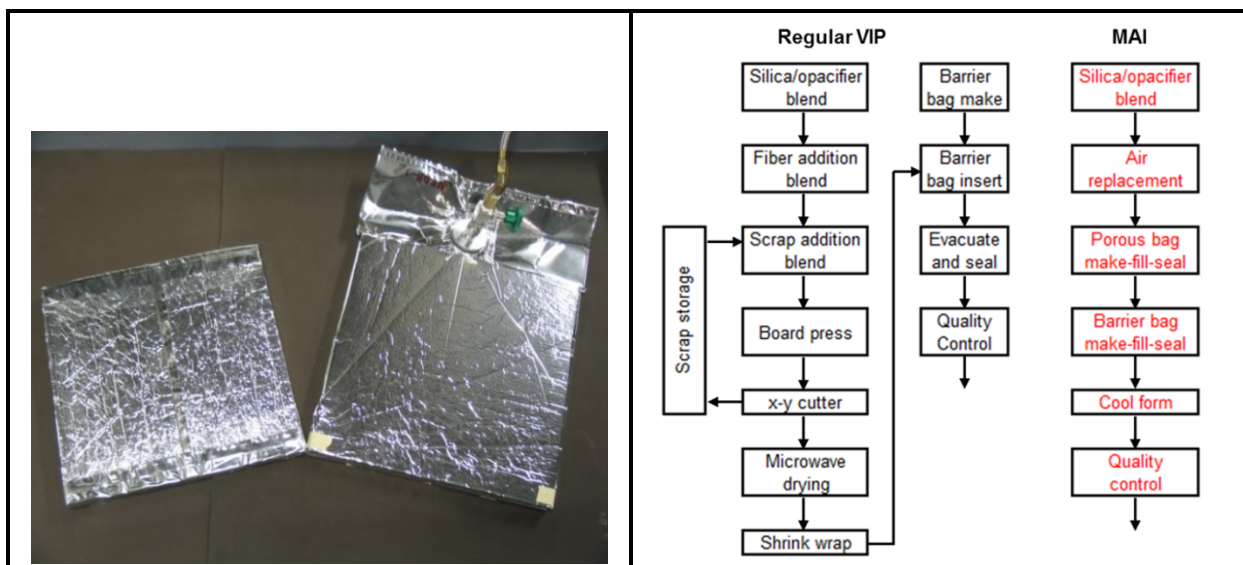


Figure 2. MAI Panels.

Figure 3. Flow Charts of VIP and MAI Production Processes.

There are three main components of MAI: (1) the nano-porous silica core material (necessary to achieve the desired high R/in.), (2) the barrier film to encapsulate the core (for the desired insulation lifetime), and (3) the process to make the advanced insulation panel (to achieve the necessary low cost). The nanoporous silica core (~60 nanometer average pore size) flows from technology developed by NanoPore, University of New Mexico, and Sandia Laboratories, which resulted in an R&D 100 award 20 years ago. Approximately 200 million tons of nano-porous silica is produced in the United States every year. The silica is the basis for the R40/in. VIPs that NanoPore Insulation (now Kevothermal LLC) has used to become the largest VIP producer in the United States and UK. This project used the same silica core enhanced with recently developed commercial-scale infrared opacifiers. For the barrier, there are a number of established options including films (multilayer metalized polyester) currently used for VIPs in buildings in Europe as well as next-generation coextruded polyvinyl alcohol films. For all films to be considered for this project, a minimum of 2 years of both real time (30 °C/86 °F) and 20x (in time) accelerated (80 °C/176 °F) lifetime testing has been completed. In this application, EvOH (ethylene vinyl alcohol) barriers were used. The final issue is the MAI process, which is critical to obtaining our cost/performance targets. ORNL demonstrated this on a laboratory scale by taking thermal performance measurements that achieved the target thermal resistance (R/in.>35).

NanoPore has a new 44,000 ft² building that contains a pilot scale (~300 ft²/hour) production line for MAI panels. All the different process steps have been demonstrated to require residence times of less than 20 seconds, which well satisfies the throughput required to meet MAI production cost targets. Figure 4 (left) shows the system for quickly unloading bulk bags (~1 per hour is used when the line is running), and (right) the second MAI chamber where air is quickly replaced with steam before the final cold-forming step. All steps are running individually and the line is now being automated to allow continuous operation.



Figure 4. Pilot-Scale Unloading (left) and MAI Chamber for Air-Steam Replaces (right).

Within DOD, this technology is expected to be applicable to wall insulation retrofits, including buildings with similar construction to those in this project (wood-frame construction with exterior metal siding, and plywood sheathing). Other building construction types within DOD (e.g., Concrete Masonry Unit [CMU], Metal Panel, etc.) are also expected to be viable candidates. The major difference in the use of this technology for various building types will be the method used to fasten/adhere the MAI panels.

3.0 TECHNOLOGY DEVELOPMENT

3.1 Performance Advantages

MAI's high thermal performance is a unique characteristic for improving building envelope energy efficiency. A thickness of 0.5 to 1 in. of MAI can dramatically improve envelope efficiency without a significant increase in wall thickness. Using conventional insulation materials to achieve a similar thermal performance improvement will require substantially higher thicknesses of the insulation material, and will hence alter the dimensions of the wall assembly and add costs associated with structural modifications (extended window and door jambs, longer fasteners, etc.).

During FY14, ORNL and NanoPore evaluated MAI panels under a DOE-funded scoping study. Under this project, the thermal resistance (R-value) of MAI panels was measured under different temperatures and internal panel pressure conditions according to standards set in American Society for Testing and Materials (ASTM) C518 (ASTM 2010). The temperatures were chosen based on the range of temperatures that are experienced by external building walls in different U.S. climate zones. The internal panel pressure was varied from 10 mbar (vacuum) to atmospheric pressure (to simulate a damaged panel). Figure 5 shows the measured R/in. of the MAI panels. The R/in. of an intact MAI panel was higher than 32 (hr-ft²-°F/Btu-in) at various temperatures. It is interesting to note that the MAI R/in. was higher at lower temperatures, which makes it naturally better suited for exterior envelope applications in cold, heating-dominated climates. Furthermore, even with complete loss of internal vacuum, the R/in. of the MAI panels was still higher than conventional insulation materials.

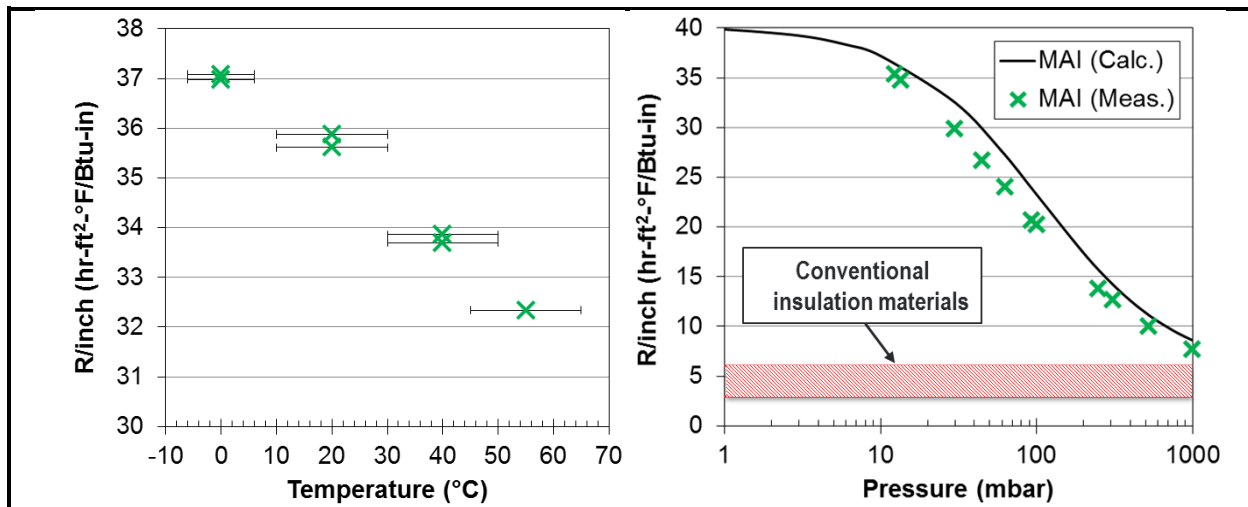


Figure 5. Thermal Resistance (R/in.) of MAI Panels, as a Function of Temperature and Pressure, Compared to Conventional Insulation Materials (Foam, Fiberglass and Cellulose).

To estimate the energy benefits of adding MAI panels to exterior walls, some preliminary EnergyPlus (E+) modeling was done (see Appendix B). Three scenarios were investigated: (1) baseline building, (2) R10 insulation added to exterior walls of the baseline building, and (3) R20 added to exterior walls of the baseline building. The simulations were performed using

standardized model residential buildings* in two climate zones (2 and 4). Buildings, including their envelopes and Heating, Ventilating, and Air-Conditioning (HVAC) designs, based on the International Energy Conservation Code (IECC) 2006 and 2012 were modeled. Wall-generated heating and cooling loads were calculated with baseline wall R-value, “baseline + R10,” and “baseline + R20.”

Table 1 lists the calculated annual heating and cooling loads and the reductions with the added R-value, for the different cases and the two climate zones. Significant savings in wall-generated space conditioning loads are possible by retrofitting walls of both new and older buildings using MAI, as shown by the results listed below. Note that old buildings needing retrofit are usually at least 20 to 30 years old and are not insulated up to 2006 IECC standards; therefore, the percent savings for older buildings can be expected to be higher than those reported below.

Table 1. Calculated Annual Wall-Generated Heating and Cooling Loads in Residential Buildings.

	San Antonio (Climate zone 2)					Baltimore (Climate zone 4)				
	Wall R-value	Heating (kBtu)	Diff. (%)	Cooling (kBtu)	Diff. (%)	Wall R-value	Heating (kBtu)	Diff. (%)	Cooling (kBtu)	Diff. (%)
2006	Baseline	9523		18375		Baseline	25466		10159	
	+R10	5435	-43	11186	-39	+R10	16516	-35	6171	-39
	+R20	4537	-52	10067	-45	+R20	13547	-47	5614	-45
2012	Baseline	8792		16725		Baseline	18059		9353	
	+R10	4716	-46	9872	-41	+R10	12743	-29	6577	-30
	+R20	3812	-57	8699	-48	+R20	10721	-41	6209	-34

Although this demonstration is not testing the use of this technology for roof insulation, the MAI panels offers significant benefits over current roof insulation technology. The high R-value/in. of the MAI panels means that a significantly lower thickness of insulation is needed. For example, due to the relatively low R-value/in. of current insulation technology, current built-up roof retrofit procedures require removal of the membrane, raising any roof-top air-conditioning equipment, placing the insulation, resealing, and then adding a new membrane. The low thickness of the MAI panels would significantly reduce the need to raise conditioning equipment. This would reduce overall cost and significantly shorten the timeline of these kinds of retrofits.

3.2 Performance Limitations

The greatest potential performance limitation of the technology is primarily related to the process of installing the MAI panels in a building. Although the panels have superior performance to traditional wall insulation technologies (fiberglass batts, blown-in cellulose, etc.), the panels are susceptible to being punctured. However, pressure testing conducted to simulate a puncture (see Figure 5, 1000 mbar) shows that the panels still maintain a higher R-value/in. than traditional insulation technology.

* Residential Prototype Building Models,
http://www.energycodes.gov/development/residential/iecc_models

As with any other insulation technology, the incremental energy savings associated with increasing the wall R-value are diminished. As shown in Figure 6, a 1500 ft² building in a mixed-humid climate was simulated with varying levels of insulation. The associated energy savings with each incremental layer in insulation is shown. As the figure shows, insulation is most effective on buildings with little or no insulation. Any additional insulation thereafter has a diminished effect on the energy savings. For this project, the chosen building already had R-19 insulation in the walls. As a result, the energy and cost savings will be less than ideal. Nevertheless, this project will still demonstrate the effectiveness and potential applicability of the technology.

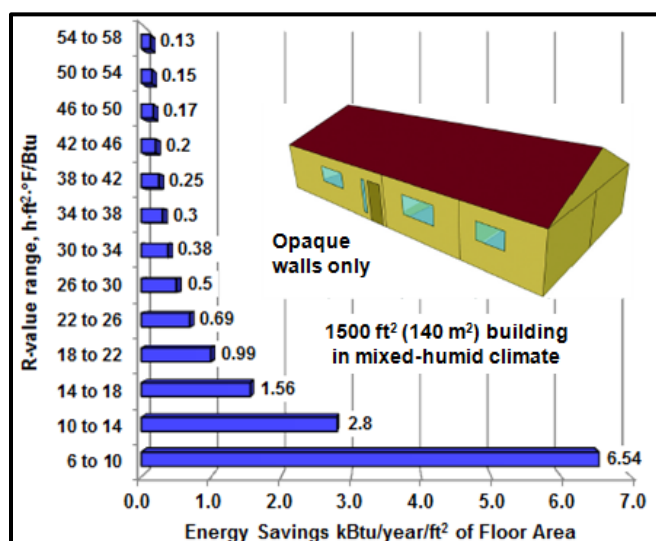


Figure 6. Effects of Increasing Insulation on Energy Savings.

Another performance limitation relates to the potential impact on HVAC systems. By significantly improving the envelope performance, there is a possibility of reduced load conditions (compared to design) on HVAC equipment. Specifically, heating and cooling equipment will likely cycle more often. In humid climates, the more rapid cycling can affect removal of moisture within the building. For this application in a heating dominant climate, HVAC cycling was monitored and found to be limited. Future applications should consider HVAC cycling because the impact will be dependent on several factors including building size, internal loads, occupancy, etc.

3.3 Cost Advantages

As part of the DOE-funded project, a cost analysis of the MAI manufacturing process was performed to compare the cost of MAI to state-of-the-art VIPs. At present, traditional VIPs cost about \$0.25/ft²/R-value, with the following breakdown of cost: 25% material and 75% processing/overhead. As mentioned earlier, processing of MAI entails about 50% fewer steps than VIP; consequently, the cost of MAI panels based on a pilot-scale production line is estimated to be \$0.12–0.16/ft²/R-value (assuming R-35/in. for the MAI panels, the cost translates to \$4.14–5.52/ft²).

3.4 Cost Limitations

MAI panels are considerably cheaper than traditional VIPs. The technology, however, is considerably more expensive than conventional fiberglass insulation. For example, traditional fiberglass batts typically cost \$0.03/ft²/R-value. MAIs are almost 4-5 times more expensive than this. However, using MAI panels can offset some of the cost of structural modifications associated with using fiberglass batts.

3.5 Potential Barriers to Acceptance

One of the most significant potential barriers to acceptance of MAI technology is the current cost of the technology compared to traditional retrofit applications. The technology is also currently more suitable for building exterior applications. Additional research is necessary to determine how the panels can be attached to different exterior structures such as CMU. The presence of a vapor barrier in cooling-dominated climates will also have to be investigated. This is an important issue. For example, past exterior insulation technologies, such as EIFS, have had issues with moisture migration that have since been resolved. Once installed, if MAI panels have issues related to moisture in their current configuration, this might be a potential barrier to acceptance.

4.0 PERFORMANCE OBJECTIVES

The innovative MAI insulation technology is expected to enhance energy efficiency in buildings by reducing the heating and cooling loads and reducing energy intensity in support of EO 13693. The MAI technology is ideally suited for cold, heating dominant climates, where the heat loss through the wall contributes to a large portion of the overall building energy losses. The MAI technology can be installed as a retrofit or used in new construction in several facility types including typical barracks, training facilities, and Command, Control, and administration buildings. Although the technology performs best in cold climates, it can be used in any climate zone where building insulation is recommended.

The POs in Section 4.1 describe the metrics, data requirements, and criteria that will measure and determine the success of this project. The objectives are related to several areas including reduction in energy usage, cost performance, effectiveness of the MAI panels, and occupant satisfaction. Each of the criteria will be evaluated separately. The energy savings and system economics are the most important for this project.

4.1 Performance Objectives Descriptions

Table 2 lists descriptions of the POs.

Table 2. Summary of Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Facility Energy Usage	Reduction in Energy Use (kWh, BTU)	Meter readings of energy used by installation (kWh and BTUs), weather data, occupancy hours, temperature setpoints	4.0% reduction compared to baseline energy usage of building	6.43% reduction, PASS
Demand Reduction	Reduction in Demand (kW)	Meter readings of energy used by buildings (kW)	2.0% reduction compared to baseline demand of building	3.5% reduction, PASS
Percent of Panels Experiencing Loss of Vacuum	Percent of Panels Experiencing Loss of Vacuum (%)	Infrared (IR) thermographic images	<5% Panels experiencing loss of vacuum	3.3% experiencing loss of vacuum, PASS
Overall R-value of walls with MAI	Increase in R-value	IR thermography images, panel layout, internal and external temperature data, heat flux	Increase in overall R-value >13.8/in.	15.2/in., PASS
Coverage of Wall Area with minimal MAI Panels	% of Total Wall Area Covered with Minimal Number of MAI Panel sizes (%)	Total wall area (ft ²), Wall area covered by MAI panels (ft ²), Number of different panel sizes	>70% coverage with four or fewer different MAI panel sizes	76% coverage, PASS
Energy Loss Through Walls	Reduction in Energy Loss through the Walls (watt/m ²)	Wall heat flux (watt/m ²), wall temperature sensors (interior and exterior)	Reductions of 20% or more over baseline wall-generated space conditioning loads	31% reduction, PASS
System Economics	Simple Payback (SP) in Years, SIR	\$ costs, discount rate, usable life, energy reduction, energy rates	SP = 33.1 years, SIR = 0.62	SP = 198 years, SIR = 0.13, FAIL
Qualitative Performance Objectives				
User Satisfaction	Degree of Satisfaction	Likert Scale Survey	90% Satisfaction	100%, PASS

4.2 Summary of Performance Objectives

4.2.1 Facility Energy Usage

Purpose: This PO determines overall reduction in normalized facility energy usage by installing the MAI panels for increased wall insulation. Reducing the overall facility energy usage is in direct support of EO 13693 to reduce overall facility energy intensity. Normalizing the facility energy usage is important because the buildings had different levels of occupancy and internal loads.

Metric: Reduction in energy usage of the facility. Using the collected data, E+ models were created and compared to determine the reduction in energy usage of the facility. The usage combines the annual reduction in electric (kWh) and natural gas (kBtu).

Data: Meter readings (gas and electric), weather data, occupancy hours, and temperature setpoints.

Analytical Methodology: The team first created E+ models of the facilities using facility dimensions, weather, solar, internal air thermocouple, occupancy and internal load data. The models were then compared and calibrated to actual heat flux, HVAC consumption and electric/gas metered data for each facility. These models are referred to as the calibrated models. Since the space usages are different, the energy usage of the facilities will vary. To accurately compare the benefits of the technology, several factors need to be normalized across the facilities. The normalized models use some information from the DOE commercial prototype building models for a small office building. The normalized factors were internal load, occupancy, and thermostat setpoint schedule. All other characteristics were not changed from the calibrated models and were those from the actual facilities.

Success Criteria: Based on the results from the normalized E+ models, the team determined the reduction in annual energy usage. Energy savings of 4.0% or greater are considered a success for these facilities. For non-insulated facilities, the savings are expected to be much higher.

4.2.2 Demand Reduction

Purpose: This PO determines the overall reduction in electrical demand for the building based on normalized models.

Metric: Reduction in electrical demand of the facility. Using the collected data, the normalized E+ models were compared to determine the reduction in electric demand (kW) of the facility.

Data: Meter readings (gas and electric), weather data, occupancy hours, and temperature setpoints.

Analytical Methodology: The analytical methodology is identical to the above PO. In this case, the change in demand was determined from the normalized models. The utility rate structure was used to determine the cost savings.

Success Criteria: Based on the results from the normalized E+ models, the team determined the reduction in electrical demand (kW). A demand reduction of 2.0% or greater is considered a success.

4.2.3 Percent of Panels Experiencing Loss of Vacuum

Purpose: Determine if any panels experience a loss of vacuum. The benefit associated with MAI panels is largely lost if any of the panels experience a loss of vacuum. The goal was to increase R-value, discussed in the next PO. By setting criteria for improved R-value, the acceptable loss was determined as <5%.

Metric: Percent of Panels Experiencing Loss of Vacuum.

Data: IR thermography images.

Analytical Methodology: IR images of the retrofit building were taken before and several times after installing the MAI panels. One set of IR images was taken immediately after the retrofit, and was used to determine if any panels have failed. This immediate IR image showed panels that were punctured during the installation and lost their vacuum (and high R/in.) before these IR images were taken. Some failed panels were discovered many months after the installation. These panels likely failed due to a slow leak. Failed panels show up as “hot spots” in IR images.

Success Criteria: <5% panels experiencing loss of vacuum.

4.2.4 Overall R-Value of Walls with MAI

Purpose: Determine the increase in R-value of the wall after the MAI panels have been installed. The overall R-value is specific for this building construction type and includes a combination of factors including available area for MAI panels. This metric is independent of fenestrations and only addresses the R-value of the wall. It is important to note that the traditional R-19 cavity insulation usually translates to R12-13 overall for the entire wall, based on the extent of thermal bridging. The improvement with MAI panels will effectively double the overall R-value. The overall R-value increase is estimated by determining the coverage of MAI panels and the impact of the number of failed panels.

Metric: Increase in R-value.

Data: IR thermography images and panel layout.

Analytical Methodology: IR thermography was performed immediately after the retrofits and several times after. At certain spots, the actual temperature and heat flux data were used to determine the R-value of the wall and to calibrate the E+ models.

Success Criteria: Increase overall R-value by 13.8 or more.

4.2.5 Coverage of Wall Area with Minimal MAI Panels.

Purpose: An objective of this demonstration is to show the applicability of the MAI panels to DOD. It is important to maximize wall area coverage with a minimal number of different sized MAI panels. This simplifies the logistics, cost and time associated with creating panels of different sizes. As the technology matures and reaches full production scale, several optimized “standard” panel sizes could be created. Although increasing the number of panels would increase coverage, there

is a rate of diminishing returns. This project attempted to maximize the wall area coverage while reducing the number of panels. Although this is not an optimization, increasing the number of panel sizes increases the production cost per unit. For this demonstration, several different panel sizes and numbers were investigated. The team ultimately settled on four different panel sizes based on building dimensions.

Metric: % of Total Wall Area covered with minimal number of different MAI panel sizes (%).

Data: Total Wall Area (ft²), Wall Area Covered by MAI panels (ft²), Number of different panel sizes.

Analytical Methodology: The locations of the fasteners were measured during the initial site visit and a set of elevation drawings were developed from these measurements. The drawings were used to determine the number of different panels that are needed for each portion of the building. Initial calculations showed that four different panel sizes were needed. The actual number of panels and sizes were tracked during installation. There were some variations in the location, but the number and sizes exactly matched the planned panels.

Success Criteria: >70% coverage with four or fewer different MAI panel sizes.

4.2.6 Energy Loss through Wall

Purpose: This PO will determine the overall reduction in energy losses through the wall. Reducing energy losses through the walls will reduce the overall facility energy usage and is in direct support of EO 13693 to reduce overall facility energy intensity.

Metric: Reduction in energy loss through the walls based on the normalized models. As described earlier, wall losses account for approximately 5% of the total DOD facility energy cost. By reducing the wall losses by 20%, the overall facility usage will also decrease. This reduction is based on previous experience and modeling with the MAI technology.

Data: Wall heat flux (Watt/m²), interior and exterior wall temperature (°F/°C).

Analytical Methodology: The team placed wall heat flux sensors and interior and exterior wall temperature/relative humidity sensors in both buildings. One set of sensors were placed on each face and the floor and ceiling for a total of at least six sets per building and 12 total. The location on each face was determined after coordinating with building occupants to ensure minimal impact on day-to-day activities. A gypsum board was placed against the sensor to cover and protect it. The heat flux on each of the walls were compared across the two buildings for both the calibrated models and normalized models. Because heat fluxes vary depending on occupancy in the buildings, temperature setpoints, internal loads, etc., only the normalized models will be considered for evaluating the POs.

Success Criteria: This PO will be considered successful if the average heat flux across all walls in the normalized retrofitted building is reduced by an area-weighted average of 20% or more compared to the baseline average heat flux across all walls.

4.2.7 System Economics

Purpose: This PO will determine the overall cost savings, simple payback, and the SIR associated with the MAI technology for the retrofit building at Fort Drum.

Metric: Simple payback in years, SIR.

Data: Dollars costs, discount rates, usable life, energy reduction, energy rates and utility rate structure, utility rate escalation factors.

Analytical Methodology: Energy reduction in the normalized models for the retrofit building compared to the baseline building were used to determine the monetary savings associated with reduced energy intensity. The National Institute of Standards and Technology (NIST) Building Life-Cycle Cost (BLCC) Program for Military Construction (MILCON) Analysis (Energy Conservation Investment Program [ECIP] Project) was used to determine the Life Cycle Cost (LCC) for this demonstration. Using the actual coverage of MAI panels on the ~2000 ft² wall area, and projected price of \$4.2/sq ft for R-35, 1-in. MAI panel, the NIST BLCC tool was used to generate the system economics using the MILCON, ECIP Project Analysis template. Note: the less favorable Simple Payback and SIR occur since the building already has a significant amount of insulation. However, the life cycle benefit for adopting this technology DOD-wide is still attractive. One of our main goals for this project was to demonstrate the installation process of the MAI panels, and the current building is a good candidate to showcase that procedure. The methods developed in this demonstration will be directly applicable to many DOD facilities that lack insulation or have minimal insulation.

Success Criteria: This PO is considered successful if the Simple Payback is less than 33.1 years and the SIR is greater than 0.62.

4.2.8 User Satisfaction

Purpose: Determine overall occupant satisfaction from the retrofit.

Metric: Degree of satisfaction.

Data: Likert Scale Survey Inputs.

Analytical Methodology: Two Likert Scale Surveys were distributed. One was intended for evaluation by Fort. Drum safety office teachers who use both facilities regularly. The second was given to the installers of the MAI technology to assess the ease and concerns with the actual installation of the technology. Each question was assigned five potential answers (i.e., strongly disagree, disagree, neutral, agree, and strongly agree). Each answer was assigned a numerical value ranging from -2 to 2, which correspond to strongly disagree and strongly agree, respectively. Questions were worded such that items with a negative impact on occupants will receive a value of -1 or -2 depending on the severity. The scores were summed and averaged for each occupant. For example, a question may be “The building was more comfortable after the retrofit.” As discussed later, only the Likert survey for installers was used. There were no occupants who regularly used the retrofit facility before and after the MAI installation.

Success Criteria: This PO will be considered successful if 90% of each of the surveys' results have an average score greater than 0, which corresponds to an overall neutral (neither positive nor negative) effect on occupants.

5.0 FACILITY/SITE DESCRIPTION

The MAI panels were installed on the walls of Fort Drum, NY Directorate of Public Works Bldg. 432B, which was used as a control building. The 2000 ft² buildings are located within 100 ft of each other and constructed in an identical manner (2X6 wood frame, metal siding, R-19 wall insulation, R-40 roof insulation, glazing size, and orientation). Bldg. 431B was used for classroom motorcycle training courses and Bldg. 432B was used for cold weather equipment training. Bldg. 431B experienced higher occupancy and usage over the course of this demonstration. Figure 7 shows the location of both buildings relative to each other. Figure 8 shows the southern face of Bldg. 432B. Both buildings are operated by the Fort Drum Safety Office.

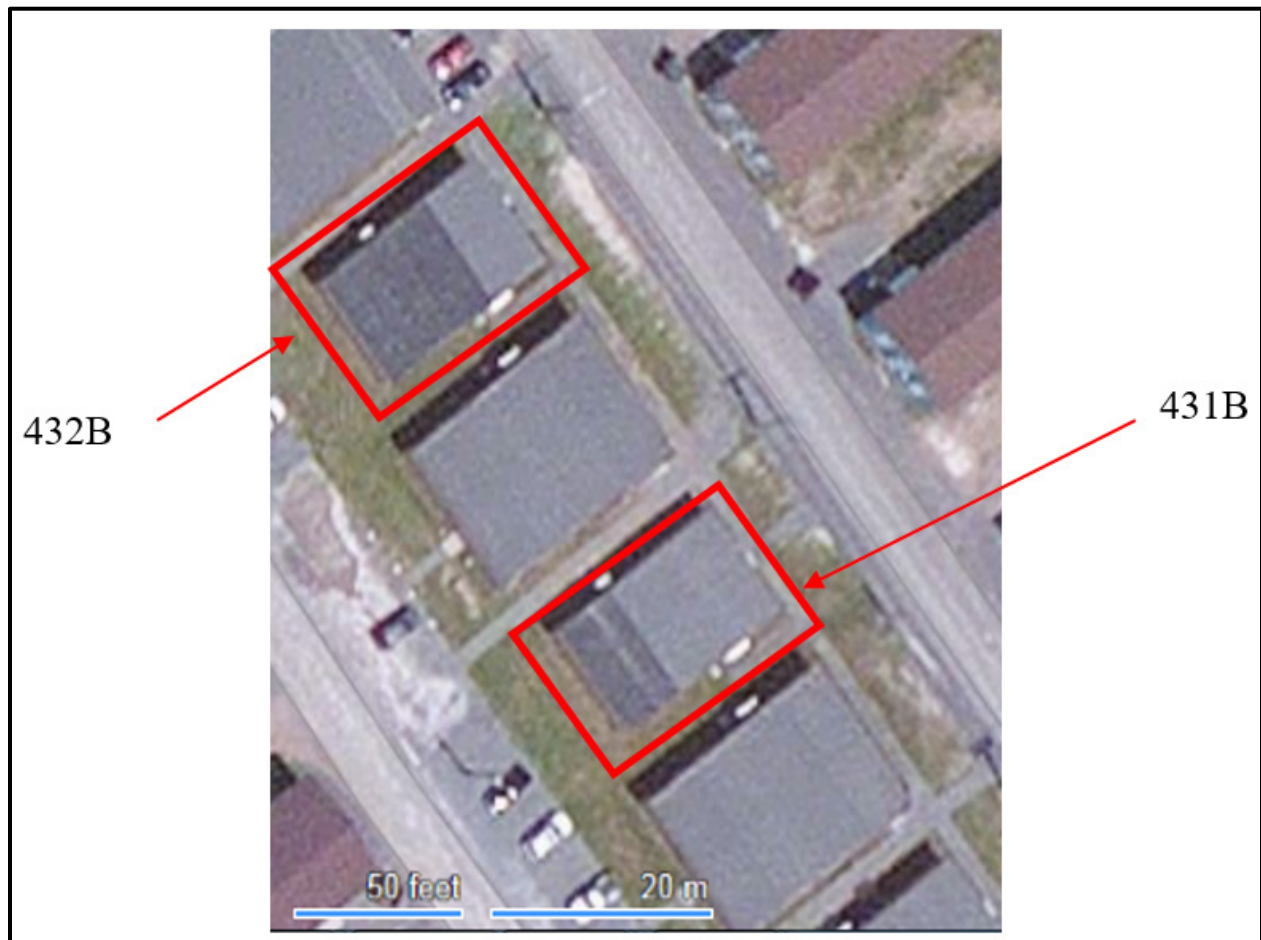


Figure 7. Plan View of Building Locations.



Figure 8. Fort Drum Retrofit Facility.

5.1 General Facility/Site Selection Criteria

The facility/building selection was based on:

1. The simple construction of the building and the ease of installing the MAI panels.
2. Availability of the building for easily installing instrumentation without detrimental interruption to normal use
3. Size of the buildings
4. Side-by-side baseline / technology demonstration.

5.2 Demonstration Facility/Site Location and Operations

One of the important factors in choosing Fort Drum for this demonstration was its climate. Fort Drum is in American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Climate Zone 5A (Figure 9). As shown in Figure 5 (p 7), colder climates increase the effective R-value/in. of the MAI technology. Furthermore, both buildings are constructed identically and are physically located within 50 yards of each other, which is needed to effectively use one of the buildings as a control building. Both buildings are operated and occupied by the Safety Office, which simplified coordination and logistics of the work activities for the buildings.

Although the two buildings have similar purposes, ORNL conducted E+ modeling to account for energy use due to varying occupancy, temperature setpoints, weather conditions, plug loads, etc. The Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) coordinated with the Safety Office and other Fort Drum staff to obtain the relevant information for the E+ models.

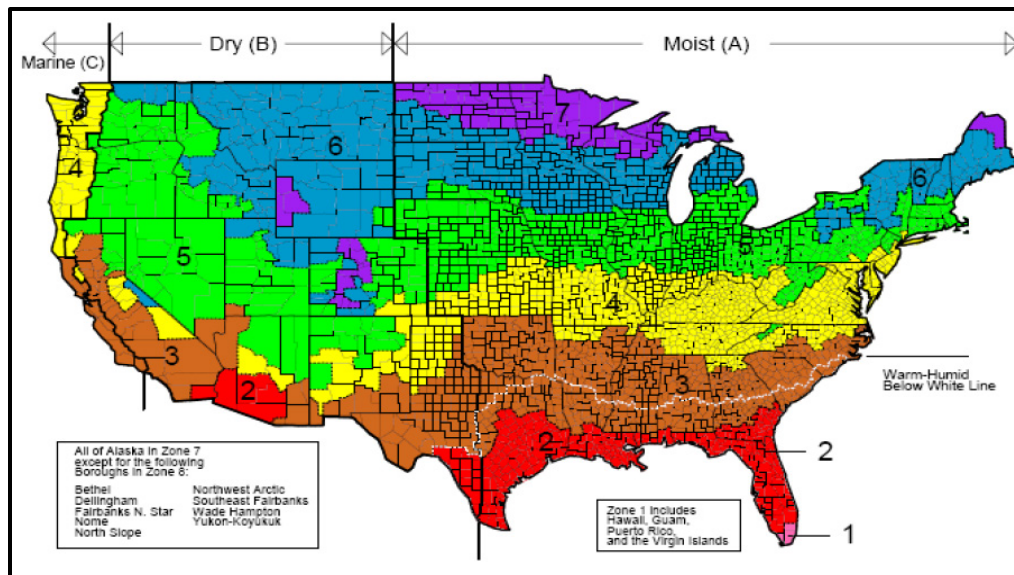


Figure 9. ASHRAE Climate Zones.

5.3 Site-Related Permits and Regulations

No site-related permit or regulations were required. The team obtained DPW's permission and authorization before any work was done. The manufacturer of the MAI panels directed and coordinated installation. Data retrieval occurred through a dedicated telephone line and there were no communications with the enterprise network at Fort Drum. Both facilities have a Building Automation System (BAS) installed. Data from the BAS were requested periodically and compared with sensor data to verify their correct operation. The BAS data were also used to determine the operational schedule. Site information technology (IT) personnel requested information on the data logger and subsequently approved installation of the dedicated telephone line.

6.0 TEST DESIGN

The demonstration was intended to show reduced energy losses through walls and overall energy savings, and to validate the effectiveness of the MAI compared to traditional insulation. Listed below are the fundamental problem and question that this demonstration addresses:

Fundamental Problem: Energy loss through the walls accounts for approximately 5% of DOD facility energy consumption.

Demonstration Question: The project will demonstrate the extent of reduced energy loss through the walls and resulting decrease in overall facility energy and utility cost through the use of improved insulation. This demonstration will determine the cost effectiveness of MAI insulation.

6.1 Conceptual Test Design

The elements of the test design were:

- Hypothesis: Installing MAI panels will reduce the energy losses through the walls and reduce overall building energy consumption.
- Independent variable: The R-value of the overall wall is being increased by adding insulation to the wall assembly.
- Dependent variable(s): Heat flux through walls, temperature/Relative Humidity (RH) across the walls, and overall electric and natural gas consumption of both buildings.
- Controlled variable(s): To mitigate the effects of various building characteristics, certain variables were held constant across both buildings including building size, building construction type, construction year, renovation year and orientation, HVAC system type and capacity, and their proximity to each other. These controlled variables are important in the E+ modeling and in comparing the baseline building to the retrofit building. The team needed to ensure that the buildings are identical in construction so that the retrofit building construction is only different in the overall wall R-value. This simplifies and ensures accuracy in the modeling of the buildings and provides data that can be directly compared. The identical orientation and proximity of each building ensures both building experience the same solar loading, weather conditions, and “climate.” The building size is also important because the overall heat transfer dynamics can vary depending on building size. This also simplifies the energy modeling aspect of the project. Other variables that cannot be controlled (such as occupancy, internal loads, and schedule) had an impact on the energy consumption of both buildings. These variables and their relative effect are discussed in Section 6.1.
- Test Design: The hypothesis was tested by using one building as a baseline and retrofitting the other buildings with the MAI panels. After the sensors are installed, calibrated, and verified, Bldg. 432B was retrofitted. Data were collected for over 12 months following the retrofit. Additional information for both buildings was collected including occupancy, internal loads, temperature setpoints, weather data, electricity use (HVAC and facility total), and natural gas consumption. These details were used to calibrate the building models to the overall electricity and natural gas consumption of each building. Once each building is

modeled, the models can be simulated with and without the MAI insulation to calculate the energy savings. Since both buildings have varying internal loads, the energy modeling is crucial in determining the actual savings associated with the MAI panels.

- Test Phases: There were six test phases for this project:
 - Phase 1: Pre-test preparation: Purchase sensors and determine sensor layout, coordinate with building occupants, purchase peripheral equipment to support data collection and reporting, determine exact sizes of MAI panels, and manufacture MAI panels.
 - Phase 2: Sensor installation: Install heat flux and temperature/RH sensors in both buildings. Record exact location within buildings. The location information was used in the energy modeling process. Install weather station and solar station on Bldg. 432B. Connect all sensors to data collection unit using conduits where necessary. Install electric meters and natural gas pulse kits. Talk to occupants to determine internal loads, occupancy, and internal setpoints.
 - Phase 3: Sensor calibration and verification: Verify all sensors are functional, calibrate sensors, and ensure that data are being transmitted over Class C phone lines.
 - Phase 4: Install MAI panels in Bldg. 432B: Distribute Likert surveys to obtain data for pre-retrofit observations, occupant comfort, and ease of installation.
 - Phase 5: Data collection: On a weekly basis, download data from both buildings. The data collection period is 9–12 months, covering the heating (winter), swing (spring or fall) and cooling (summer) periods. Calibration of the models was conducted using 1 week from each of the winter, summer and spring/fall periods. Periodic IR images of the walls were captured.
 - Phase 6: Data analysis: Data analysis included developing E+ models, calibrating the models against heat flux, temperature/RH sensors, weather data, utility electric and natural gas data. The data analysis relies heavily on energy modeling. Section 7.4 details the energy modeling process.

The MAI supplemented the existing R-19 fiberglass batt insulation currently in the walls of Bldg. 432B at Fort Drum. Bldg. 431B was the baseline building. The MAI panels are expected to provide additional insulation and to reduce heat gains and losses (heat transfer) through walls by 20% or greater. A comparison of the energy consumption in both buildings and subsequent energy modeling is expected to show the benefit of using this high R-value/in. technology for retrofit applications.

Two facilities with identical construction were used for the study. The team measured differences in temperatures and heat fluxes using a suite of instruments, flush with the internal walls and the exterior insulation layer. The team originally installed thermocouples flush with the internal and external walls. During initial modeling, the team discovered that this placement required several assumptions to estimate air temperature near the walls. Because these assumptions affected the model drastically, the team re-installed the internal thermocouples and placed them 6 in. away from the wall. This significantly reduced the number of required assumptions and resulted in a better energy model.

The impacts of installing the insulation were measured by the reduction heat transfer through the walls. Heat flux curves were generated from the data collected. The areas underneath the heat flux curves versus time provide a means to correlate excess heat loss or heat gain for each day.

Periodic IR inspections were conducted before and during the demonstration period to: (1) compare thermal bridging reduction in the baseline and post-retrofit cases, and (2) determine if there is any degradation in performance of the MAI panels. Immediately after the retrofit, results from the IR inspection were used to determine if any panels failed during the installation process. Information on these thermal breaks will be used to inform and improve the design for future MAI installations. Ongoing periodic IR inspections helped determine whether additional panels had failed or were slowly failing due to slow leaks.

The E+ software allowed the team to develop accurate building models using data from the temperature and heat flux sensors. Instrumentation was installed to capture impacts of weather and solar radiation on the building consumption. The weather data were used as inputs to the energy models. Each model was calibrated for both the baseline and the retrofit building. The models were then normalized to eliminate the effects of varying occupancy, internal loads, and schedule (normalized models). The models were used to determine the reduction in energy loss through the walls, reduced building energy consumption, resulting utility cost savings, and success/failure against the POs. Figure 10 shows a diagram that locates the placement of the sensors.

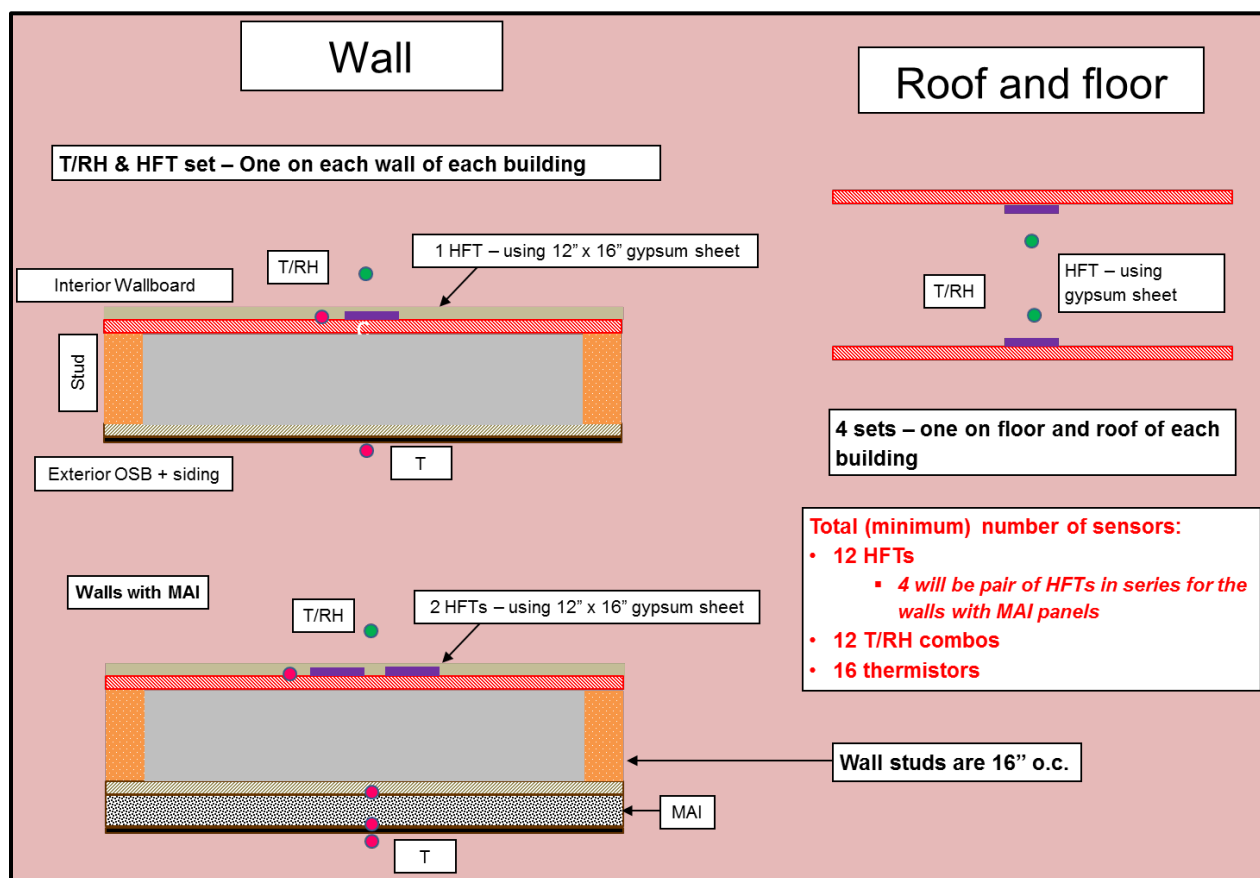


Figure 10. Sensor Layout and Locations.

Figure 11 shows a photograph of an installed sensor. The weather station, solar sensor and data loggers were installed according to the diagram shown in Figure 12. The weather station was mounted as shown in Figure 13. To minimize roof penetrations, the solar tracker was mounted as shown in Figure 14.



Figure 11. Photographs of a Set of Installed Heat Flux Transducer (HFT) and Temperature/Relative Humidity (T/RH) Sensors.

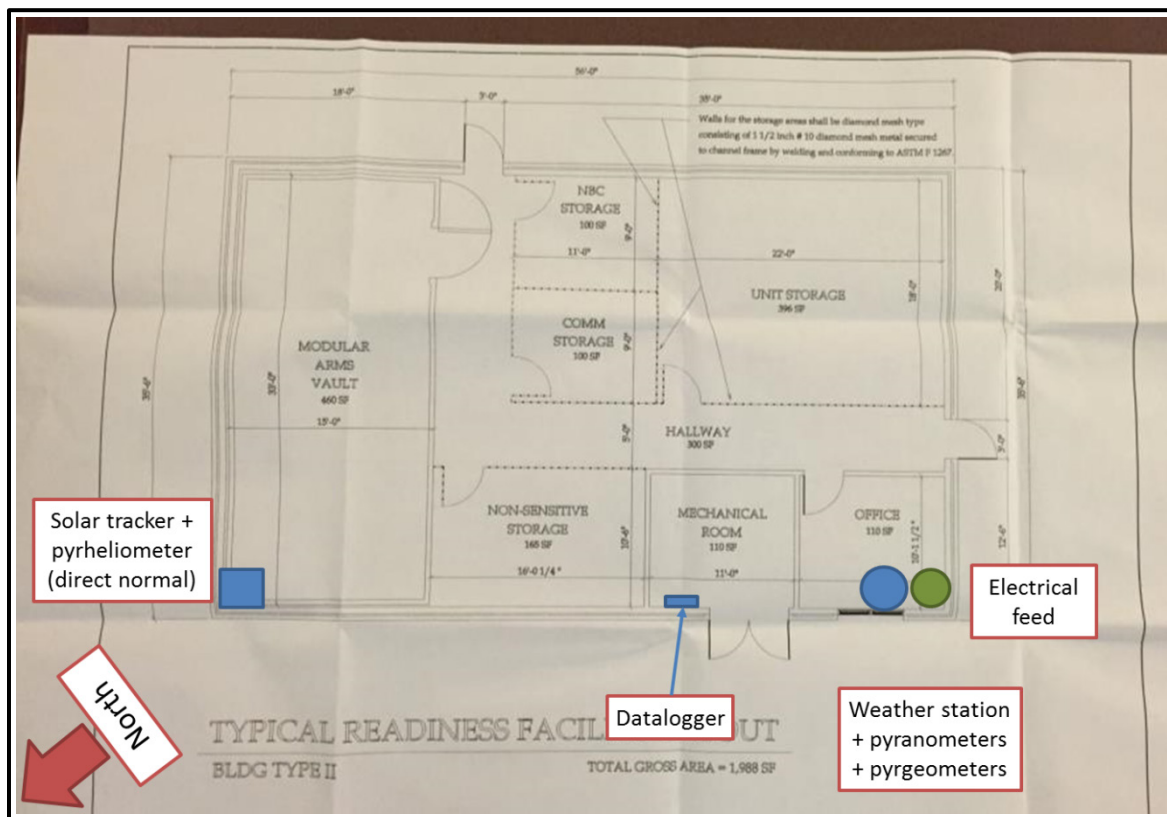


Figure 12. Planned Solar Tracker and Weather Station Location.



Figure 13. Weather Station Mount Methodology.



Figure 14. Solar Tracker Mounting (Side).

6.2 Baseline Characterization

Bldg. 431B was used to characterize the baseline for this project. This building was monitored for over 12 months, in a side-by-side comparison with the retrofit building, to ensure that the effects of seasonal variations were captured. The baseline building energy model will be used to determine the energy losses and energy consumption of a building without the MAI panels. Identical sensors will be placed in identical locations in both buildings. Only the weather and solar stations will be installed in 432B. Due to the proximity and orientation of both buildings, the weather is also identical. Baseline project parameters were:

- Reference conditions: Building temperature, heat flux through the wall, floor and ceiling, interior and exterior temperature on each wall, interior temperature on floor and ceiling, electric consumption, natural gas consumption, HVAC energy consumption, weather data

- Baseline Collection Period: 9–12 months.
- Existing Baseline Data: None.
- Baseline Estimation: Data from the weather stations, temperature and heat flux sensors, and energy consumption of the building were combined with information about internal loads, occupancy and temperature setpoints to create an energy model. The model was calibrated to 1 week of actual data in summer, winter, and fall/spring to match information from the sensors. Other weeks were investigated to ensure that the models still matched collected data. See Section 7.4 for additional details about the energy modeling. The heat flux sensors will be used to determine heat loss in the building. The operating costs of the building were determined using utility rates and building meter data.
- Data Collection Equipment: At least six heat flux sensors (one on each wall and one each on the ceiling and floor); 10 sets of Temperature/RH sensors (across the wall cross-section from the exterior surface to 6 in. away from the interior surface, and on the interior surfaces of the ceiling and floor); and weather and solar stations (WST-520 Vaisala instrument suite), which consisted of:
 - Huskeflux NR01 - consisting of a flux pyrgeometer for long-wave (LW) far infrared solar flux, and a pyranometer for measuring short wave solar radiation),
 - Hukseflux DR02 - Direct Normal Incidence Pyrheliometer, and
 - Hukseflux SR20 - Global Secondary Std. Pyranometer.

Four-pair conductor cables were wired to all sensors and connected to a Campbell Scientific data collection buss, consisting of a wiring panel, a data logger, and a modem that collected, multiplexed and transmitted the temperature, heat flux and weather data . Except for the weather and solar stations on top of the roof, these instruments and data collection devices were not visible to most of the building users (The Campbell Scientific buss was located on a wall in the mechanical room). None of the devices interfered with normal building operations.

6.3 Design and Layout of System Components

For this project, custom sized 1 in. thick (R-35 equivalent) MAI panels were manufactured. Fort Drum did not have elevation drawings of the proposed buildings. ERDC-CERL staff travelled to Fort Drum in April 2015 to obtain measurements of the exterior face of the building. Computer-Aided Design (CAD) drawings of the fastener locations were created. These drawings were used to select the most common sizes for the MAI panels. Since the fasteners need to go into the oriented strand board (OSB), the areas with the fasteners did not have MAI under them. Instead, 1 in. thick foam strips were used. Appendix C includes the dimensions of the building along with locations of the fasteners (red lines) and the sizes of the four different MAI panel types. A gap of 1 in. was left on each side of the fasteners. Since all the fasteners are not perfectly aligned with each other, this allowed for some flexibility in installing the MAI panels and provided a margin of safety.

The basic process for installing the panels was:

1. Remove fasteners and remove metal panels.
2. Attach MAI panels to building using adhesive. The buildings had Tyvek-type wraps on the OSB. Commercially available construction glue was used to adhere the MAI panels to the wrap. However, the team determined that the glue was not necessary. The clearance between the foam strips (see next step) and the MAI panels was small enough that the panels were held in place by friction.
3. Apply foam strips between panels as necessary (and according to drawings).
4. Attach temperature/RH sensors at designated locations.
5. Reattach metal panels.

The MAI panels were not installed on the exterior of the mechanical room. The high number of penetrations would have required many different sizes of MAI panels. To ease the logistics of panel manufacturing, the project team decided to exclude this section from the MAI. The mechanical room is conditioned and mechanical room heat losses were accounted for in the models.

The MAI panels were sized to ensure sufficient room to reinstall the rows and columns of fasteners between the MAI panels. This was done to ensure that the panels are not punctured when the metal panels are reattached to the OSB. During the installation, the team accidentally punctured a panel. This panel was not replaced, because it allowed the team to obtain a good IR image showing a failed panel. Three more post-retrofit IR images were conducted to determine if any other panels failed during the testing phase.

6.4 Operational Testing

Test phases 4–6 (described in Chapter 5.0) assess the cost and performance of the proposed technology. These phases included MAI installation, followed by a 12+ month data collection and monitoring period, followed by a data analysis period. The data analysis determines the cost and energy performance of the technology.

- Operational Testing of Cost and Performance: All relevant sensors and data collection units were set up and commissioned in Test Phases 1–3.
- Modeling and Simulation: Once sufficient data were collected, the energy performance assessment was conducted via E+ (see Chapter 7.0) to determine the energy savings with the MAI technology. The E+ models were calibrated as additional data became available. The team estimated costs of manufacturing and installing the MAI panels. The NIST BLCC tool was used to estimate the life cycle cost of the technology.

Table 3 lists descriptions of the POs and the relevant operation testing activities associated with each cost and energy PO. For additional information regarding energy modeling, refer to Chapter 7.

Table 3. Performance Assessment Methodology.

Performance Objective	Performance assessment methodology
Facility Energy Usage, Demand Reduction, Energy Loss through Walls (Energy Performance)	Energy modeling to compare energy usage of retrofit building and baseline building after normalization across buildings. Energy models were calibrated to installed sensors and meters to ensure accurate models. The models were then normalized for temperature setpoint schedule, occupancy and internal loads. These normalized models were used to determine savings.
System Economics (Cost)	1. From normalized energy models, estimate reduction in facility energy usage and demand by using MAI panels. 2. Using utility rate structure, determine cost savings. 3. Estimate cost of manufacturing and installing MAI panels. 4. Use NIST BLCC tool to calculate life cycle economics of system.

Table 4 below lists the actual start dates and duration of each activity.

Table 4. Anticipated Timelines.

Activity	Start Date	Actual Duration
Install sensors	08/17/2015	1 week
Data monitoring	08/24/2015	2 months
Retrofit bldg. with MAI panels	11/15/2015	1 week
Data collection	09/18/2015	18 months

6.5 Sampling Protocol

Table 5 lists and describes the sampling protocol that was used.

Table 5. Sampling Protocol.

Data Collector	ORNL
Data Recording	• Method: Automated using Campbell Scientific Data Logger CR1000. Data logger connected to Class C phone line • Data retrieval: Weekly • Data intervals: 15 minutes
Data Description	Data samples • 6 heat flux sensors per building (12 in total) • 10 temperature/RH sensors in baseline building; 14 temperature/RH sensors in retrofit building (24 in total) • Electric and natural gas meters in each building, four total. • Solar station: Long wave, short wave solar radiation, Direct Normal and Global Irradiance • Weather station: Temperature, RH, wind speed
Data Storage and Backup	The data logger has 4MB of memory for storage. In case of loss of phone line communications, this will hold at least 30 days of memory. A backup unit was left with the Fort Drum energy manager for replacement if necessary.
Likert Surveys	See Appendix D.

6.6 Equipment Calibration and Data Quality Issues

All heat flux transducers, thermocouples, and relative humidity sensors were calibrated by ORNL before installation. All weather station sensors and data collection units were also tested and calibrated, or testing/calibration documents were requested from the vendors. Communication with all on-site equipment was also tested before data collection begins.

Temperature sensors (thermistors) and RH sensors used factory calibrations. The RH sensors are HHH-4000 Series humidity sensors from Honeywell and a specification sheet is attached in Appendix E. The solar sensors were also factory-calibrated and the calibration certificates are also included.

The heat flux transducers (HFTs) were calibrated at ORNL using a heat flow meter apparatus (HFMA) while sandwiched by a gypsum board on one side and appropriate layers of building materials (insulation and/or gypsum board) on the other side. The goal is to create similar configurations as the actual HFT locations in the baseline and retrofit buildings. In the building, the HFTs were installed using a 0.5 in. sheet of gypsum board on existing drywall/sheetrock on the walls or on the floor or ceiling tile. The HFMA is used for thermal transmission property measurements following ASTM Test Method C518 (ASTM 2010) and is accurate within 1%. The HFMA consists of two independently temperature-controlled plates, both of which are equipped with heat flow sensors. The HFMA plates were maintained at prescribed temperatures to create a temperature difference across the sandwich specimens containing the HFTs; the heat flows at the HFMA plates were measured. The calibration constants of the HFTs were obtained by correlating the measured heat flows of the HFMA to the HFT voltage outputs.

6.6.1 Sampling Results

The sampling results for all sensor data in this section are discussed in context with the calibrated energy models. The Performance Assessment section will contain the analysis with regards to the normalized energy models.

The following section presents data from the final calibrated models. Weather data (solar, wind, temperature) were used to set the boundary conditions of the model. Another boundary condition was the internal air temperature 6 in. from each face of the wall. Using these boundary conditions, known setpoints (from BAS), and estimated occupancy profiles, several trends were simulated. As mentioned before, trends were developed for 1 week in each summer (Aug 2016), winter (Dec 2016) and shoulder season (Oct 2016). The graphs below include actual and simulated data (for non-boundary conditions) for both the retrofit and the baseline facilities (as appropriate).

6.6.2 Wall Sensor Data and Initial Model Calibration

E+ models were created with modeled sensor locations that matched the physical locations of the sensors in the baseline and retrofit buildings. The time period chosen for this analysis was September through November 2016. During early-September 2016, the interior T/RH sensors were relocated from the surface to about 6 in. away from the surface (Figure 11). This enabled measurement of the air temperatures near the walls, which served as the interior boundary condition for the E+ calculations of the temperatures and heat flows across the walls. This

calibration was done during end-2016 and early-2017. Figure 15 shows the Energy+ model of the facilities and their relative location to each other. The purple plan reflects shadows imposed on Bldg. 431B from another facility.

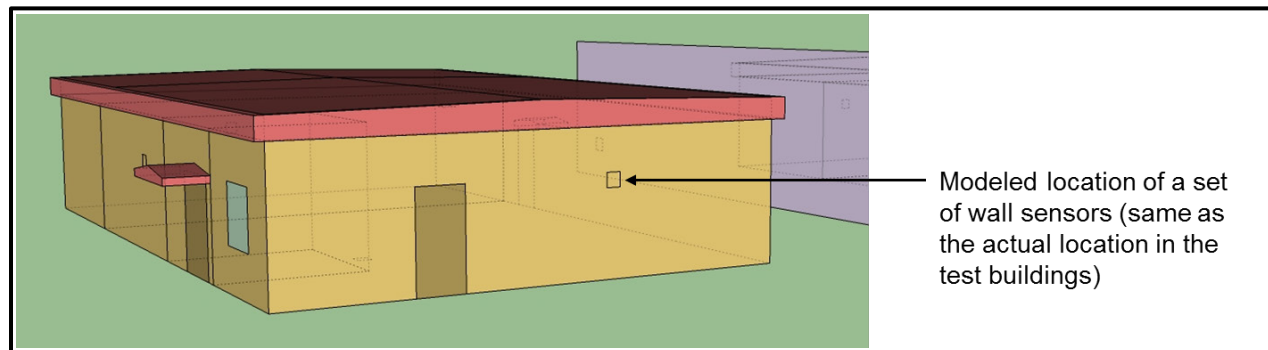


Figure 15. E+ Model for Calibration against Wall Sensor Data.

Due to an error with the solar-tracker that was installed on-site, the solar weather data (direct normal and diffuse solar irradiance) were obtained from a nearby weather station located at the Wheeler-Sack Airfield. To verify the appropriateness of using off-site weather data, the data from the Wheeler-Sack Airfield weather station were compared to the data from the on-site weather station. With some exceptions, there was good agreement between the weather data from the two sources (Figure 16).

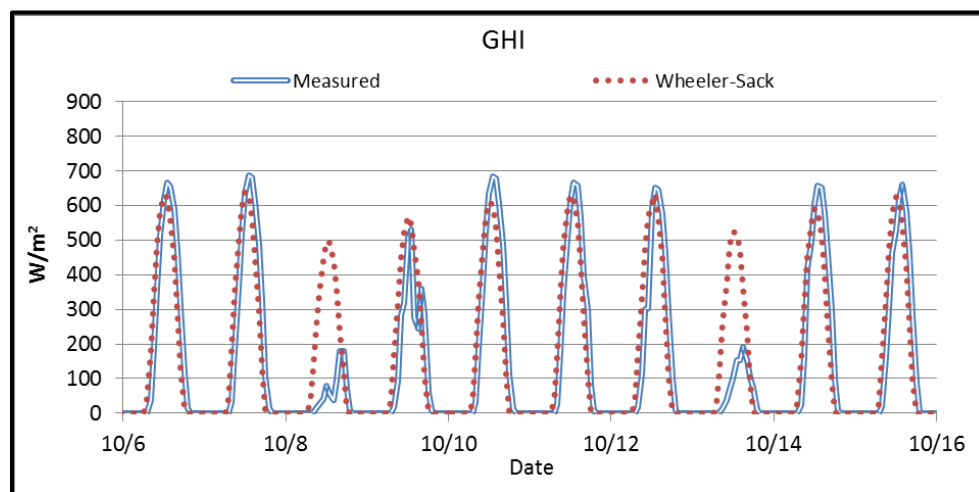


Figure 16. Comparison of Global Horizontal Solar Incidence Data from the on-Site Weather Station and from Wheeler-Sack Airfield.

Figure 17 shows the simulated vs. measured outdoor air temperatures. Figures 17 to 21 show the comparisons between the Energy+ simulated and measured interior air temperatures adjacent to the surface of the south and north walls of the baseline and retrofit buildings. The measured outdoor and indoor air temperatures were used as inputs to the model, so there is perfect agreement between the calculated values of those parameters.

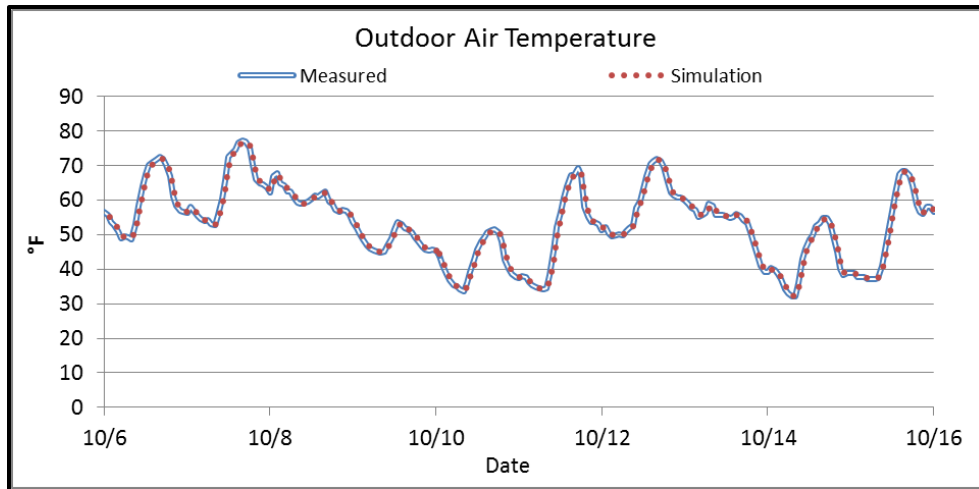


Figure 17. Simulated vs. Measured Outdoor Air Temperatures.

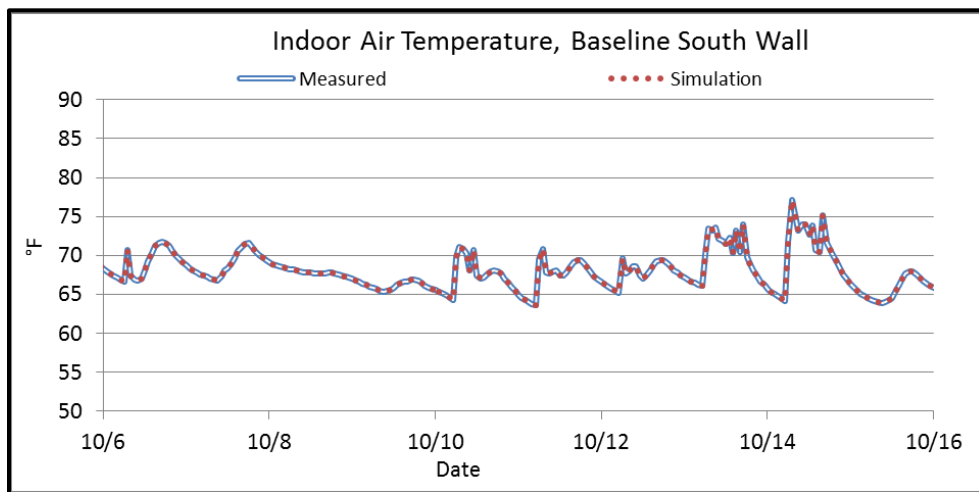


Figure 18. Simulated vs. Measured Indoor Air Temperature Baseline South Wall.

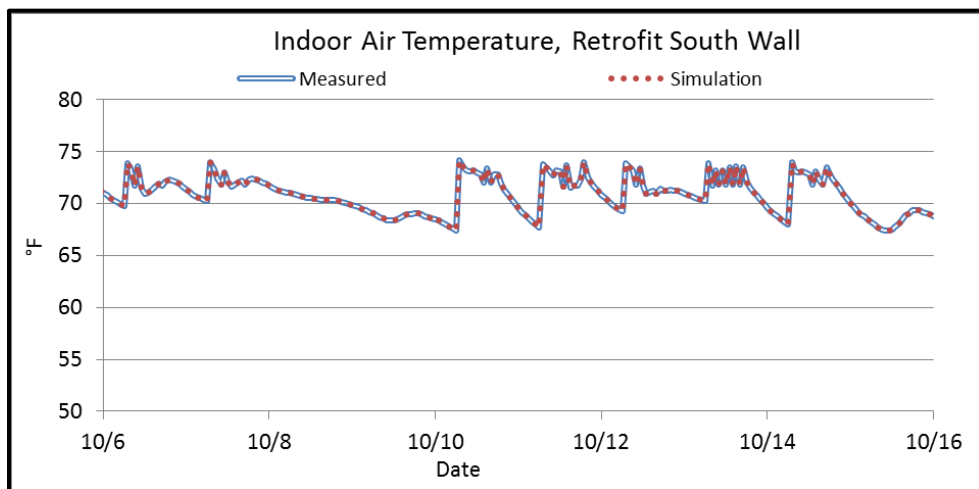


Figure 19. Simulated vs. Measured Indoor Air Temperature Retrofit South Wall.

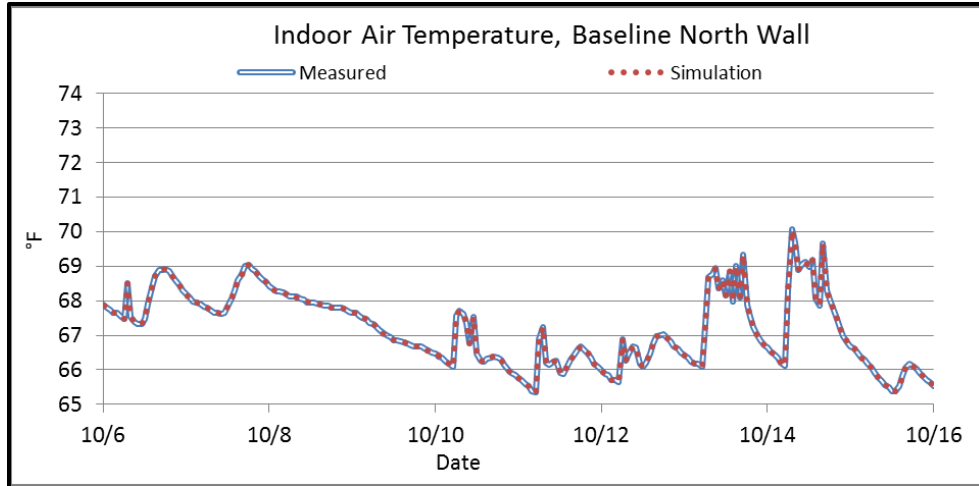


Figure 20. Simulated vs. Measured Indoor Air Temperature Baseline North Wall.

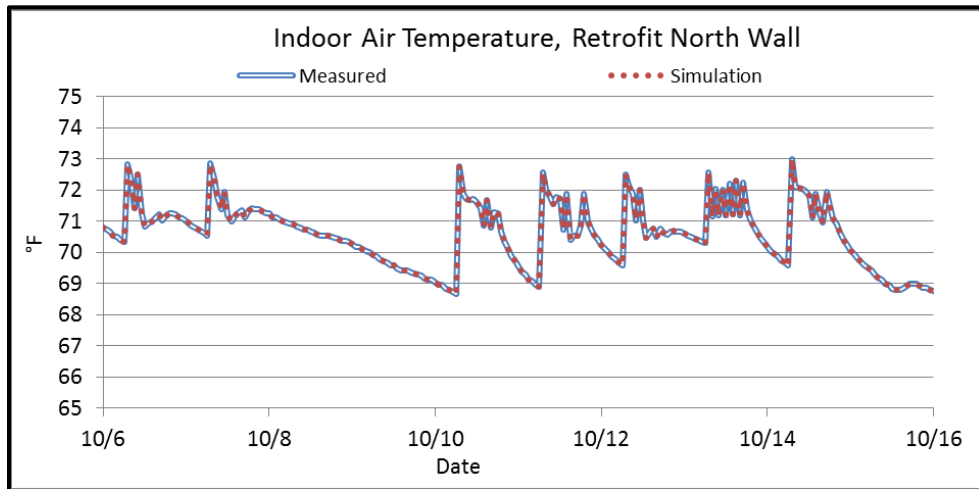


Figure 21. Simulated vs. Measured Indoor Air Temperature Retrofit North Wall.

Figures 22 to 33 compare the calculated and measured inner and outer surface temperatures and the heat flows through the south and north walls. Note that the north wall in both buildings was part of a vault and comprised of the 2x6 stud wall and a thermally-massive 10–12 in. concrete wall.

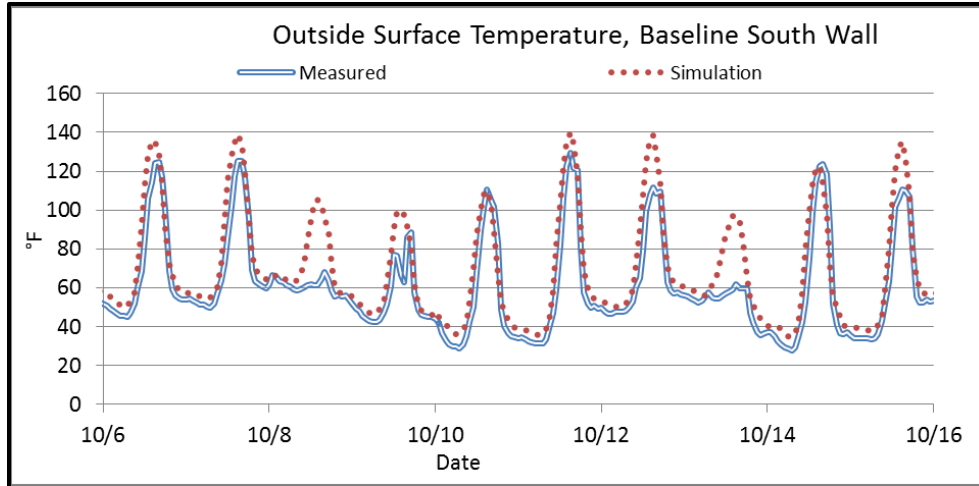


Figure 22. Simulated vs. Measured Outdoor Surface Temperature Retrofit North Wall.

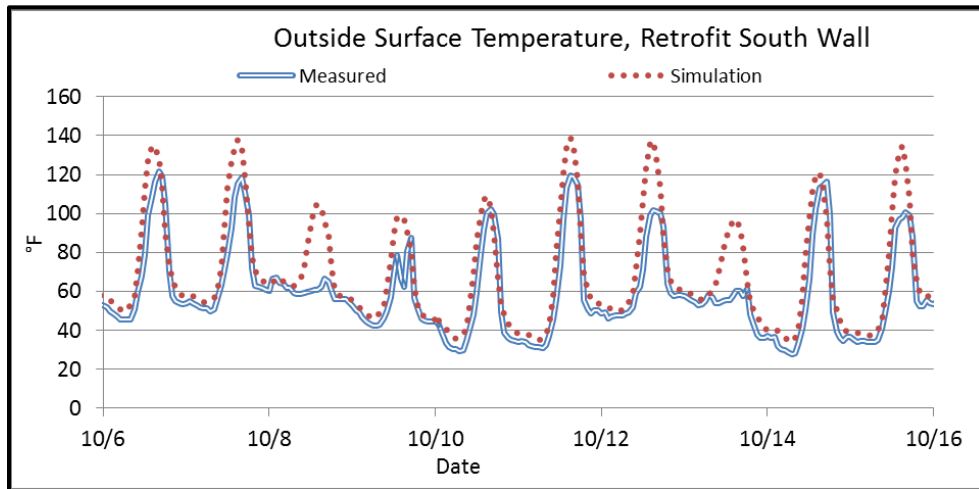


Figure 23. Simulated vs. Measured Indoor Air Temperature Retrofit South Wall.

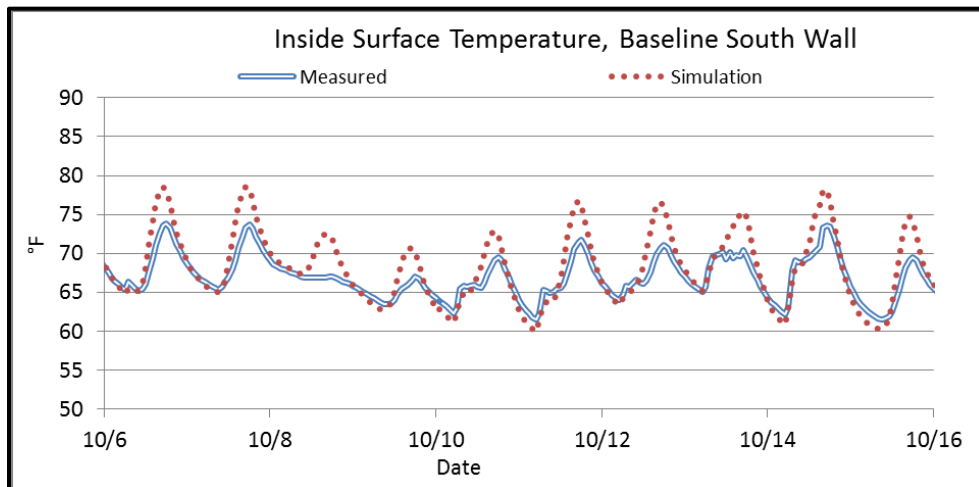


Figure 24. Simulated vs. Measured Indoor Surface Temperature Baseline South Wall.

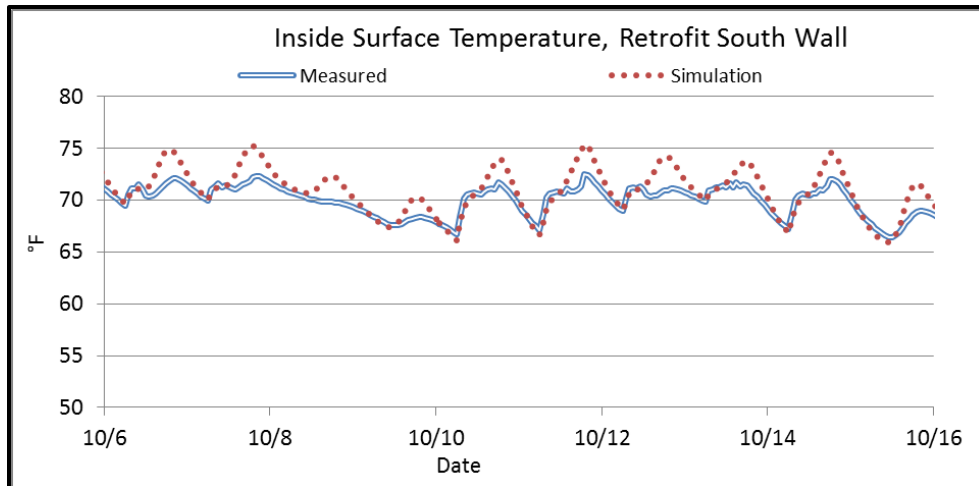


Figure 25. Simulated vs. Measured Indoor Surface Temperature Retrofit South Wall.

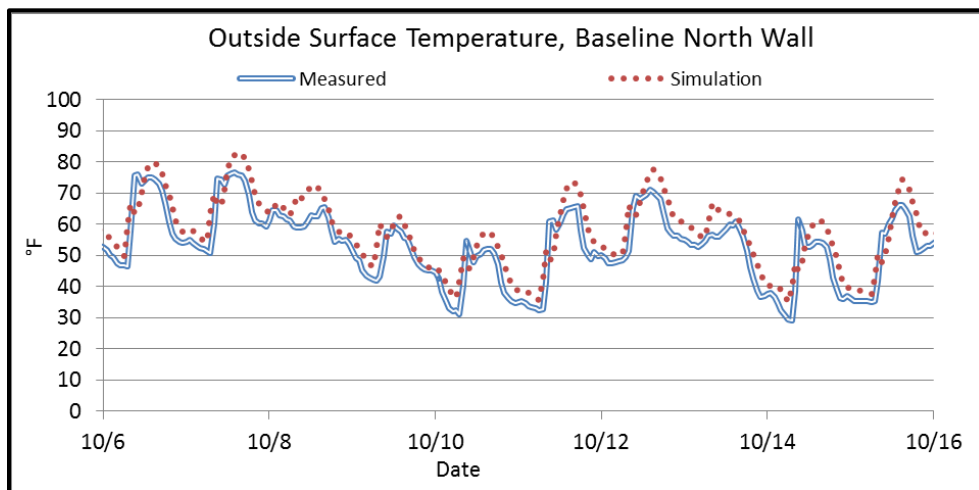


Figure 26. Simulated vs. Measured Outside Surface Temperature Baseline North Wall.

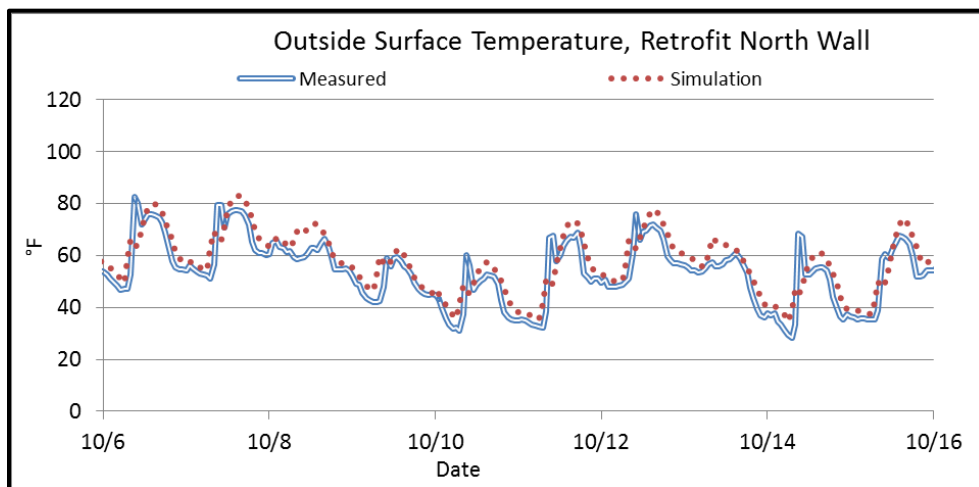


Figure 27. Simulated vs. Measured Outside Surface Temperature Retrofit North Wall.

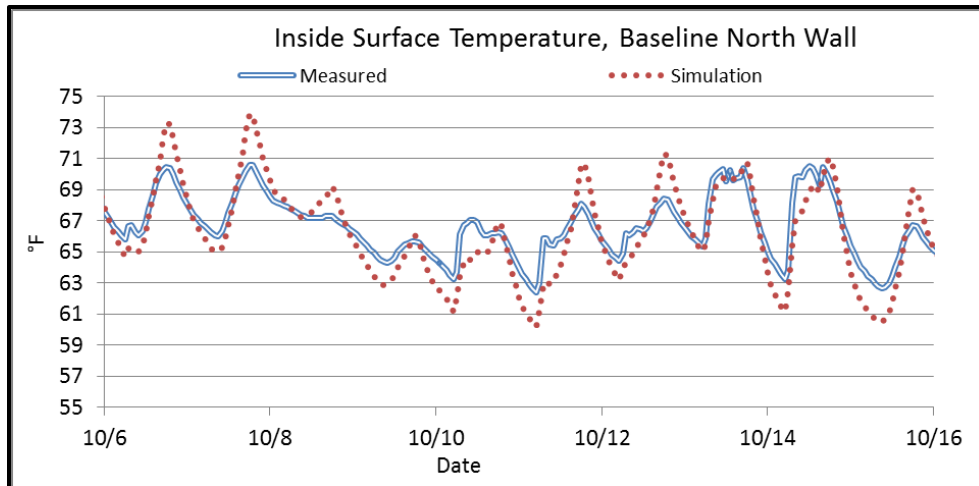


Figure 28. Simulated vs. Measured Indoor Surface Temperature Baseline North Wall.

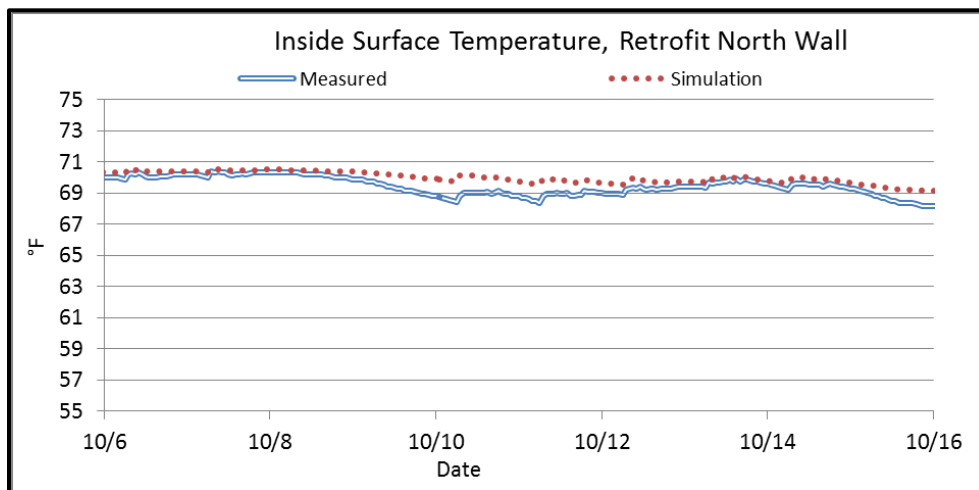


Figure 29. Simulated vs. Measured Indoor Surface Temperature Retrofit North Wall.

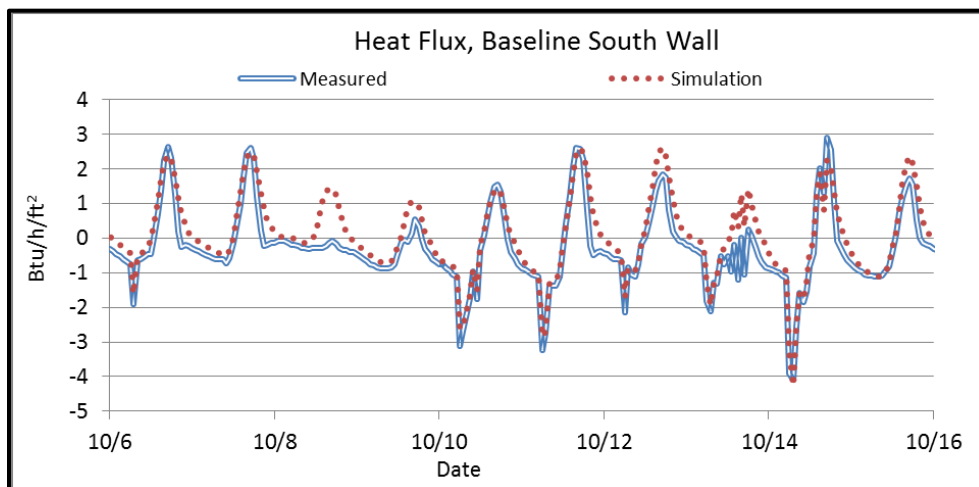


Figure 30. Simulated vs. Measured Indoor Heat Flux Baseline South Wall.

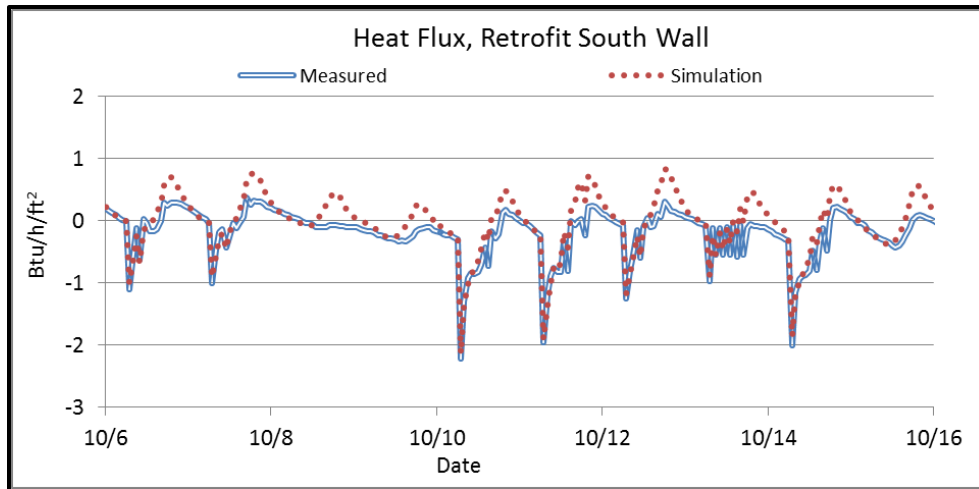


Figure 31. Simulated vs. Measured Indoor Heat Flux Retrofit South Wall.

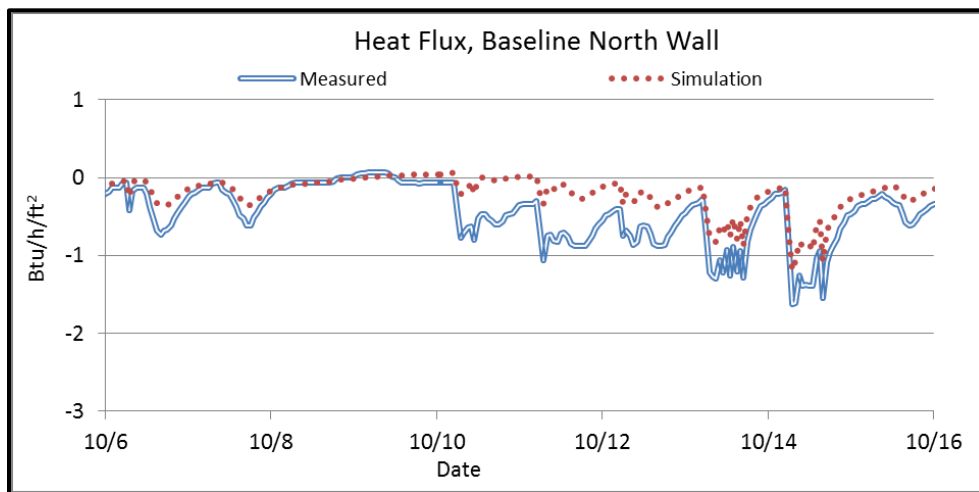


Figure 32. Simulated vs. Measured Heat Flux Baseline North Wall.

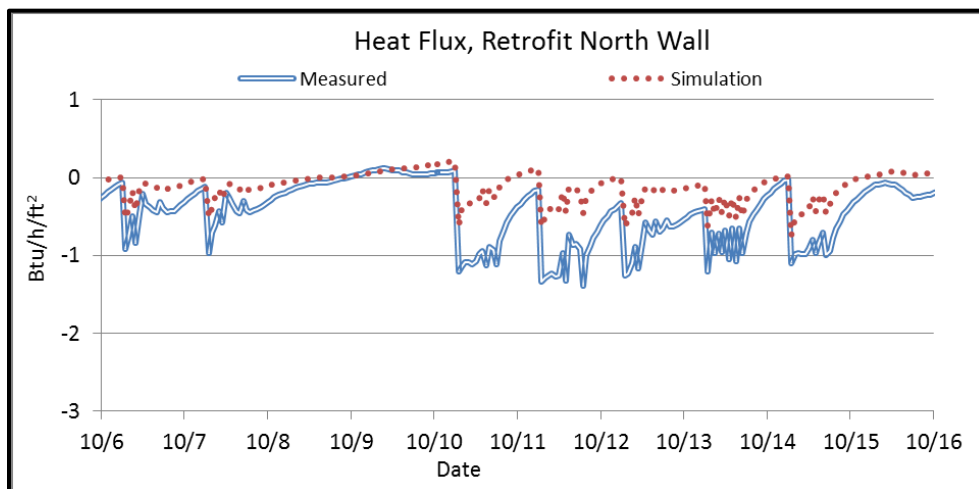


Figure 33. Simulated vs. Measured Heat Flux Retrofit North Wall.

6.6.3 Whole Building Energy Consumption and Final Model Calibration

The next step in the analysis was to use the E+ models with the calibrated wall structures (baseline and retrofit) and to extend the calibration to the whole-building energy consumption. As part of the final calibration, parameters like internal loads, occupancy, interior thermal mass (furniture, equipment, etc.), and schedule were tuned to achieve agreement between the calculated and measurement energy consumption. The internal temperatures were based on the measurements using temperature sensors located close to the wall surfaces, floor, and ceiling. For internal mass, approximately 538 sq ft of 12 in. concrete walls were considered as the internal mass, based on the wall area of the vault.

Internal loads for the E+ models were assumed based on the measured base loads (i.e., energy consumption when there is not heating or cooling) from the two buildings. A further assumption was made, that 50% of heat from the base loads are dissipated to the conditioned space. This assumption was necessitated by the lack of precise details about the nature of the base loads in the two buildings and the assumption of 50% heat dissipation within the conditioned space provided good agreement between the calculations and measurements with respect to annual energy consumption.

6.6.4 Summer 2016 (August 01 – 31)

Figure 34 shows the outdoor air temperature (identical for both facilities). The temperature is a boundary condition. Therefore, the simulated temperature is the same as the measured.

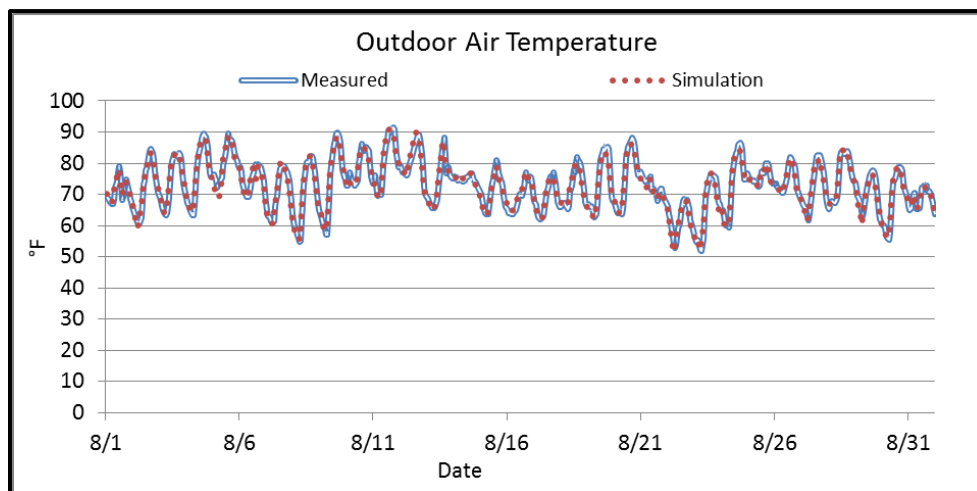


Figure 34. Summer Outdoor Air Temperature (Both Facilities, Boundary Condition).

Figures 35 and 36, respectively, show the measured and simulated indoor air temperatures for the baseline and retrofit facilities. As seen, the baseline indoor temperature varies more than the retrofit facility even though both facilities had similar temperature setpoints. This is because the baseline facility has a higher occupancy. Opening/closing doors and higher interior loads can cause these effects. The differences between simulated vs. measured temperature can be attributed to the assumption that 50% of the internal loads are dissipated within the conditioned space. Based on audits of the building, this assumption can vary, but is very difficult to adequately model.

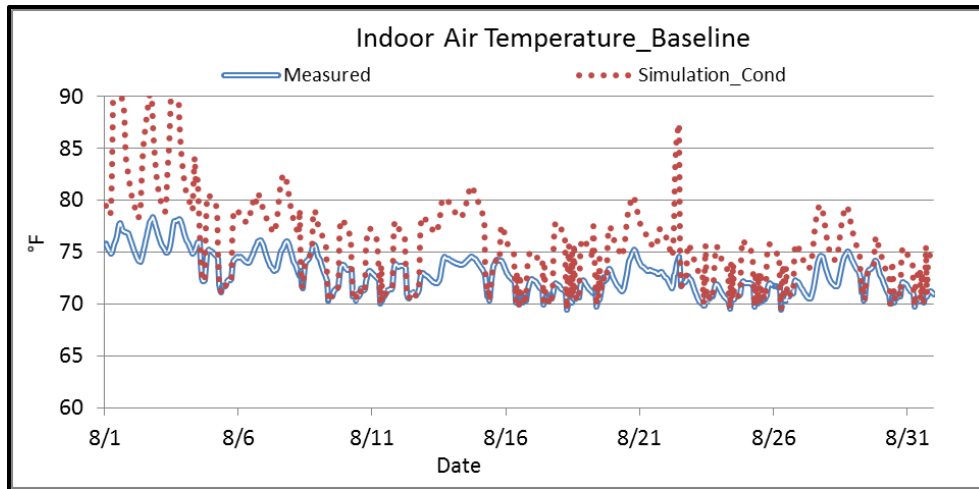


Figure 35. Summer Baseline Indoor Air Temperature.

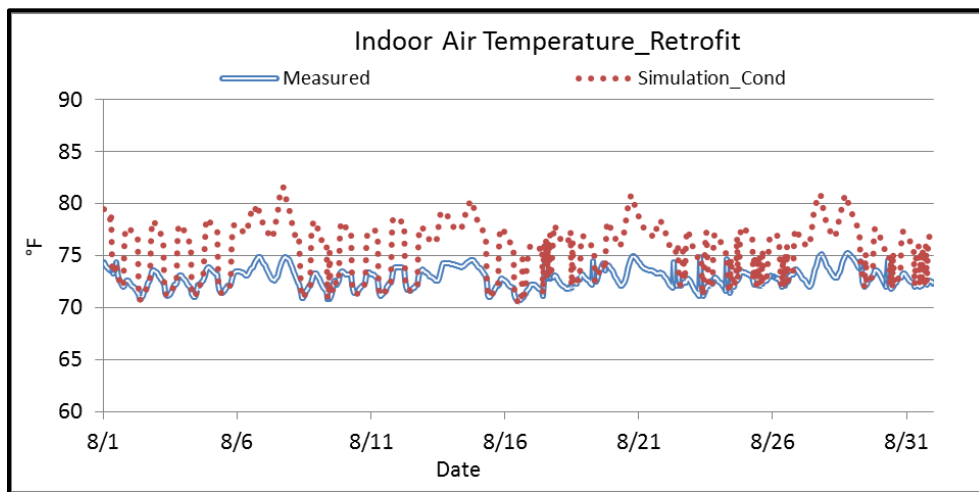


Figure 36. Summer Retrofit Indoor Air Temperature.

Figures 37 and 38 show the measured whole building and HVAC electric use for both facilities. The team noticed intermittent issues with the HVAC electric sensors. However, the HVAC was functioning and was verified through the BAS logs. This discrepancy was recorded, but it is important to note that the HVAC data were used only for comparison purposes. The total electric facility meter was independent of the HVAC meter.

As discussed before, the baseline facility had a higher occupancy rate. This is evident in the whole building energy use. The baseline facility peaks are consistently higher than the retrofit facility. The HVAC peaks are also generally higher for the same time. The whole building energy use can be attributed to internal loads such as lighting, plug loads and sensible and latent heat from the occupants. HVAC loads are already included in the whole building energy usage. It is also important to note that the baseline load of each facility is different. The baseline facility between 1–2 kW whereas the retrofit facility baseline is approximately 2.25 kW.

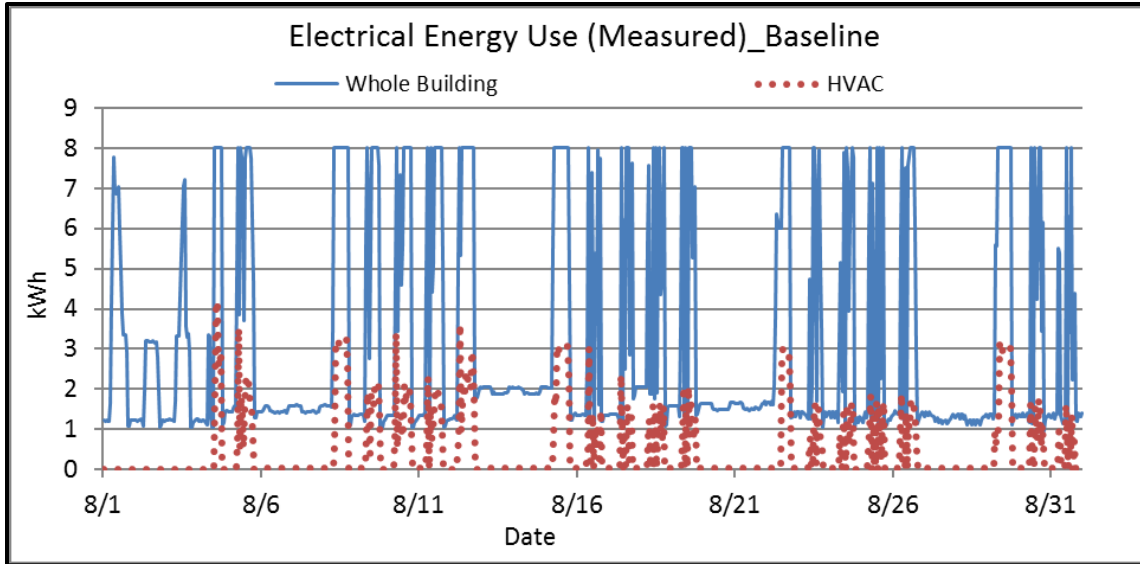


Figure 37. Summer Baseline Electric Energy Use.

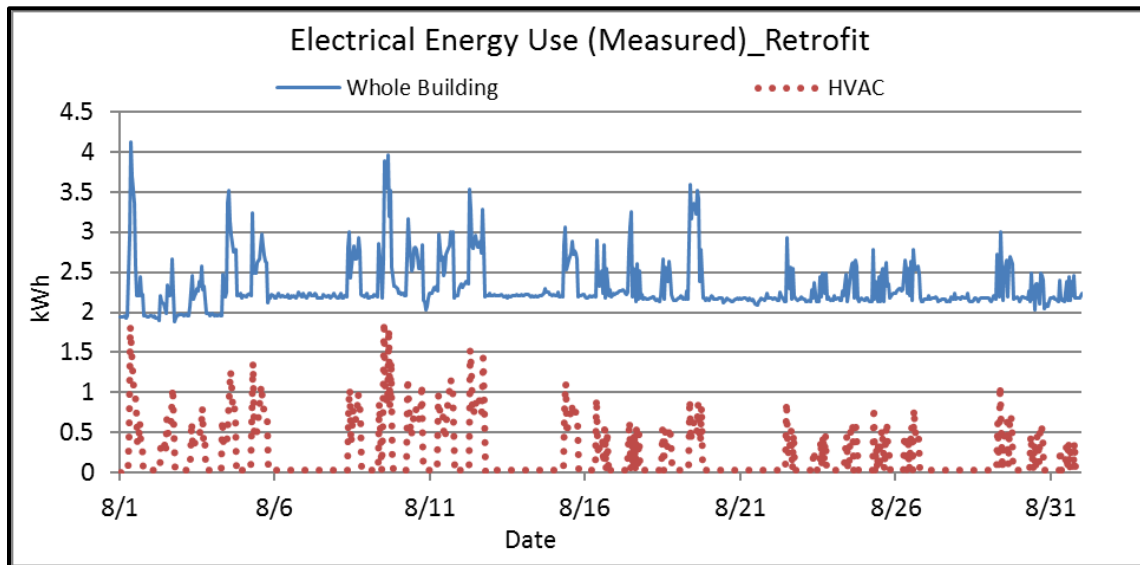


Figure 38. Summer Retrofit Electric Energy Use.

For comparison, Figure 39 shows the simulated and measured electric baselines. As seen, the simulated electric trends match well with the measured trends. In some cases, the trends vary on certain days. This could be due to higher plug loads, higher than normal number of occupants, or other variables that were not measured. The team did not change these parameters to reflect day to day building operation, but rather to represent seasonal variations. This results in a more representative model.

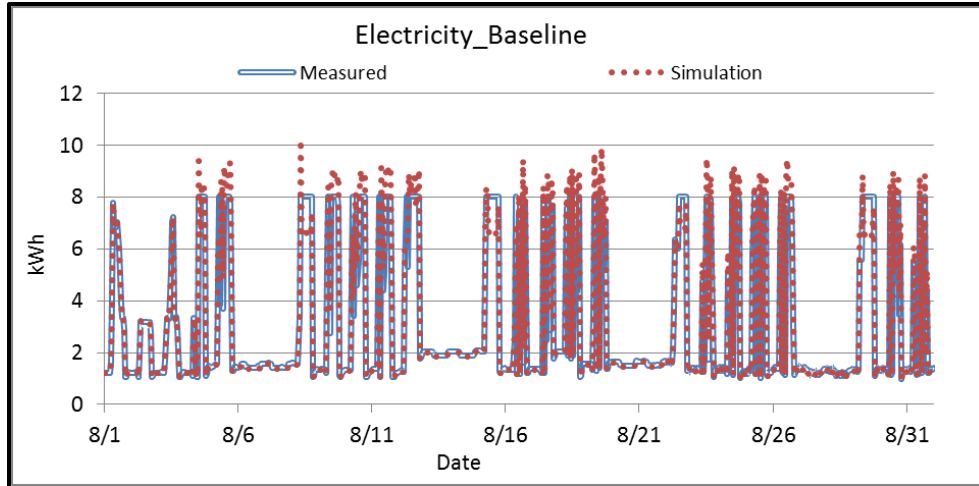


Figure 39. Summer Baseline Total Electric Use.

For comparison, Figure 40 shows the simulated and measured total electric usage. In this case, the simulated loads are generally lower than the measure loads. During occupied periods, the plug loads in these facilities were found to vary quite significantly depending on the activity. Because these plug loads were not measured independently, there are some discrepancies in the measured vs. simulated values.

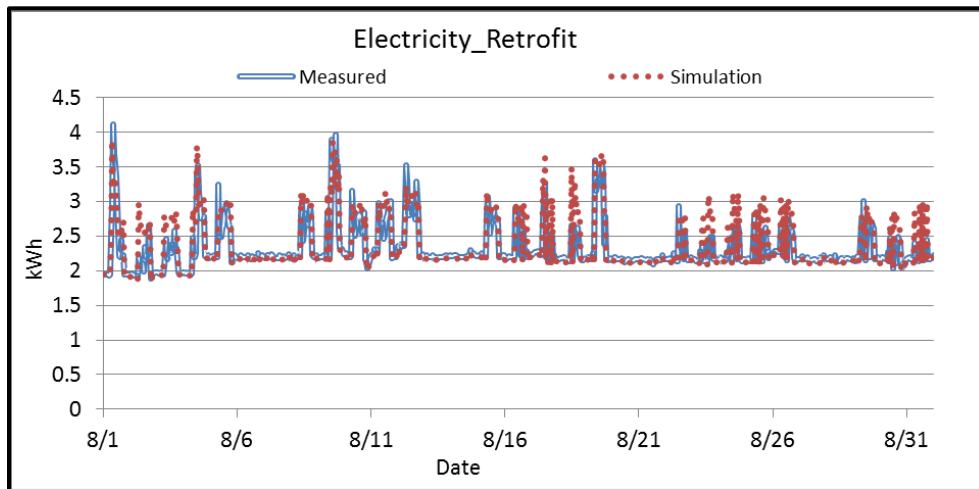


Figure 40. Summer Retrofit Total Electric Use.

For comparison, Figure 41 shows the HVAC measured electric baseline alongside the simulated data (includes blower fan and condenser) for the baseline facility. As seen, the trends generally match well. In some cases, due to varying internal loads, the measured HVAC usage will be different from the simulated value. In some cases, the HVAC meters experienced issues and recorded no activity even though the HVAC was on (as verified through BAS logs). In this case, the simulations also predict zero HVAC consumption, since the HVAC schedule of the E+ model is based on the measured HVAC data, i.e., when measured HVAC consumption is zero, the E+ model also assumes that the HVAC was off.

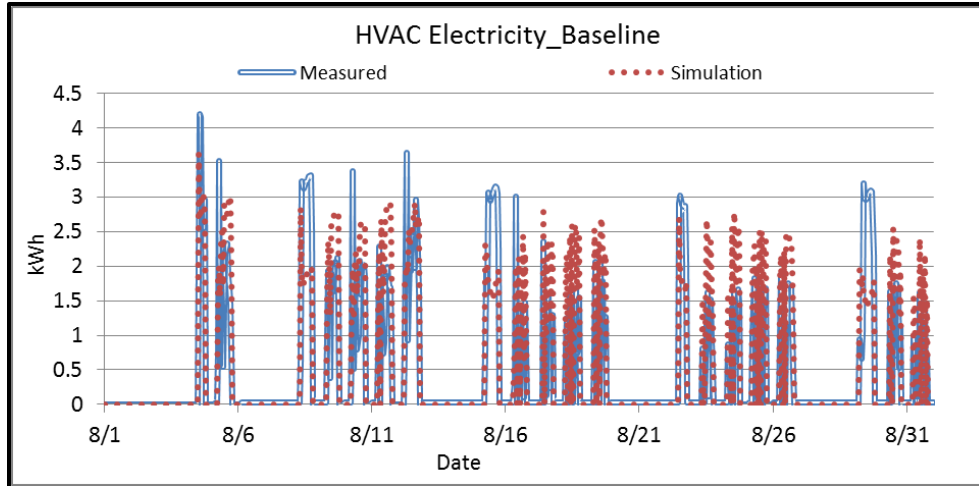


Figure 41. Summer Baseline HVAC Electric Use.

For comparison, Figure 42 shows the HVAC electric measured alongside the simulated data (includes condenser *only*) for the retrofit facility. As discussed above, the trends generally match well. In some cases, due to varying internal loads, the measured HVAC usage will be different from the simulated value.

In cases where the HVAC was off (measured HVAC = 0 kWh), the models also assumed that the HVAC was off. This was the case even if the models called for cooling. This was done to ensure good agreement between the models and actual data. This is evident, for example, from August 01–03.

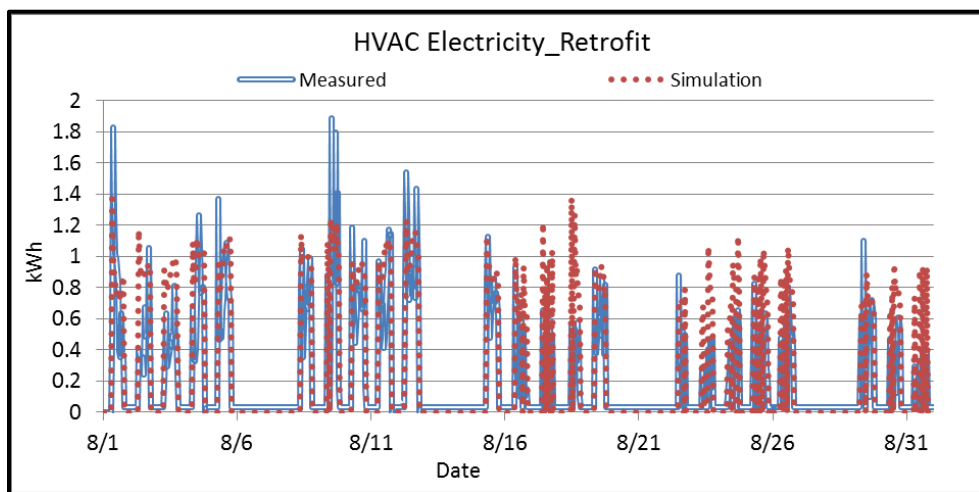


Figure 42. Summer Retrofit HVAC Electric Use.

Figures 43 and 44 show the natural gas consumption (measured and simulated) for the baseline and retrofit facilities. As seen, the baseline facility did not use natural gas for most of August. However, the retrofit facility did use natural gas at least seven times during the month.

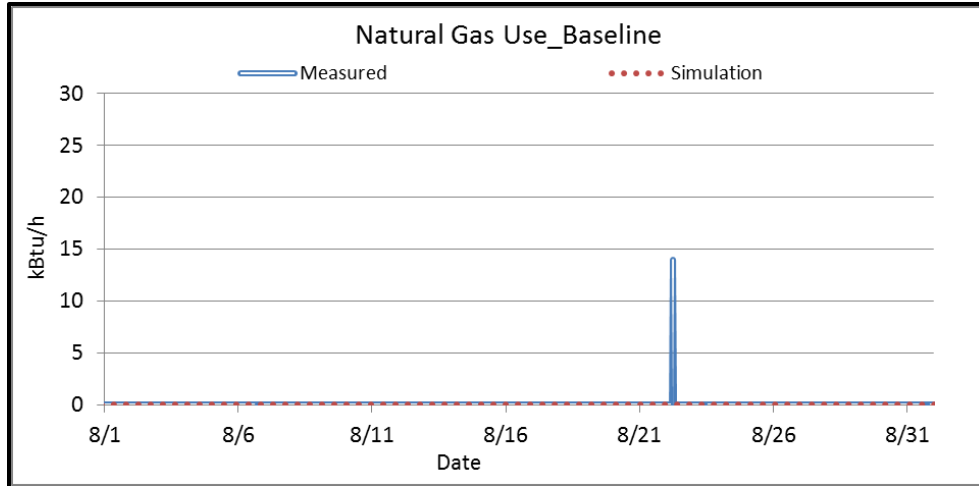


Figure 43. Summer Baseline Natural Gas Use.

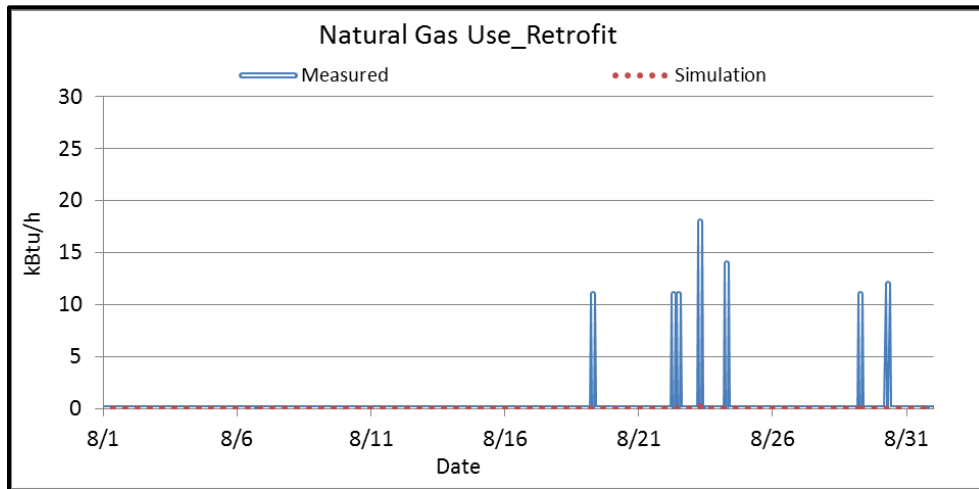


Figure 44. Summer Retrofit Natural Gas Use.

6.6.5 Fall 2016 (Sep 30-Oct 30)

Results from the measured and simulated data are shown for a shoulder season. Figure 45 again shows the boundary condition outdoor air temperature for both facilities.

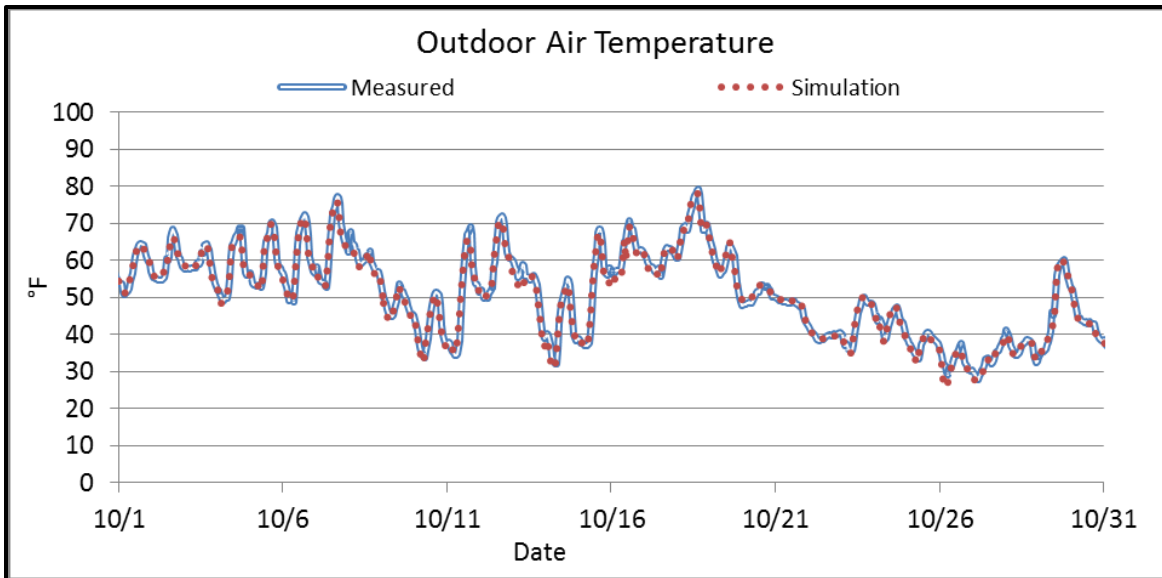


Figure 45. Fall Outdoor Air Temperature (Both Facilities, Boundary Condition).

The data in Figures 46 and 47 show that the indoor air temperature trends match well.

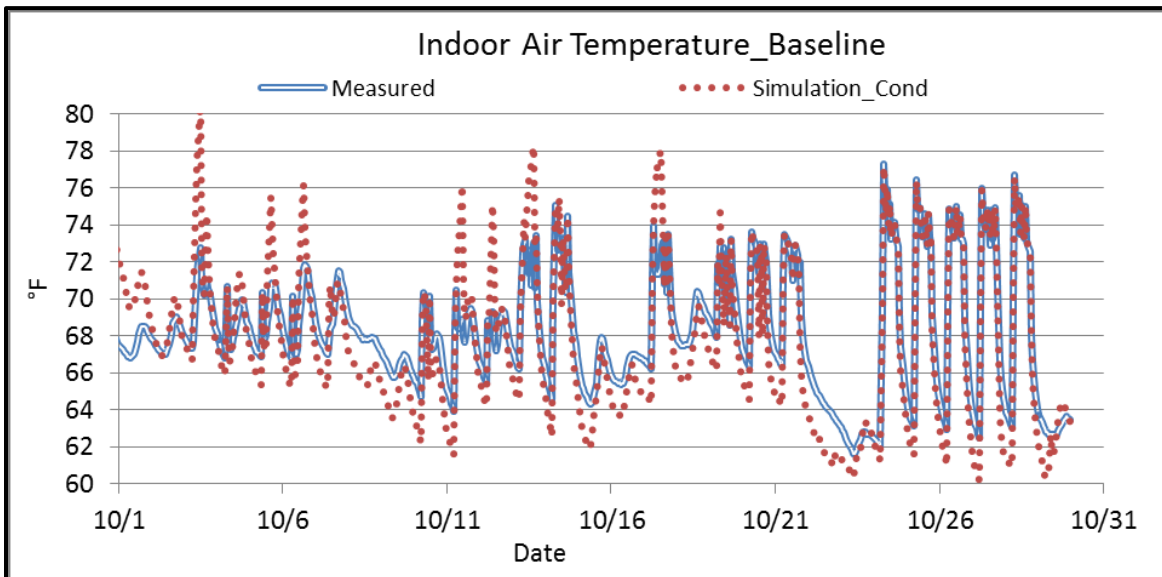


Figure 46. Fall Baseline Indoor Air Temperature.

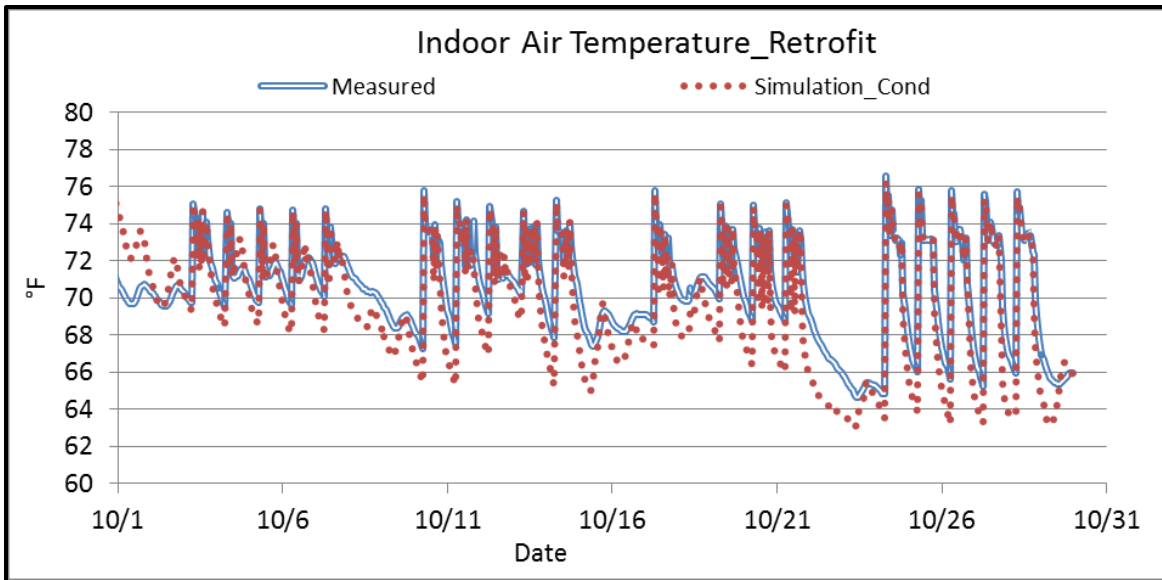


Figure 47. Fall Retrofit Indoor Air Temperature.

Figures 48 and 49, respectively, show the measured electric use for the baseline and retrofit facilities. As seen, the occupancy for the baseline facility appears to be low; significant increases are only seen on 10/26 and 10/27. The retrofit facility appears to have no significant occupancy during this time. Also, there was no HVAC (cooling) usage in either facility due to the low outdoor temperatures.

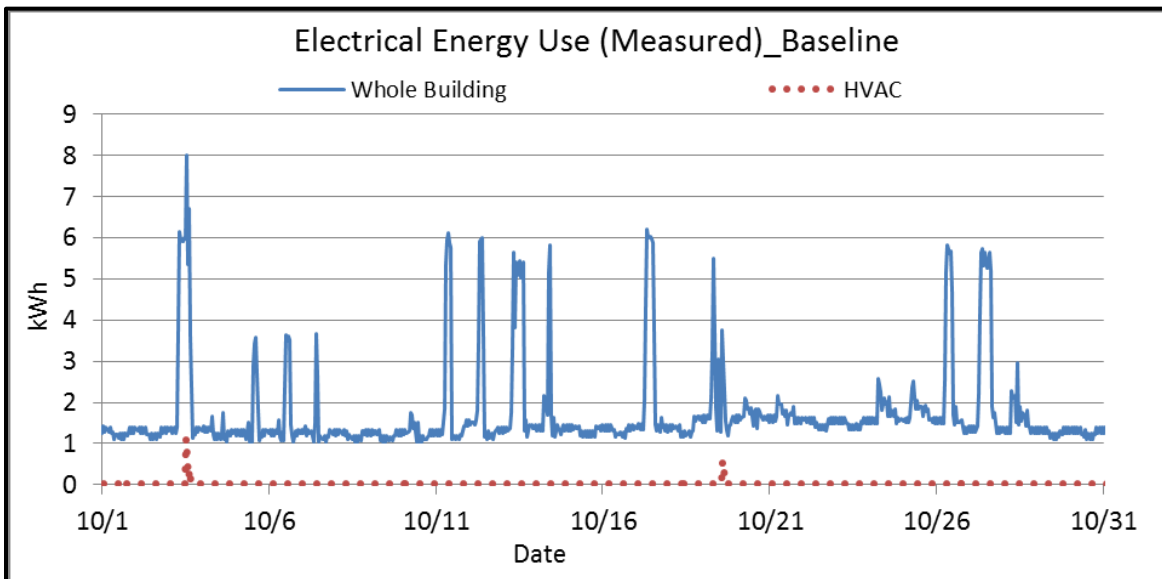


Figure 48. Fall Baseline Electric Energy Use.

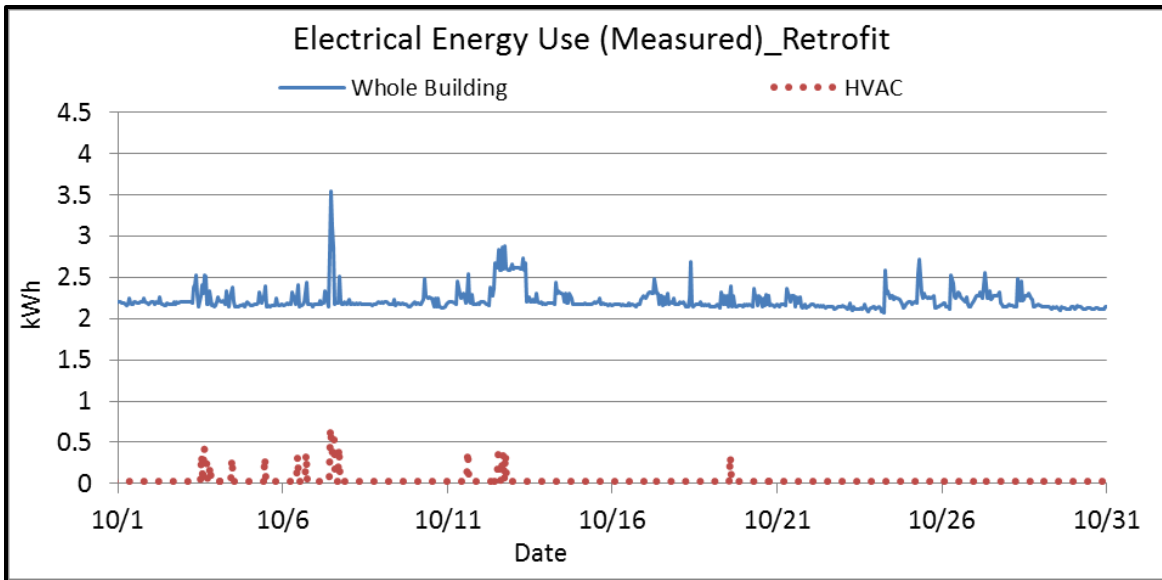


Figure 49. Fall Retrofit Electric Energy Use.

For comparison, Figures 50 and 51, respectively, show the total electric metered and the simulated loads for the baseline and retrofit facilities. The simulated trends match well for the baseline facility. For the retrofit facility, some cycling of loads is not captured.

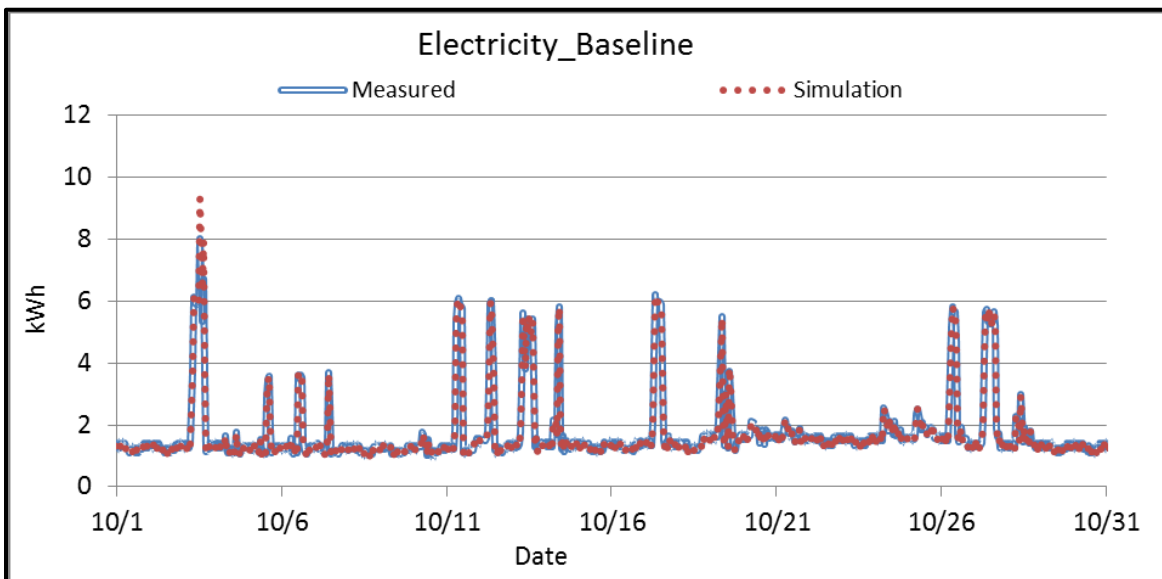


Figure 50. Fall Baseline Electric Measured vs. Simulated Use.

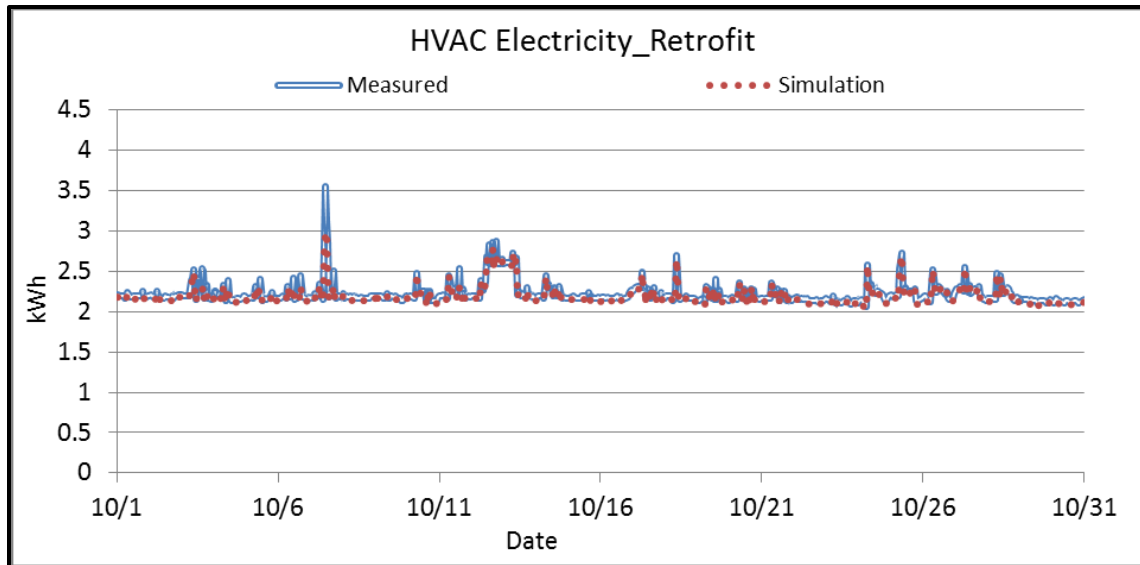


Figure 51. Fall Retrofit Measured vs. Simulated Electric Use.

Figures 52 and 53 show the natural gas consumption for both facilities. As seen, the trends for the baseline facility match well. The initial peak in the gas consumption occurs because the building heats up from a night setback. Throughout the day, the measured gas consumption appears to cycle. This cycling is likely to meet indoor setpoint conditions because the facility appears to be lightly loaded. The trends for the retrofit facility also match well. It is important to note that although the initial magnitude of natural gas usage is higher in the retrofit facility than in the baseline facility, the measured gas consumption in the baseline facility (1130 kBtu) was higher than the retrofit facility (1068 kBtu) during this period of lower occupancy. However, no assumptions about the effectiveness of the MAI can be made without normalizing the models.

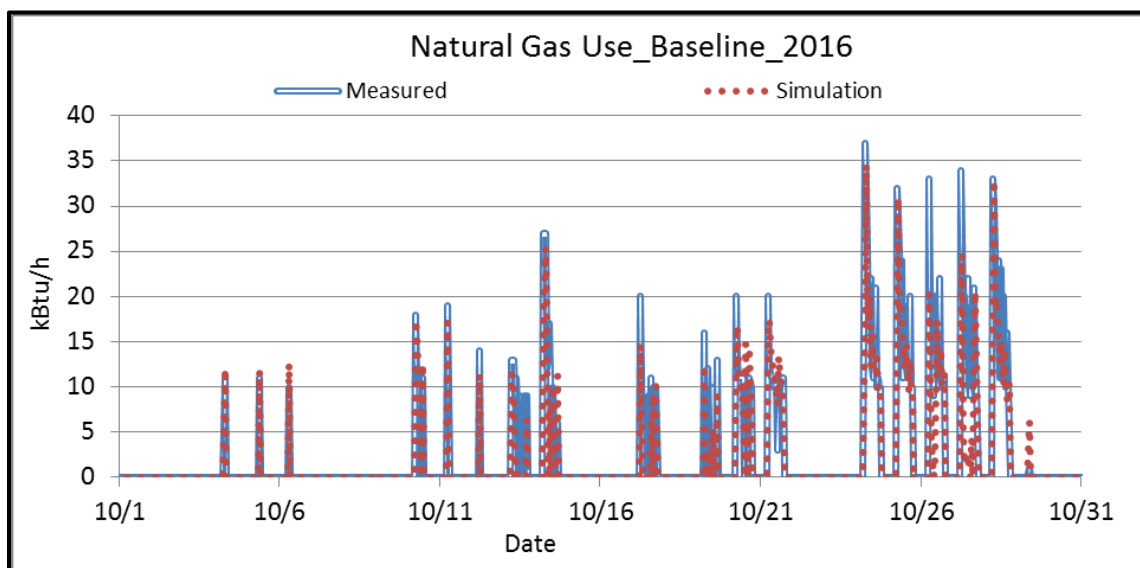


Figure 52. Fall Baseline Natural Gas Consumption.

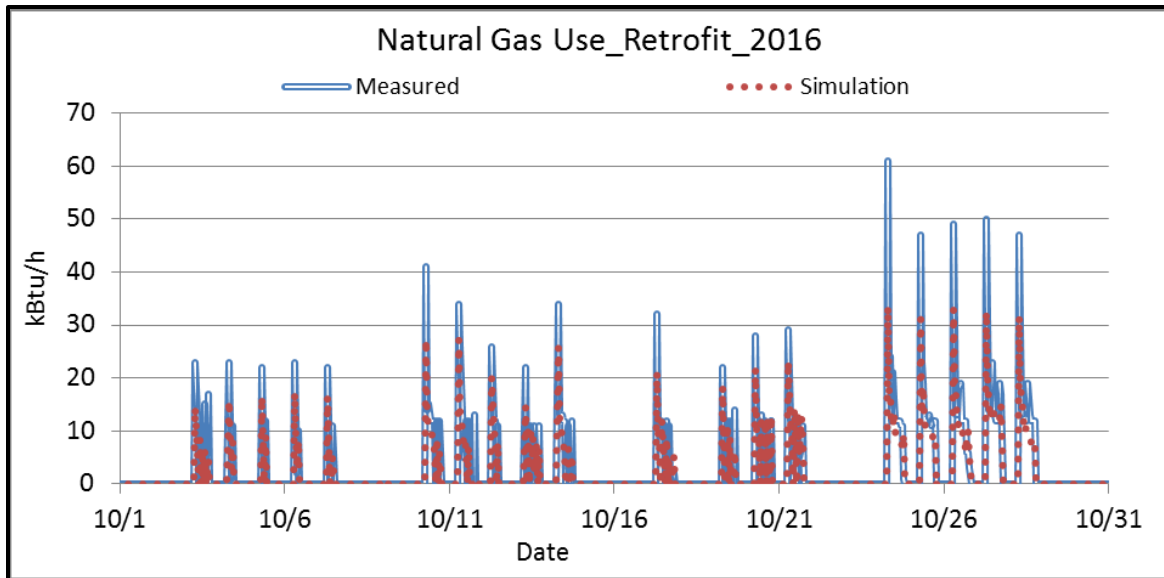


Figure 53. Fall Retrofit Natural Gas Consumption.

6.6.6 Winter 2016 (December 01 - 31)

Results from the measured and simulated data are shown for a winter season. Figure 54 again shows the boundary condition outdoor air temperature for both facilities.

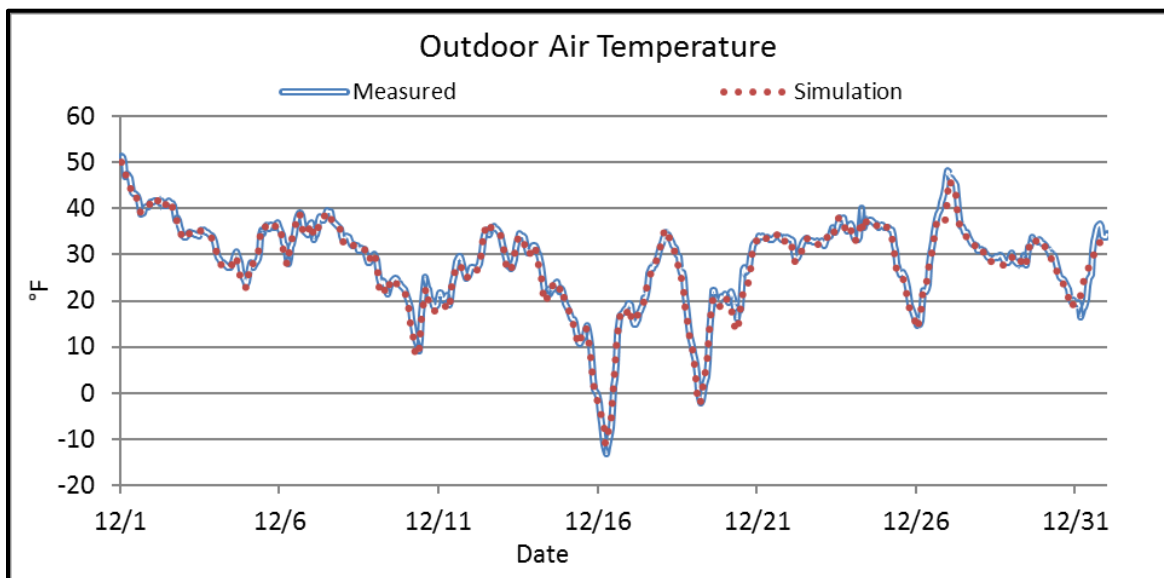


Figure 54. Winter Outdoor Air Temperature.

Figures 55 and 56 show the measured and simulated indoor air temperatures both facilities. The simulated trends match the measured data well. As before, due to differences in occupancy, the baseline internal air temperature fluctuates more than the retrofit facility.

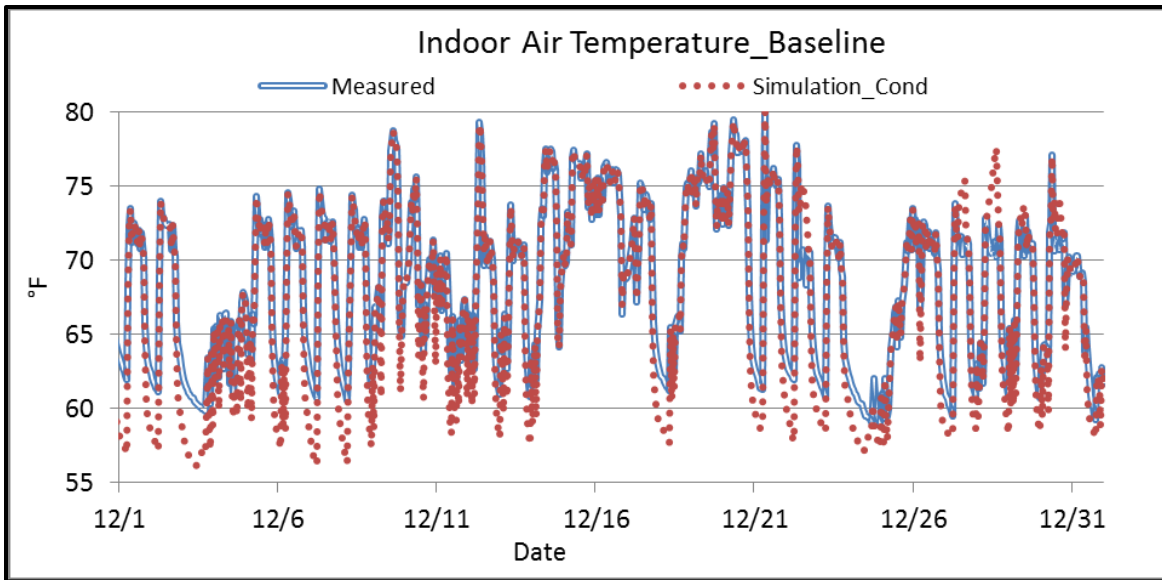


Figure 55. Winter Baseline Indoor Air Temperature.

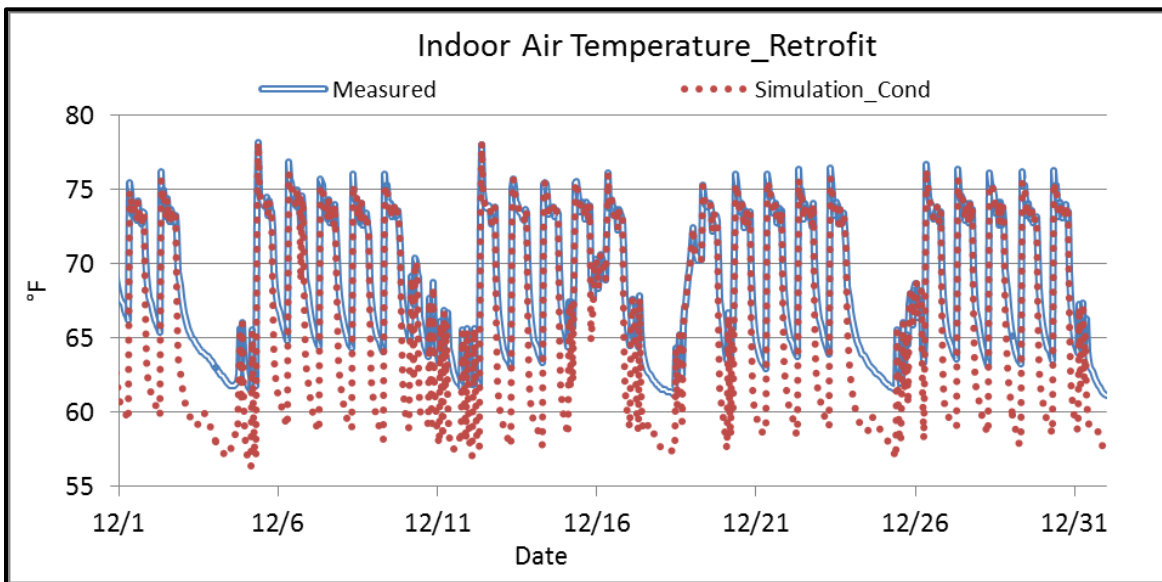


Figure 56. Winter Retrofit Indoor Air Temperature.

Figures 57 and 58 the measured electric and HVAC energy use for both facilities. The baseline facility energy usage indicates that the facility is more frequently occupied than the retrofit facility, which shows minimal signs of occupancy. There is no HVAC (cooling use) during the winter.

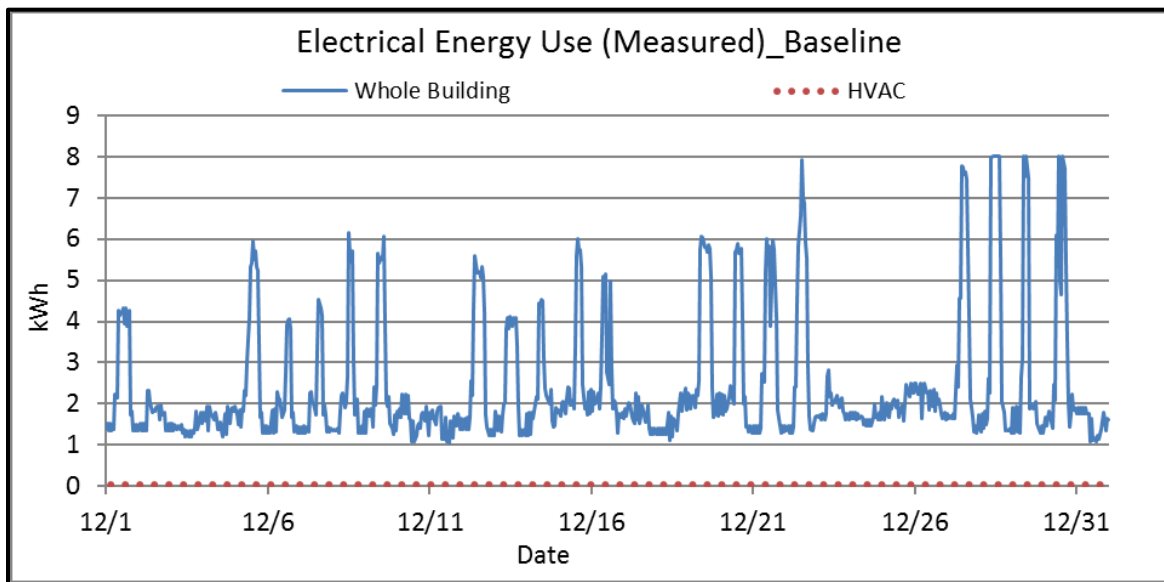


Figure 57. Winter Baseline Electric Energy Use.

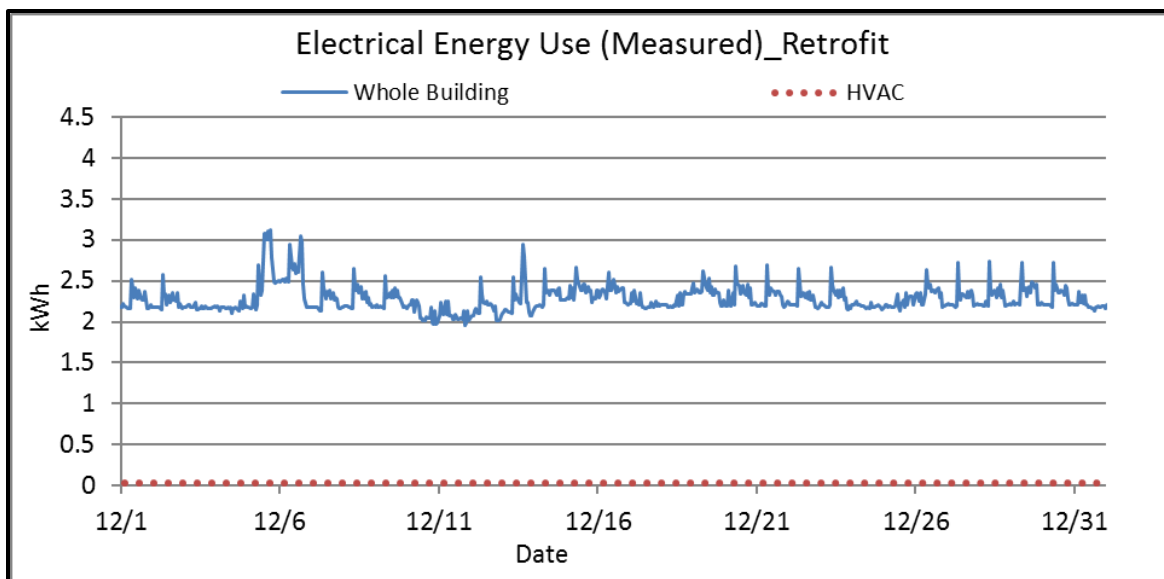


Figure 58. Winter Retrofit Electric Energy Use.

For comparison, Figures 59 and 60 show measured and simulated electric consumption for both facilities. In both cases, the simulated trends match well with measured data. There are some discrepancies in peaks due to incomplete occupancy and plug load data.

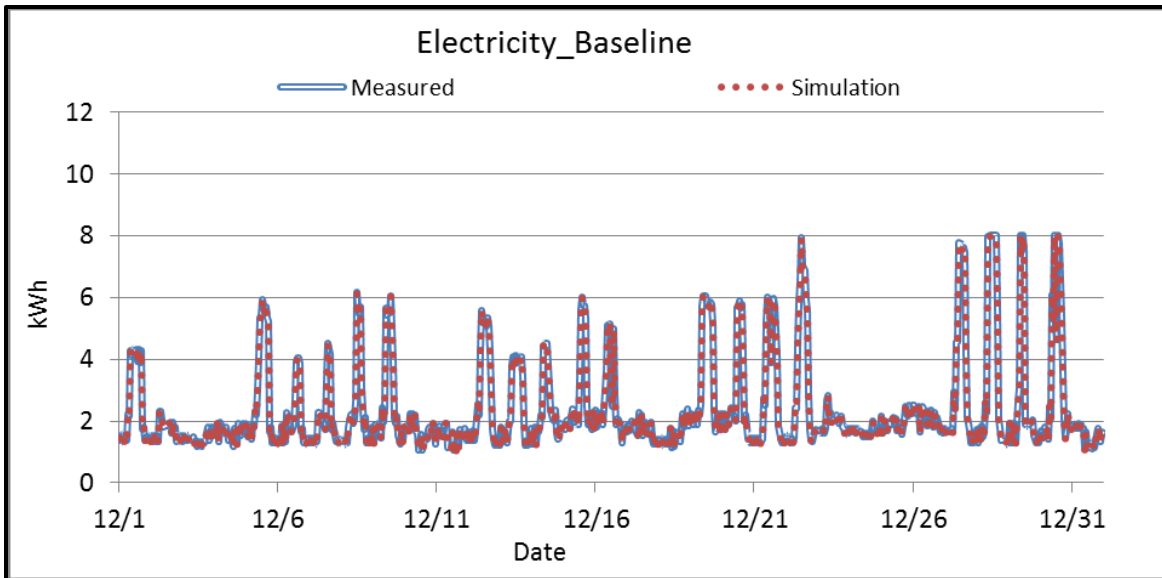


Figure 59. Winter Baseline Electric Simulation.

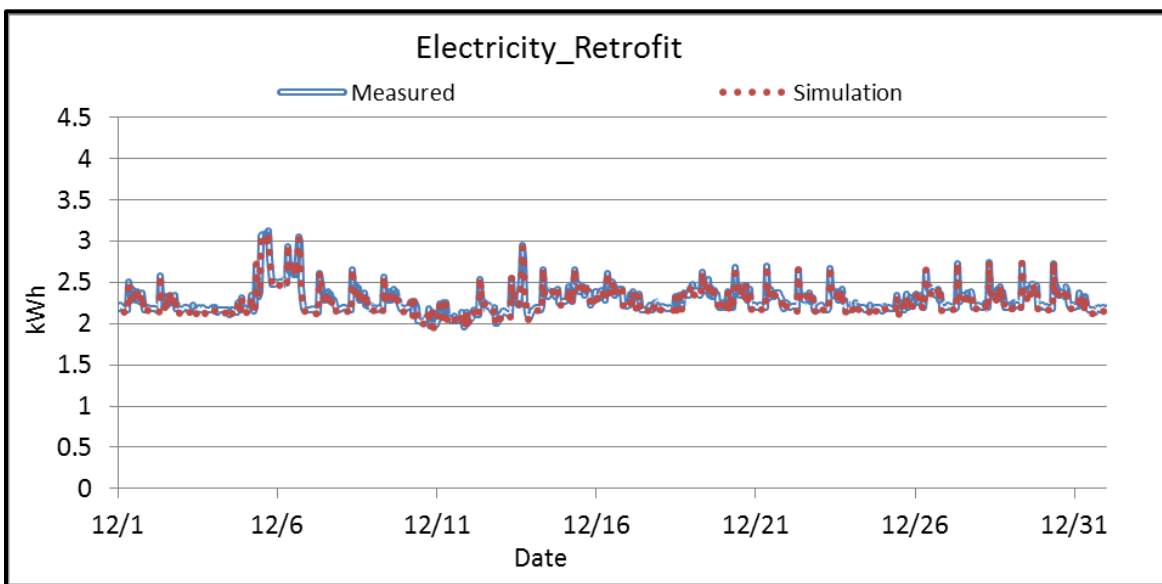


Figure 60. Winter Retrofit Electric Simulation.

Figures 61 and 62, respectively, show natural gas consumption (metered and simulated) for the baseline and retrofit facilities. The simulated trends for both facilities match well. As discussed in the previous section, although the retrofit initial gas peak is higher than the baseline facility initial gas peak, the total consumption for the baseline facility (9161 kBtu) is higher than the total consumption for retrofit facility (7543 kBtu) for that time.

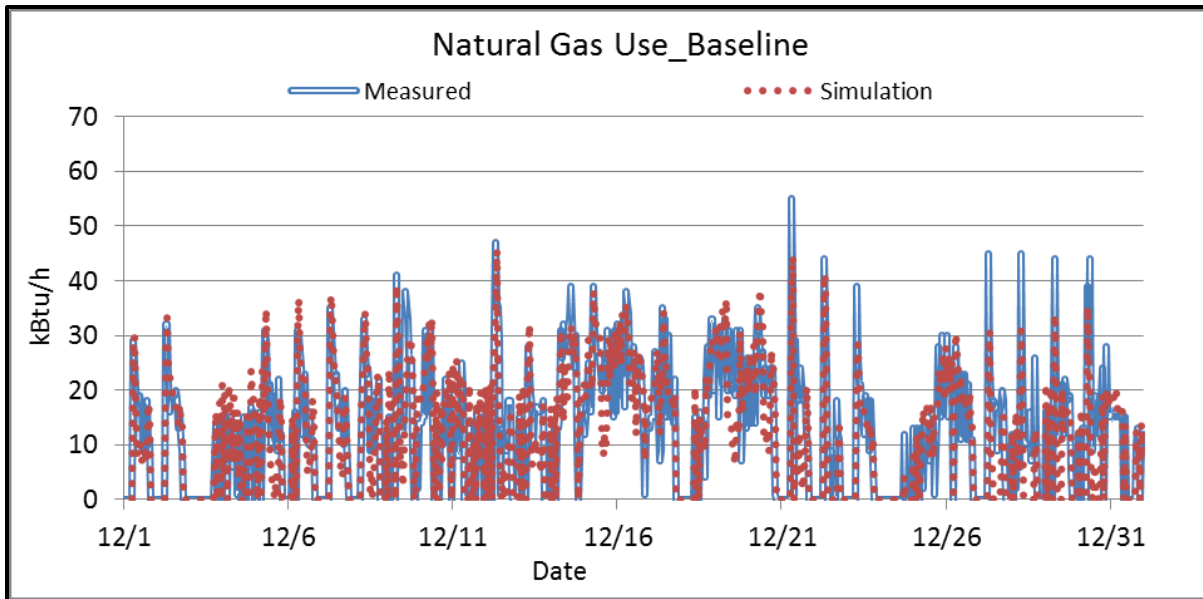


Figure 61. Winter Baseline Natural Gas Consumption.

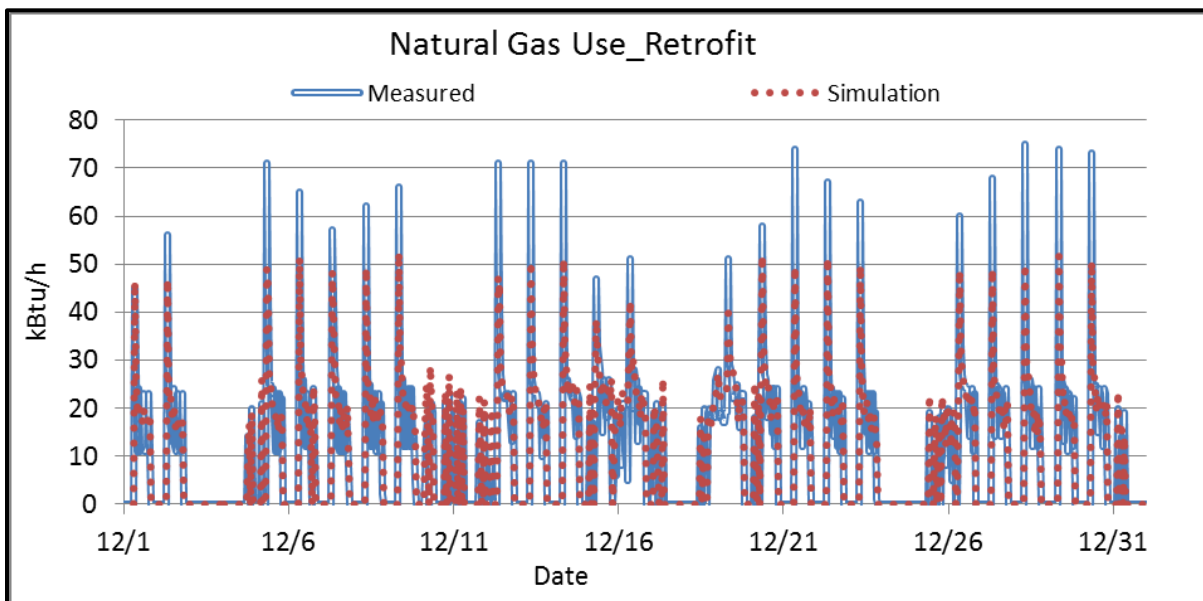


Figure 62. Winter Retrofit Natural Gas Consumption.

6.6.7 Full Year Results (06/01/2016 to 05/01/2017)

The simulated trends for each season, in the sections above, match relatively well with the measured data. However, it is important to quantify the differences between the simulated versus measured data to assess the impact of the calibrated models. Table 6 lists the magnitude and percent difference in the various data.

Table 6. Measured vs. Simulated Annual Data (Calibrated Models).

Data	Baseline			Retrofit		
	Measured	Simulated	Difference (%)	Measured	Simulated	Difference (%)
Total Electric (kWh)	18,085,237	18,088,247	0.0%	17,521,710	17,450,426	-0.4%
HVAC Electric (kWh)	614,116	618,298	0.7%	409,201	339,406	-17.1%
Natural Gas (kBtu)	49,258	47,236	-4.1%	45,660	45,537	-0.3%
Total (Electric and NG) (kBtu)	110,967	108,955	-1.8%	105,447	105,081	-0.3%

The calibrated models match the measured energy consumption very well. The total energy discrepancy for the baseline and retrofit facilities are -1.8% and -0.3% , respectively. The individual electric and natural gas consumption also match very well. As can be seen, the greatest difference is in the HVAC electric consumption. Although the root cause is not clear, the team suspects an issue with the HVAC electric meter. Because the “total electric” meter measures all power into the facility (including HVAC), the team is confident in the results of the simulations.

7.0 PERFORMANCE ASSESSMENT

After the calibrated models were complete, the team then normalized the two facilities by using DOE small office commercial prototype building models to normalize the internal loads, occupancy, and thermostat set-point schedules. Although the two facilities at Fort Drum are not necessarily small offices, their construction, loads and schedules match most closely with the DOE small office prototype. The following section includes results and comparisons based on the POs. For these purposes, annual normalized simulations are conducted with actual weather data from May 2016 to April 2017. The results are presented from January through December, for ease of discussion.

Some of the assumptions for the models used for the annual energy simulations, based on load profile from prototype building model were: internal load, occupancy, and thermostat setpoint schedule (used on the commercial prototype building model for small office building). Although those schedules and points are not included in this report, they are available by request. The following schedules from the prototype building model were used: BLDG_LIGHT_SCH, BLDG_EQUIP_SCH, BLDG_OCC_SCH, HVACOperationSchd, HTGSETP_SCH, and CLGSETP_SCH. The infiltration schedule listed was not used since blower door test results were used for infiltration modeling.

7.1 Facility Energy Usage

Figures 63, 64, and 65, respectively, show a month-by-month comparison of the facility electric, HVAC (cooling) electric, and natural gas use for both facilities. As seen, the results from the total electric and HVAC electric use are somewhat counter-intuitive. Rather than decreasing, these loads are slightly higher. One probably reason is that the retrofit building captures and retains heat from internal loads better than the baseline facility. As expected, natural gas usage is substantially lower for the retrofit facility.

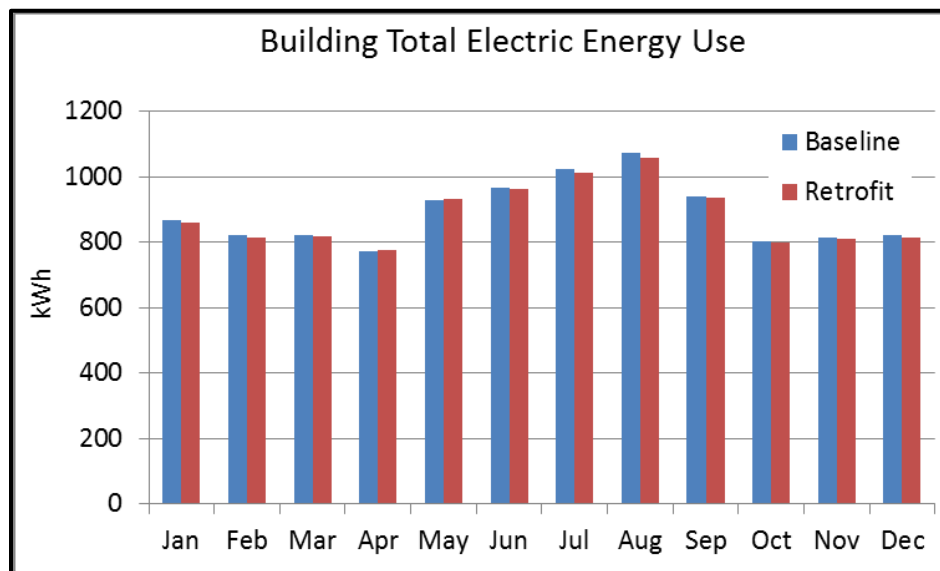


Figure 63. Normalized Total Electric Energy Use.

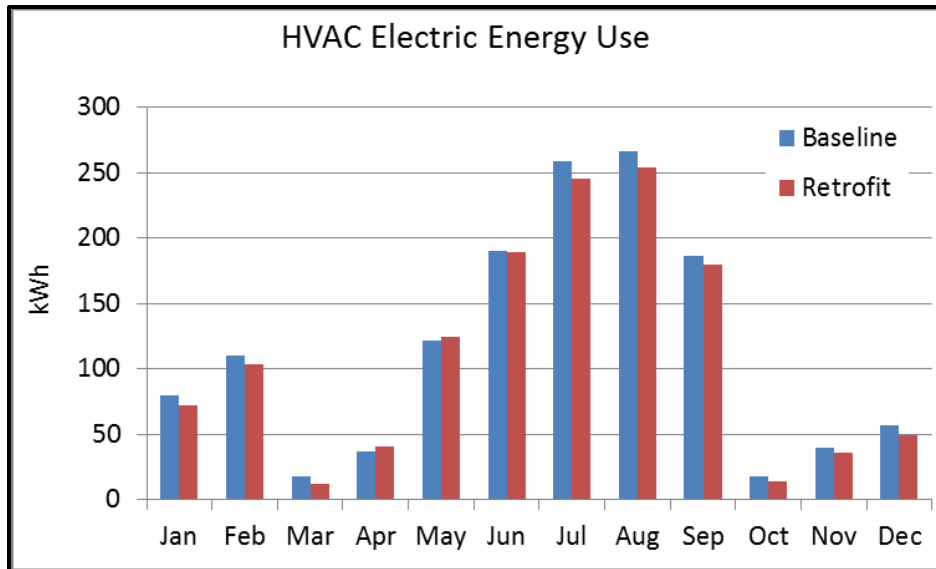


Figure 64. Normalized HVAC Electric Energy Use.

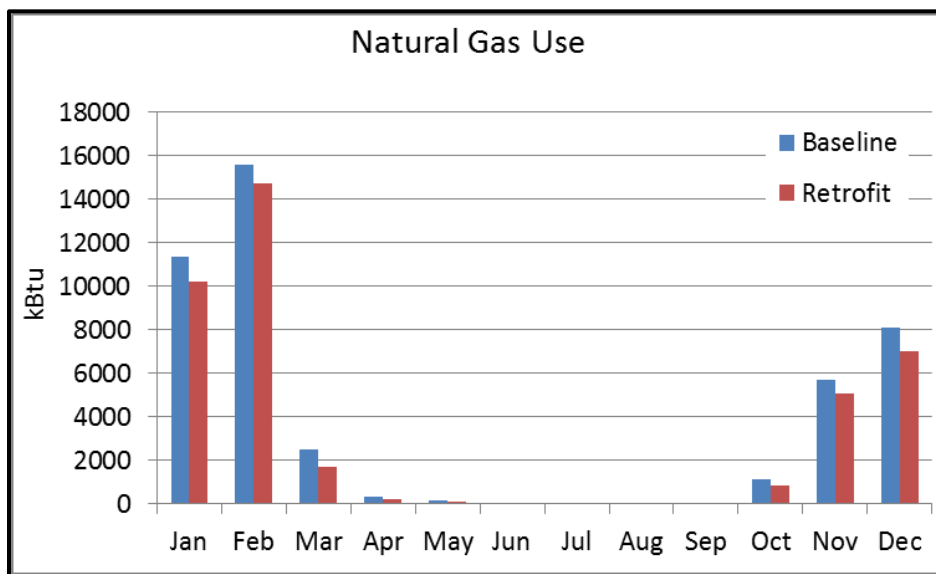


Figure 65. Normalized Natural Gas Use.

Table 7 lists the normalized energy usage.

Table 7. Normalized Energy Usage.

	Baseline	Retrofit	% Difference
Total electric (kWh)	10660.4	10597.9	-0.58%
Natural gas (kBtu)	44919.9	39908.9	-11.15%
Total (kBtu)	81294.6	76070.3	-6.43%

The overall reduction in energy was 6.43%, which exceeds the PO by 4%. Therefore, this metric is a success.

7.2 Demand Reduction

Figure 66 shows the maximum electric demand during any 1-hour interval for both facilities. The data in Figure 66 and Table 8 indicate that the peak demand occurs in August. Generally, the highest rates are charged during summer months and result in the greatest savings. As seen, during the highest peak month, there is a 3.5 % reduction in peak demand. This meets the PO requirements and is therefore a success. If the average peak demand is considered, then there is an average 2.2% reduction.

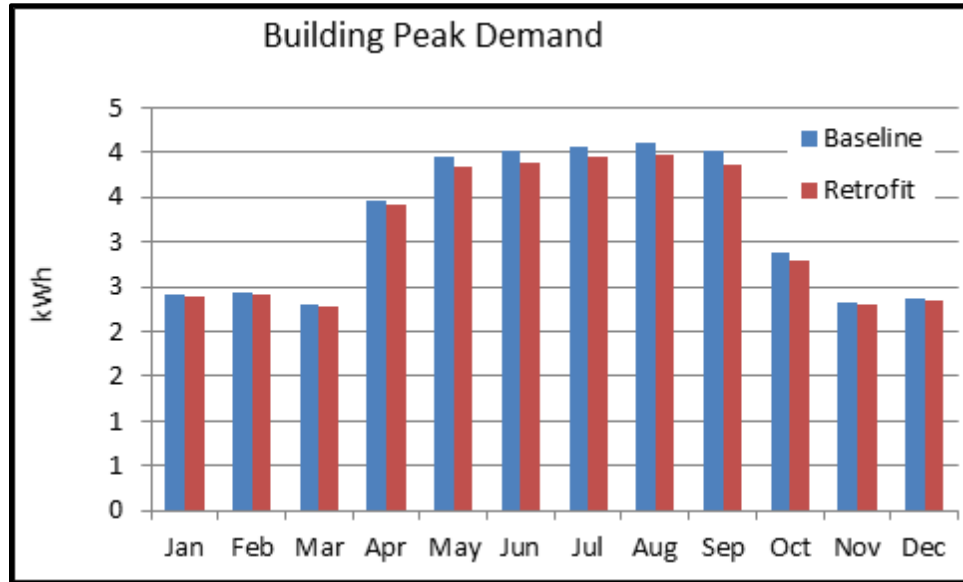


Figure 66. Normalized Peak Demand (kW).

Table 8. Peak Demand by Month.

Peak Demand	Baseline (kW)	Retrofit (kW)	Difference (%)
Jan	2.406	2.381	-1.0%
Feb	2.433	2.415	-0.7%
Mar	2.295	2.289	-0.3%
Apr	3.469	3.418	-1.5%
May	3.954	3.840	-2.9%
Jun	4.013	3.895	-2.9%
Jul	4.064	3.950	-2.8%
Aug	4.118	3.973	-3.5%
Sep	4.019	3.869	-3.7%
Oct	2.884	2.798	-3.0%
Nov	2.317	2.305	-0.5%
Dec	2.364	2.341	-1.0%
Avg	3.195	3.123	-2.2%

7.3 Percent of Panels Experiencing Loss of Vacuum (%)

Infrared thermography (IR) images of the facility were taken immediately after the installation. These images were used to determine whether any panels have failed. Figures 67 to 70 show IR images taken at various times after the installation. All images were taken during winter.

In Figure 67, the darker squares show the MAI panels. The lighter rows between the panels, and the left column show the polyiso foam. Because the R-value of the polyiso foam is significantly less than MAI, there is relatively-higher heat loss from those sections. Figure 68 shows an image of a panel that was damaged, but not removed. The failed panel is clearly visible and the temperature differences confirm this. Figures 67 and 68 were taken immediately after the retrofit.

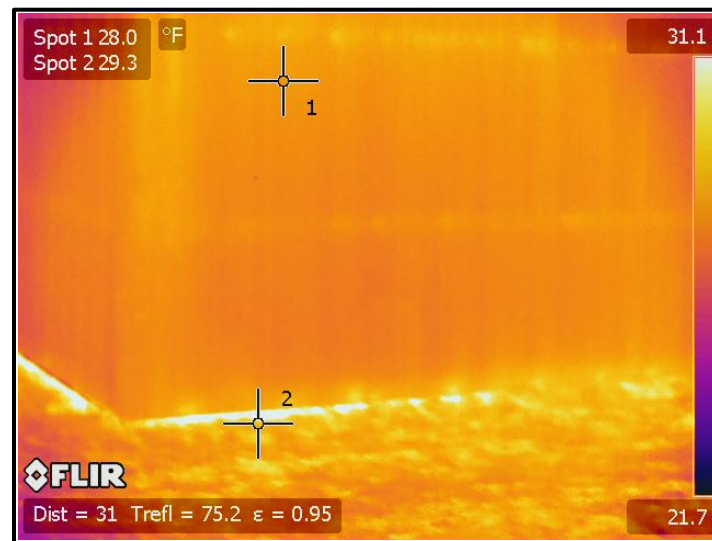


Figure 67. IR Image of East Face.

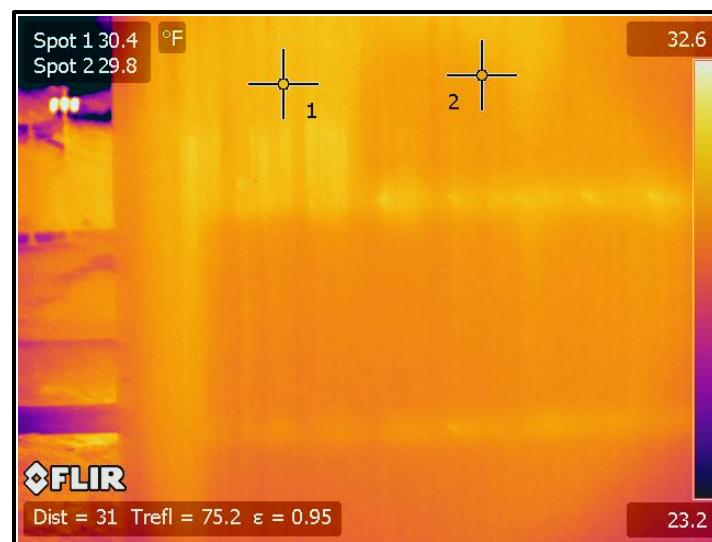


Figure 68. IR Image Showing Failed Panel (top left).

Figures 69 and 70 show IR images taken on a subsequent trip (Feb 2016), approximately 3 months after the installation. After the installation, Fort Drum staff installed building signs in both facilities. Due to a lack of coordination, the signs were installed with 2 in. screws and punctured several panels in the process.



Figure 69. Failed Panels above Sign (South Face).

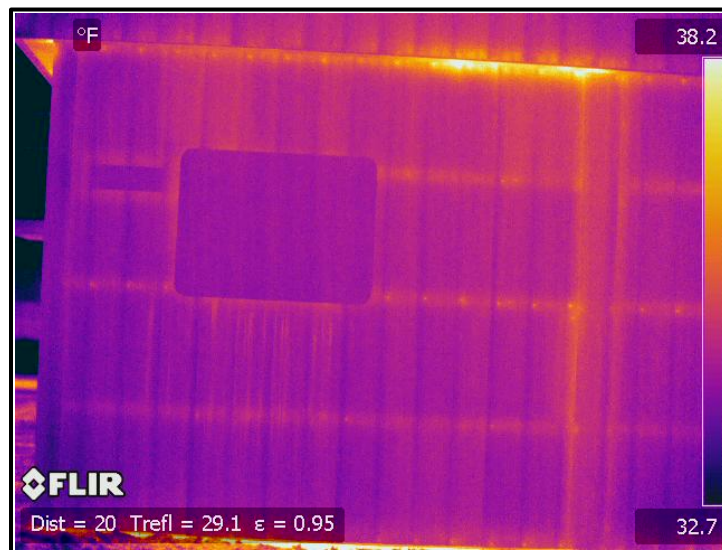


Figure 70. Failed Panels above Sign (North Face).

A total of five panels had failed above two signs in the retrofit facilities. In addition to the single punctured panel that was intentionally left in place, the team found an additional five panels that had failed (11 total). Although it was not immediately evident why these last five had failed, the team suspects the panels were damaged during the install and slowly leaked over time.

With 331 total panels installed, 11 total panels were found to have failed (3.32%). This exceeded the PO criteria and is therefore a success.

7.4 Overall R-Value of Walls with MAI (%)

The overall R-value increase was calculated by using the planned MAI layout and associated dimensions. The layout (see Appendix C) was developed with a combination of four different MAI panel sizes. The R-value of each face can be calculated by first calculating the overall conductance (U). The conductance is dependent on both the intact MAI panels, failed MAI panels, and the foam. Using the ASHRAE Handbook of Fundamentals, the U-value and R-value can be conducted as shown in Equation 1, below.

Equation 1. Parallel heat flow paths

Average conductance: $U_{av} = aU_a + bU_b + \dots + nU_n = \frac{a}{R_a} + \frac{b}{R_b} + \dots + \frac{n}{R_n}$

Average resistance: $R_{av} = 1/U_{av}$

$a, b, \dots, n$ – surface-weighted path fractions.

The resistance was calculated for each face of the retrofit facility based on the planned layout in Appendix C. Table 9 lists the values used in the equations.

Table 9. Calculation of R-Value.

Value	East	West	North	South
Clear wall area (no doors/windows) (in ²)	83,340	83,250	49,260	49,260
Intact MAI Coverage on Wall (a) (fraction of wall)	0.7519	0.6917	0.7718	0.7452
Failed MAI Coverage on Wall (b) (fraction of wall) – 3.3% failure	0.0257	0.0236	0.0263	0.0254
Polyiso Coverage on Wall (c) (fraction of wall)	0.2224	0.2847	0.2019	0.2294
R_MAI_intact - (hr-ft ² -°F/Btu-in) – R _a	37			
R_MAI_failed - (hr-ft ² -°F/Btu-in) – R _b	7.5			
R_Polyiso (hr-ft ² -°F/Btu-in) – R _c	5.5			
U _a (Btu/hr-ft ² -°F)	0.0203	0.0187	0.0209	0.0201
U _b (Btu/hr-ft ² -°F)	0.0034	0.0031	0.0035	0.0034
U _c (Btu/hr-ft ² -°F)	0.0404	0.0518	0.0367	0.0417
Net R (1/(U _a +U _b +U _c) (hr-ft ² -°F/Btu)	15.58	13.58	16.37	15.32
Area weighted average R-value (hr-ft ² -°F/Btu)	15.16			

The area weight average R-value increase is 15.16, which exceeds the PO requirement. Therefore this metric is considered successful.

7.5 Coverage of Wall Area with Minimal MAI Panels

Achieving optimal coverage of the wall area is dependent on the shape of the facility, the number of penetrations, and the size/number of windows and doors. To achieve the desired increase in R-

value and coverage, the team worked with the manufacturer to determine the cost and increased resistance associated with multiple sizes of panels. Table 10 lists the final MAI panel sizes and respective numbers of MAI panels.

Table 10. Final MAI Panel Sizes.

	X (in)	Y (in)	No. of MAI panels
A	19.95	28.00	87
B	21.29	28.00	83
C	19.17	25.50	26
D	20.58	25.50	135
		Total	331

Using the size of the panels and their layout (Appendix C), it is easy to calculate the percent of total wall coverage. Figure 71 shows the calculated coverage for various number of panel sizes. As seen, there is a large increase on all faces from two to four panel sizes. However, the benefits in increased overall coverage are significantly reduced after four sizes.

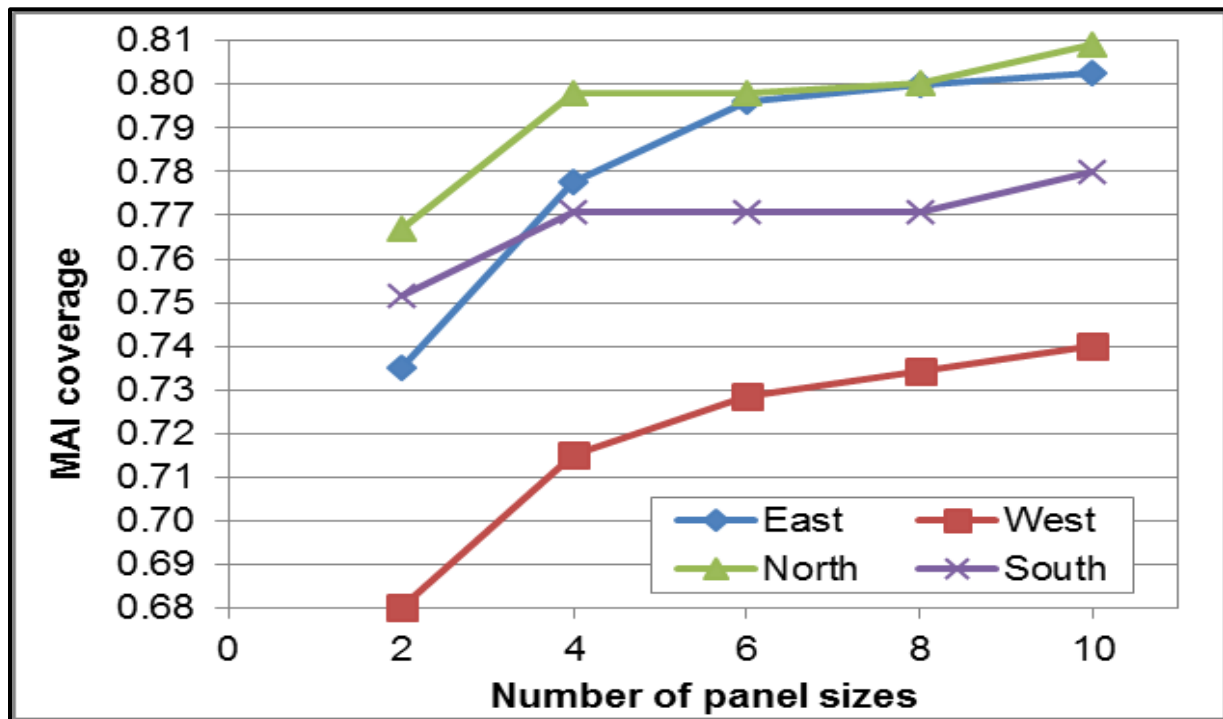


Figure 71. Number of Panel Sizes vs. Wall Coverage.

Figure 72 shows the area weighted MAI coverage for each face. As seen in this graph, using four different panel sizes provides ~76% coverage.

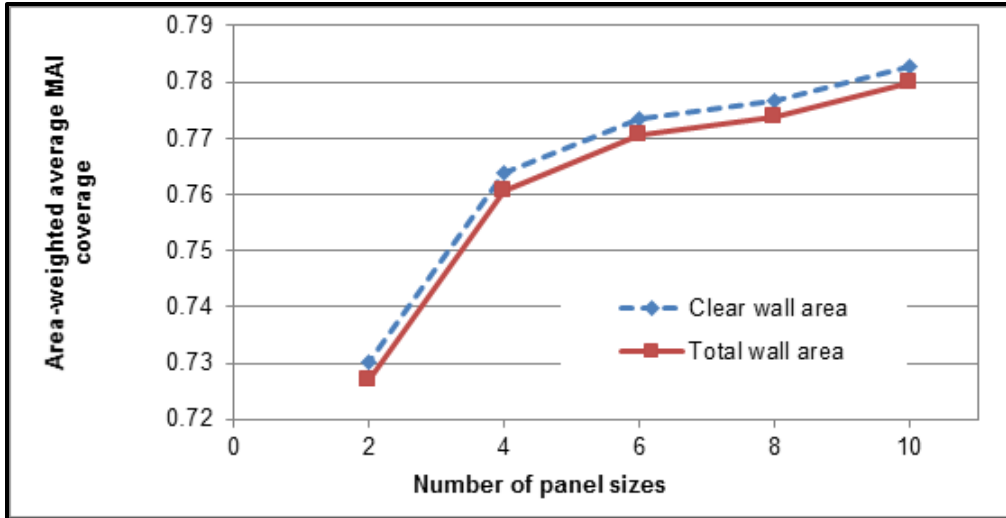


Figure 72. Number of Panel Sizes vs. Area Weighted Coverage.

Since the area weighted coverage for four panels exceeds 70%, this PO is considered successful.

7.6 Energy Loss through Walls

The energy lost through walls is comprised of both heat gain across the walls and heat loss across the walls. The heat gain (into the building) is dominant during the cooling season (i.e., summer) whereas the heat loss (out of the building) is dominant during the heating season. However, day-to-day fluctuations in temperature, internal loads, and occupancy can cause walls to experience heat gain or heat loss depending on these conditions. Heat flux from the normalized models was time-integrated into monthly bins to produce the total heat gain/loss across the walls during each month. Figures 73 and 74 show the results.

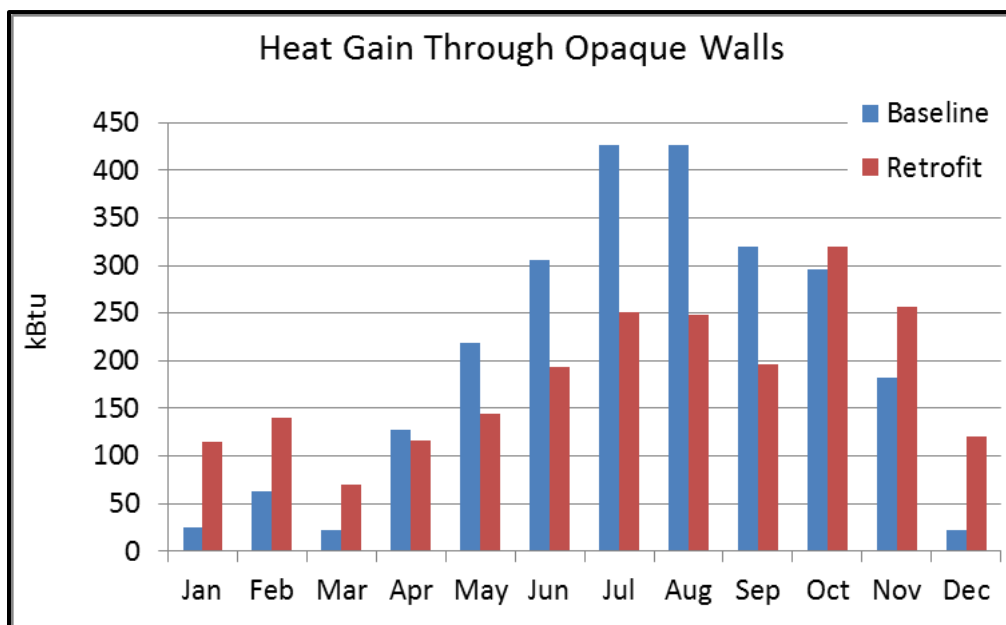


Figure 73. Normalized Heat Gain through Walls.

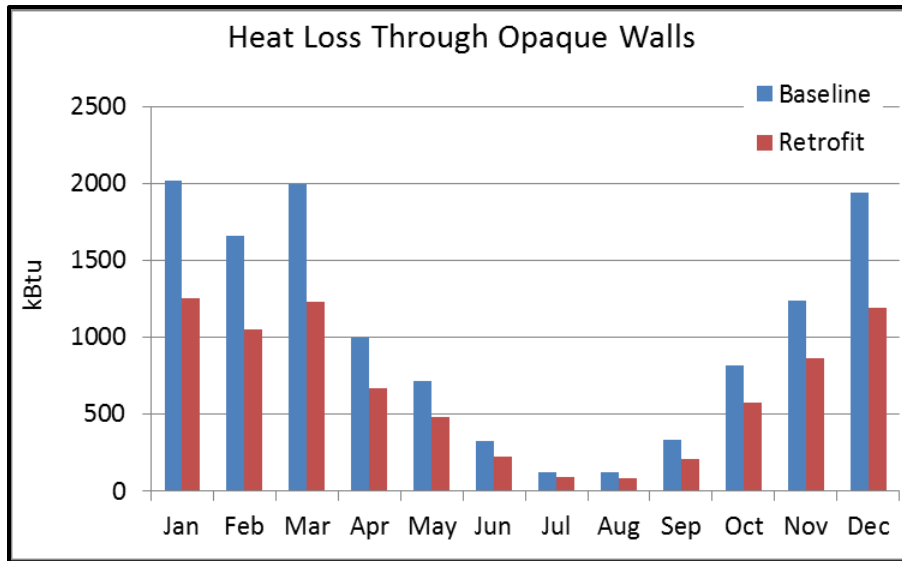


Figure 74. Normalized Heat Loss through Walls.

As seen, the heat gain for the retrofit facility is higher than the baseline facility for many months. This is somewhat counter-intuitive, and was attributed to the complex interaction of thermal mass, storage and heat transfer across the walls.

The heat loss through the walls is as expected. The retrofit facility showed significantly reduced heat loss through the walls. Table 11 lists the magnitude of gain/loss through the walls and the total percent reduction/increase over the baseline facility. As seen, the percent reduction across the year was 31%, greater than the PO of 20%.

Table 11. Total Heat Loss/Gain through Wall.

Month	Baseline heat gain (kBtu)	Baseline heat loss (kBtu)	Retrofit heat gain (kBtu)	Retrofit heat loss (kBtu)	Baseline - total wall heat gain/loss load (kBtu)	Retrofit - total wall heat gain/loss load (kBtu)	% difference
Jan	24	2018	115	1256	2042	1370	-33%
Feb	63	1656	140	1050	1719	1190	-31%
Mar	22	1995	69	1232	2017	1302	-35%
Apr	127	997	117	665	1124	782	-30%
May	219	713	144	484	932	629	-33%
Jun	305	329	193	228	634	422	-34%
Jul	426	123	250	91	548	341	-38%
Aug	427	120	248	82	547	330	-40%
Sep	320	336	197	208	656	404	-38%
Oct	296	815	319	573	1111	892	-20%
Nov	182	1235	257	864	1416	1121	-21%
Dec	22	1937	121	1193	1959	1314	-33%
Total	2432	12273	2170	7927	14705	10097	-31%

7.7 Economics

See Chapter 8.0, “Cost Assessment.”

7.8 Likert Scale Results

The team originally planned to conduct Likert surveys for both installers and occupants. However, due to the nature of the retrofit facility usage, the team was unable to find any occupants that used the facility regularly both before and after the retrofit. Additionally, because the facilities were unoccupied during the retrofit, many of the Likert questionnaire questions are not applicable. Therefore, this project did not conduct the Likert questionnaire for occupants. Three installers completed questionnaires and those results are used to assess this metric. These questionnaires are included in Appendix D. Table 12 lists the results from each questionnaire.

Table 12. Likert Questionnaire Tabulated Responses.

Questionnaire #	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree	N/A	Weighted Score
1	0	0	3	3	3	0	9
2	0	0	2	4	3	0	10
3	0	0	2	3	4	0	11

Each of the surveys (100%) resulted in a weighted score greater than 0. Therefore this metric is considered a success.

7.9 Performance Assessment w/out Insulation

As discussed in previous sections, the existing cavity insulation results in lower energy savings. Using the normalized models, a secondary scenario analysis was conducted to determine the potential economic impact of retrofitting a facility that did not already have existing insulation. This secondary analysis is more relevant for new buildings where alternative insulation technologies are being considered. The following sections provide the full year results for the energy reduction, and heat transfer through the walls for this secondary analysis.

7.9.1 Energy consumption

Table 13 lists the simulated difference in energy consumption for the secondary analysis scenario.

Table 13. Energy Comparison for Non-Insulated Facility Retrofit.

	Baseline	Retrofit	% Difference
Total electric (kWh)	11,233.2	10,692.9	-5%
Natural gas (kBtu)	77,699.7	43,970.3	-43%
Total (kBtu)	116,029.1	80,456.0	-31%

The 31% reduction is higher than the 6.41% reduction in a facility with existing cavity insulation.

7.9.2 Heat transfer through the walls

Figures 75 and 76 show the reductions in heat loss and heat gain in the walls for the secondary scenario. Table 14 lists the values of the heat gain and loss in the walls. The analysis shows that the total heat transfer reduction in the walls is 73%, which is significantly higher than the 31% shown in the previous sections.

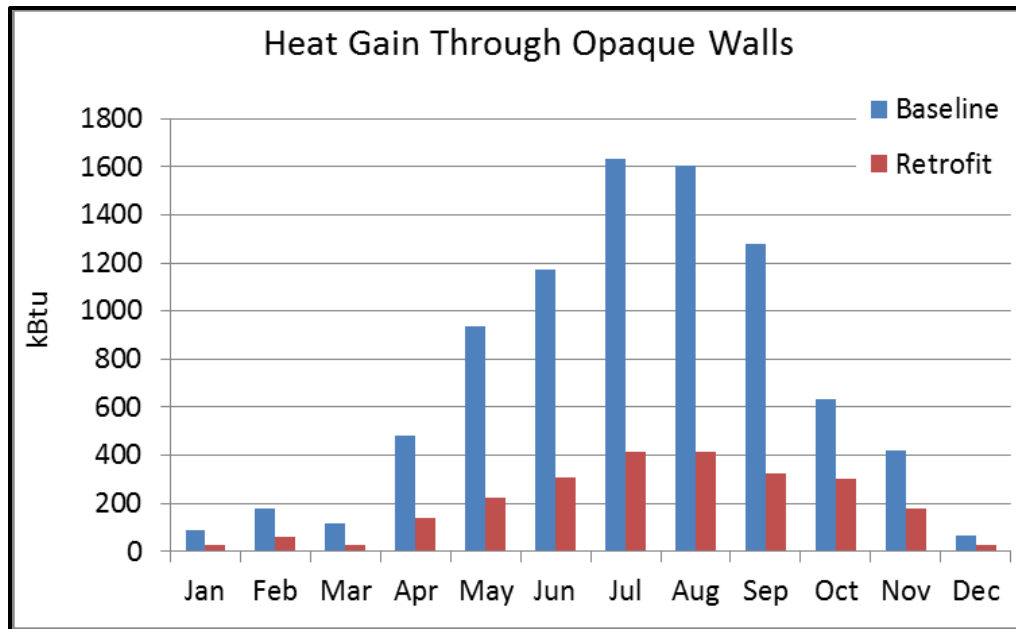


Figure 75. Heat Gain through Opaque Walls Secondary Scenario Analysis.

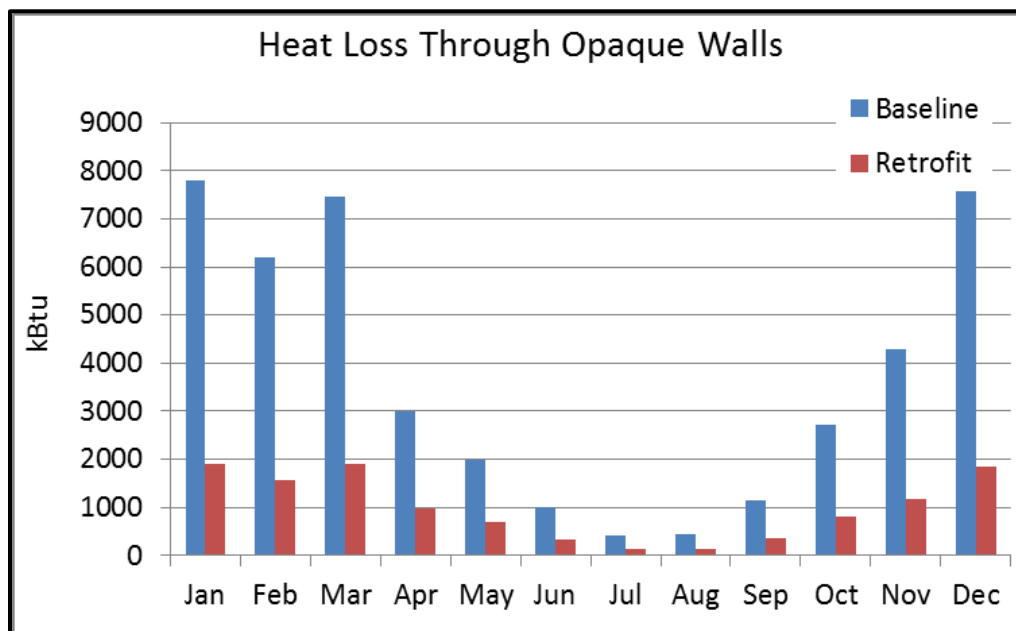


Figure 76. Heat Loss through Opaque Walls Secondary Scenario Analysis.

Table 14. Secondary Scenario Wall Heat Transfer.

Month	Baseline heat gain (kBtu)	Baseline heat loss (kBtu)	Retrofit Heat Gain (kBtu)	Retrofit Heat Loss (kBtu)	Baseline - total wall heat gain/loss load (kBtu)	Retrofit - total wall heat gain/loss load (kBtu)	% difference
Jan	89	7,809	27	1,911	7,898	1,938	-75%
Feb	179	6,198	61	1,562	6,377	1,623	-75%
Mar	114	7,468	30	1,896	7,582	1,926	-75%
Apr	479	3,002	138	965	3,482	1,103	-68%
May	935	1,974	223	692	2,909	915	-69%
Jun	1,170	1,002	306	334	2,172	641	-71%
Jul	1,632	419	413	133	2,051	546	-73%
Aug	1,605	434	416	131	2,039	547	-73%
Sep	1,277	1,155	325	350	2,432	675	-72%
Oct	635	2,718	300	799	3,353	1,099	-67%
Nov	422	4,289	181	1,185	4,711	1,366	-71%
Dec	63	7,657	28	1,835	7,720	1,862	-76%
Total	8,602	44,124	2,448	11,793	52,726	14,241	-73%

8.0 COST ASSESSMENT

8.1 Cost Model

To determine the life-cycle costs of this technology, the hardware and labor costs of the installation were tracked. Cost estimates for the MAI panels at full scale production are used for the economic analysis. The annual reduction in facility energy (based on normalized models) serves as the basis for cost savings and performance of the technology. There are no maintenance costs for this technology. Table 15 lists the elements of the cost model and Table 16 lists each cost element and how it was collected.

Table 15. Cost Model.

Cost Element	Data Tracked During the Demonstration
Hardware capital costs	Cost of purchasing the MAI panels (\$/sq ft), (\$/R-value/sq ft) at full scale production
Installation costs	Labor and material required to install. (\$/sq ft of wall area)
Facility operational costs	Reduction in energy required vs. baseline data

Table 16. Data Collection for Each Cost Element.

Cost Element	Data collection methodology
Hardware capital costs	• Hardware costs from this demonstrations • Estimated costs at full scale production
Installation Costs	• Labor costs and time from this demonstration • Estimated labor costs for buildings of a similar size
Facility Operational Costs	• Collected data from electric and gas meters in baseline and retrofit buildings • Estimated energy reduction based on E+ models • Using utility rates, estimate facility operational costs.

8.2 Cost Drivers

This section discusses cost drivers for individual components.

8.3 Cost Analysis and Comparison

8.3.1 MAI Panels

The team worked with the manufacturer to project costs for three different sized MAI plants. The economic analysis for this particular demonstration assumes that a commercial plant of 5M SF is in place for this technology. Projected costs range between \$2.49/ft² and \$3.24/ft² for 1-in. thick MAI (similar to that used in the demonstration). For simplicity, an average of \$2.87/ft² will be used for the economic analysis. The following sections describe the economic analysis in detail.

MAI offers a significant decrease in cost per area for high performance ($>R30/in.$) thermal insulation panels as compared to traditional VIPs. VIP use in building applications have been limited by their high cost per unit area, the large number of different panel sizes (which complicates automation and optimization), and the fact that handling on job sites is difficult unless the panels have been pre-made into a construction system. Traditional VIP production is not highly automated because of:

1. The large number of panel sizes (x, y, z).
2. Different barrier materials for different applications (short-lifetime packaging, medium-lifetime refrigerators and trucks, and long-lifetime buildings).
3. Very different dimensional and shape tolerances for different applications.
4. The small production scale of most VIP plants, which should be considered primarily as pilot plants.
5. The residence time and complexity of powder compaction into a board, drying, and evacuation.

In contrast, by eliminating the powder compaction, drying, and evacuation steps, MAI enables the use of conventional, high-speed packaging equipment simplifying automation and large scale production. In this study, we explore the economics of two scales of plants. A pilot plant with a capacity of 300,000 ft²/year and two commercial plants of 5,000,000 and 25,000,000 ft²/year are used as the design basis for the economic analysis. The main elements of the cost are; raw materials, labor, overhead, and equipment cost (capital and operating). These costs are a function of plant size, plant location, and the number of different panel sizes (one to five sizes [all 1 in. thick] are assumed). For a pilot plant, the MAI cost (ex-works) ranges between \$4.79/ft² and \$6.22/ft² with an initial capital cost of \$1.5M assuming an existing building. Because of the economies of commercial scale, costs decrease to between \$2.49/ft² and \$3.24/ft² with an initial capital cost of \$2.3M for a 5,000,000 ft²/year plant. Costs further decrease to between \$1.97/ft² and \$2.56/ft² with an initial capital cost of \$6.8M for a 25,000,000 ft²/year plant. All costs are in 2017 dollars.

8.3.1.1 Design Basis

As with all cost predictions, one must make a set of assumptions to form the basis for the analysis. In this report, we explore three different size plants; a 300,000 ft²/year pilot plant, and commercial-scale plants of 5,000,000 and 25,000,000 ft²/year. Table 17 lists the key operating parameters for each plant.

Table 17. Operating Parameters for All Three Plant Sizes.

Parameter	Pilot Plant	Commercial Plant #1	Commercial Plant #2
Weeks/year	48	50	50
Days/week	5	7	7
Hours/day	16	20	24
% uptime ¹	90	95	97
¹ Exclusive of product changeover time			

Another key variable that affects cost (both production and capital) is the panel size and size mix. For the basis of this study, we expect to make between one and five sizes. For building applications, almost all panels will be 1 in. thick so we will fix this. Table 18 lists the five sizes to be studied.

Table 18. Assumed MAI Panel Sizes.

Panel #	1	2	3	4	5
Width (in.) ¹	12.0	12.0	12.00	16.00	16.00
Length (in.) ¹	12.0	24.0	32.00	24.00	32.00
Area (ft ²)	1.0	2.0	2.67	2.67	3.56
¹ Dimensional tolerances: +/- 1/8 in. on x-y, +/- 1/16 in. on z					

8.3.1.2 Plant Location

As with most insulation plants, its location is important in an economic analysis, but a MAI plant is different than conventional foam or fiberglass insulation plants. With conventional insulation, the raw material volume is usually much smaller than the resulting insulation volume so it is best for the plant to be close to the customer to minimize total freight costs, and so the cost of incoming raw material freight will be a very small fraction of the total cost of goods sold (COGS). However, the situation is reversed if fumed silica is used as the core as in-coming fumed silica has a bulk density $\sim 0.04 \text{ g/cm}^3$ whereas the final MAI panel has a silica density of 0.14 g/cm^3 . Thus depending on insulation plant scale, the plant location relative to the fumed silica supplier becomes a significant consideration in insulation plant location. There are currently four fumed silica plants in the United States (Midland MI, Tuscola IL, Mobile AL, and Watervliet, NY) with a fifth plant under construction in Charleston, TN. The distance between the fumed silica and MAI plant drives, not just freight, but transport method (less than load (LTL), truckload, railcar, or direct pipe) and packaging costs as well.

8.3.1.1 Raw Material Costs

For a MAI panel, there are four main raw materials:

1. Fumed silica: This is the major component and cost. For MAI (and VIPs), this is typically $300 \text{ m}^2/\text{g}$ grade produced by Evonik, Cabot, or Wacker for on-shore suppliers or a number of off-shore suppliers. The final density of fumed silica in a MAI panel is 0.14 g/cm^3 , which fixes the weight of fumed silica required per ft^2 of panel at 1 in. thickness.
2. Opacifier: A range of opacifiers and opacifier weight loadings can be employed. This study assumes the use of silicon carbide at a 10% weight percent of the core. As the weight percent is low and industrial grade silicon carbide (SiC) is much cheaper than fumed silica, the COGS uncertainty associated with this opacifier choice and weight loading is small.
3. Barrier film: There are a wide range of barrier films available for use in MAI panels including foils, laminated foils, coextruded films with EvOH barrier layers, and multi-layer laminates based on multiple mPET (metalized PET) layers with a linear low-density polyethylene (LLDPE) seal layer. For this test, we will assume the use of Hanita's V085HB3 multi-layer laminate. The area of film required per unit area of insulation is a function of panel size because of the z-dimension and the material required for flaps. Based on our experience in panel production, we take the barrier film area for a given 1 in. thick panel as; $2 \times (\text{width} + 3 \text{ in.}) \times (\text{length} + 3 \text{ in.}) / 144$.
4. Porous inner bag: We assume the use of spun-bound polypropylene (SPB) as the inner bag material because of its high strength, high gas/vapor permeation, hydrophobicity, and processability. As with the barrier film, the area of SPB required is a function of panel size. We take the SPB area for a given 1 in. thick panel as; $2 \times (\text{width} + 2 \text{ in.}) \times (\text{length} + 2 \text{ in.}) / 144$.

Based on the above, we can calculate how much of each raw material is required for the different plant size scenarios (Table 19). Both SiO₂ and SiC consumption are independent of panel size. However, the barrier and porous films are a function of panel size, and we report the minimum (all 16x32 in. panels) and maximum (all 12x12-in. panels) areal demand.

Table 19. Raw Material Consumption for All Three Plant Sizes.

Nameplate plant capacity (ft ² /year)	300,000	5,000,000	25,000,000
Hours of operation per year	3,840	7,000	8,400
Hours of production per year	3,456	6,650	8,148
Required capacity (ft ² /hr)	86.81	751.88	3,068.24
Silica use (lb/hr)	63.19	547.37	2,233.68
Powder capacity (lbs/hr)	70.22	608.19	2,481.86
Annual silica use (lbs)	218,400	3,640,000	18,200,000
250 lb supersack/day	4	42	208
Truck of SS (8,000 lb)/week	0.57	9.10	45.50
Railcar (20,000 lb) per week	0.23	3.64	18.20
Annual SiC (lbs)	24,267	404,444	2,022,222
Annual SBP ft ² (minimum)	717,188	11,953,125	59,765,625
Annual SBP ft ² (maximum)	816,667	13,611,111	68,055,556
Annual SBP ft ² (average)	766,927	12,782,118	63,910,590
Annual barrier ft ² (minimum)	779,297	12,988,281	64,941,406
Annual barrier ft ² (maximum)	937,500	15,625,000	78,125,000
Annual barrier ft ² (average)	858,398	14,306,641	71,533,203

8.3.1.1.1 Fumed Silica

Because of the low density of fumed silica before processing, freight and packaging are key cost considerations. Depending on the quantity, fumed silica is normally transported as palletized 10 kg paper bags, 250 lb FIBC's (supersacks), bulk tank trucks, rail cars, or a direct pipeline. The method of transportation affects both the freight cost and the supplier's cost of packaging. Another factor in fumed silica logistics is incoming raw material storage. The following sections summarize realistic options for the various plant scenarios being modeled.

8.3.1.1.1.1 Pilot Plant

The data in Table 19 indicate that supersacks are the logical best choice at this scale as consumption is only four supersacks per day (a truckload every other week). This choice both decouples insulation plant location from the fumed silica plant, and minimizes capital investment in fumed silica storage. The general rule for the cost of a 250 lb supersack is that there is \$0.25/lb in packaging cost and \$0.25/lb in transport. Our experience is that this yields a delivered cost of \$2.25/lb (\$1.75/lb material, \$0.25/lb packaging and \$0.25/lb transport) based on our direct experience at these quantities (<300,000 lb/yr). Table 20 lists the raw material costs for all three plant sizes.

8.3.1.1.1.2 Commercial Plant #1

At the 5,000,000 ft²/year scale, supersacks reach their range of economic viability as shown above (depending on distance from the fumed silica plant) and a much better solution is to be located on a rail siding and to receive the fumed silica in bulk railcars (~20,000 lbs./railcar). This also helps with raw material storage as the cost of demurrage, if any, will be less than a dedicated series of silos. Railcars must go back to the plant empty (to prevent contamination) so the insulation plant must be within 500 miles of the fumed silica supplier. Since there is no packaging, the delivered cost is reduced to \$1.75/lb (\$1.65/lb material and \$0.10/lb freight).

8.3.1.1.1.3 Commercial Plant #2

At 25,000,000 ft² per year plant scale, any kind of packaging/shipment becomes cost prohibitive given the volumes of fumed silica required. So just like most silicone companies (DowCorning, Momentive, Bayer, Wacker, etc.), a large MAI plant would be located in a fence-line operation with a fumed silica plant. This reduces the silica cost to ~\$1.50/lb (based on supplier discussions). Note that, as with any large volume procurement, issues like “take or pay” clauses, supply chain guarantees, etc. can affect the cost by ±20%.

8.3.1.1.2 Silicon Carbide

This application requires only impure opacifiers, which are available at low cost and in large quantities. For the pilot plant, this would be received in 2,000 lb supersacks at a cost of \$0.80/lb (delivered). For the larger plants, the cost would be reduced to \$0.60/lb because of both higher usage and reduced freight cost because full truck-loads would be purchased.

8.3.1.1.3 Barrier Film

Although there is a wide range of possible barrier films available, we would use Hanita’s (a division of AveryDennison) V085HB3 film that is \$1.20/m² delivered. At the larger volumes, this would come down to \$1.1/m² and \$1.0/m² based on quotes from the supplier.

3d Porous inner bag: This is spun-bond polypropylene (SPB) that NanoPore’s sister company, Nan°Cool, uses in quantities similar to the pilot plant size of this study. The current price Nan°Cool pays is \$0.024/ft². At larger scales, this would reduce to \$0.02/ft² and \$0.018/ft² because of the higher volumes and full truck-load freight.

So even at the largest scale with a fence-line operation for fumed silica, the cost of the fumed silica is 75% of the raw materials cost. Hence, we have a continued interest in finding lower cost/higher performance core materials for MAI panels.

Table 20. Raw Material Costs for All Three Plant Sizes.

Nameplate plant capacity (ft ² /year)	300,000	5,000,000	25,000,000
Raw material cost			
Silica	\$ 491,400	\$ 6,370,000	\$ 27,300,000
SiC	\$ 19,413	\$ 242,667	\$ 1,112,222
SBP	\$ 18,406	\$ 255,642	\$ 1,150,391
Barrier	\$ 95,823	\$ 1,463,963	\$ 6,654,376
Raw material cost/ft²	\$ 2.08	\$ 1.67	\$ 1.45

8.3.1.2 Labor and Overhead Cost

The number of people and their costs (Table 21) are based on NanoPore experience with its sister company, Nan°Cool LLC, and its VIP production operation, which was formerly known as “NanoPore Insulation” before being sold to Sealed Air Corporation, and which is now known as “Kevothermal.” The overhead rate of 30% of combined raw materials and labor reflects the overhead at the two production operations described above (Table 22). At the higher volumes, the COGS are similar to foams on a \$/R-value basis. That said, the COGS does not include the cost of capital equipment or facility, and does not provide for a profit margin.

Table 21. Labor Costs with Benefits for All Three Plant Sizes.

Nameplate plant capacity (ft2/year)	300,000	5,000,000	25,000,000
Labor			
Plant Manager	\$ -	\$ 175,000	\$ 175,000
Shift supervisor	\$ 160,000	\$ 320,000	\$ 480,000
Operators, warehouse, maintenance, admin	\$ 320,000	\$ 768,000	\$ 1,024,000
Labor/ft2	\$ 1.60	\$ 0.25	\$ 0.07

Table 22. Overhead and Total COGS for All Three Plant Sizes.

Nameplate plant capacity (ft2/year)	300,000	5,000,000	25,000,000
Overhead			
Overhead/ft2	\$ 1.11	\$ 0.58	\$ 0.45
COGS	\$ 4.79	\$ 2.49	\$ 1.97

8.3.1.3 Capital Equipment, Description and Cost

Table 23 lists equipment (and costs) required for each of the three different plant sizes. All employ the same MAI process flow as shown in Figure 3 (p 5), but differ primarily in raw material sourcing and handling. The 25,000,000 ft²/year is essentially four 5,000,000 ft² production lines in parallel as the VFSS machines reach their capacity limits. The sources of equipment costs are:

1. Previous NanoPore and affiliated company purchases: Flexicon bulk bag unloading station, powder conveying system, Tecweigh weigh feeder, conveyors, dust collection systems, Quality Control (QC) inspection.
2. Quotes from Solids Technology: 1,000 ft³ silo, Viking VFSS machines, gravimetric opacifier mixing, inserter.
3. Quotes from Supply 1: Pallet wrapper, automatic palletizer, and fork lift,
4. NanoPore Estimate based on scale-up of existing lab-scale equipment: Air replacement tunnel and cold forming conveyor.

For simplicity, an average of \$2.87/ft² will be used for the economic analysis. For this demonstration, a total of 1261 ft² of MAI was used. Therefore the cost of the MAI panels (at full production scale) is 1261 ft² * \$2.87/ft² = \$3,619.07.

Approximately thirteen (13) 4-ft x 8-ft x 1-in. boards of polyiso were used at a cost of \$20 per board. This is a total of \$260. Therefore the cost of MAI and Polyiso is **\$3,879.07**.

Table 23. Capital Equipment Costs for All Three Plant Sizes.

Nameplate plant capacity (ft2/year)	300,000 ft2/year		5,000,000 ft2/year		25,000,000 ft2/year	
Description	Unit cost	#	Total Cost	#	Total Cost	#
Flexicon bulk bag unloading station	\$ 38,000	2	\$ 76,000	1	\$ 38,000	2
1,000 ft3 silo	\$ 52,000	0	\$ -	2	\$ 104,000	4
Powder conveying systems	\$ 25,000	1	\$ 25,000	4	\$ 100,000	8
Gravimetric opacifier mixing system	\$ 40,000	1	\$ 40,000	2	\$ 80,000	4
Techweigh weigh feeder	\$ 22,000	1	\$ 22,000	4	\$ 88,000	8
Viking VFFS machine for SPB bag	\$ 95,000	1	\$ 95,000	1	\$ 95,000	4
Air replacement tunnel	\$ 150,000	1	\$ 150,000	1	\$ 150,000	4
Viking VFFS machine for barrier bag	\$ 80,000	1	\$ 80,000	1	\$ 80,000	4
Insertor for VFSS	\$ 30,000	1	\$ 30,000	1	\$ 30,000	4
Cold forming conveyors	\$ 45,000	1	\$ 45,000	1	\$ 45,000	4
Material handling conveyors	\$ 8,000	4	\$ 32,000	4	\$ 32,000	16
Pallet wrapper	\$ 40,000	0	\$ -	1	\$ 40,000	0
Automatic palletizer	\$ 110,000	0	\$ -	0	\$ -	1
Forklift	\$ 25,000	1	\$ 25,000	1	\$ 25,000	4
Air handling/dust collection system	\$ 60,000	1	\$ 60,000	2	\$ 120,000	4
QC inspection station	\$ 15,000	1	\$ 15,000	1	\$ 15,000	4
Total equipment			\$ 695,000		\$ 1,042,000	
Design and Engineering (20% of equipment)			\$ 139,000		\$ 208,400	
Equipment Install (50% of equipment)			\$ 347,500		\$ 521,000	
Automation/integration (30% of equipment)			\$ 208,500		\$ 312,600	
Contingency (20% of equipment)			\$ 139,000		\$ 208,400	
Total			\$ 1,529,000		\$ 2,292,400	\$ 6,727,600

8.3.2 Installation Costs

The installation costs for this demonstration were tracked during the week of the install. The installation took 3.5 days with multiple people and hours worked per day. Other costs included a portable table saw for cutting foam, and power tools. These costs are not included in this estimate because they are common for most commercial construction contractors. Table 24 lists the detailed labor breakdown and assumes a cost of \$60/hr per person.

Table 24. Detailed Labor for Installation.

Day	Number of personnel	Hours worked ea.	Total hours	Tasks
Monday	1	3	3	Verify layout against building dimensions. Clean and prep site.
Tuesday	8	9	72	Unpack items, setup site, assign responsibilities, remove siding and install MAI. 60 panels installed on east side total. Reinstall siding in case of rain.
Wednesday	8	9	72	Continue MAI install. 120 panels installed. East and north completed. Reinstall siding
Thursday	7	9	63	Continue MAI install. 162 panels installed. South completed. West side complete (except around window). Reinstall siding
Friday	6	4	24	Complete install. Reinstall siding. Clean up.
Total	—	—	234	

The labor cost of the installation for the demonstration is estimated as \$14,040. The installation covered almost 2000 ft² of wall area, which is approximately \$7.02/ft². Based on the assignment of tasks, future installations could easily require one less person for the installation. In that case, the total labor hours are reduced to 187 at a total cost of **\$11,220**. This installation cost is used for the economic analysis.

8.3.3 Total Cost

For purposes of this economic analysis, two separate costs are considered. The first only includes the cost of the MAI and Polyiso foam. Because the technology is not completely mature, the cost of the installation is extremely high. Installation costs are expected to be reduced by 80% or more. This will be achieved through large 4x8-ft MAI/foam integrated boards that are produced on the manufacturing line. These boards are currently under pilot development and as such there are no cost estimates yet.

8.3.3.1 Cost with Installation

$$\text{MAI } (\$3,879) + \text{Installation } (\$11,220) = (\$15,099 + \text{Supervision, Inspection, and Overhead (SIOH) (6\%, \$905) and Design (10\%, \$1,510)}) = \$17,514 \quad (2)$$

8.3.3.2 Cost without Installation

$$\text{MAI } (\$3,879) + \text{SIOH (6\%, \$233) and Design (10\%, \$388)} = \mathbf{\$4500} \quad (3)$$

8.3.4 Savings and Rates

In 2017, the cost of electricity at Fort Drum Electric was \$0.0732/kWh. There is no demand based pricing at Fort Drum because there is an on-site biomass plant that provides electricity. However, the cost was obtained by averaging Fort Drum FY17 Army Energy and Water Reporting System (AEWRS) Data:

$$\text{Natural Gas (2017)} = \$3.633 \text{ (Obtained by averaging Fort Drum FY17 AEWRS Data)} \quad (4)$$

Table 25 lists the normalized energy savings.

Table 25. Normalized Energy Savings.

	Baseline	Retrofit	Savings	% Difference
Total electric (kWh)	10660.4	10597.9	62.5	-0.58%
Natural gas (kBtu)	44919.9	39908.9	5,011	-11.15%
Total (kBtu)	81294.6	76070.3	5,224	-6.43%

The system economics for the technology were calculated using the BLCC tool. The economics were calculated with and without installations costs (Figures 77 and 78). The low SIR and Simple Payback can be attributed to the low energy savings (due to existing insulation) and the low utility rates.

NIST BLCC 5.3-17: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2017.

Location: New York Discount Rate: 3%

Project Title: Ft. Drum ESTCP MAI Analysis Analyst: Tapan Patel

Base Date: September 1, 2017 Preparation Date: Sun Sep 17 16:09:15 CDT 2017

BOD: September 1, 2017 Economic Life: 30 years 0 months

File Name:

1. Investment

Construction Cost	\$15,099
SIOH	\$905
Design Cost	\$1,510
Total Cost	\$17,514
Salvage Value of Existing Equipment	\$0
Public Utility Company	\$0
Total Investment	\$17,514

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage	Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	\$21.45281	0.2 MBtu		\$5	23.444	\$107
Natural Gas	\$3.63300	5.0 MBtu		\$18	25.514	\$464
Energy Subtotal		5.2 MBtu		\$23		\$572
Water Subtotal		0.0 Mgal		\$0		\$0
Total				\$23		\$572

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
Non-Annually Recurring Subtotal	\$0			\$0
Total	\$0			\$0

4. First year savings	\$23
5. Simple Payback Period (in years)	768.96 (total investment/first-year savings)
6. Total Discounted Operational	\$572

Figure 77. Economics with Installation Costs.

NIST BLCC 5.3-17: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2017.

Location: New York Discount Rate: 3%

Project Title: Ft. Drum ESTCP MAI Analysis Analyst: Tapan Patel

Base Date: September 1, 2017 Preparation Date: Sun Sep 17 16:03:50 CDT 2017

BOD: September 1, 2017 Economic Life: 30 years 0 months

File Name:

1. Investment

Construction Cost	\$3,879
SIOH	\$233
Design Cost	\$388
Total Cost	\$4,500
Salvage Value of Existing Equipment	\$0
Public Utility Company	\$0
Total Investment	\$4,500

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage	Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	\$21.45281	0.2 MBtu		\$5	23.444	\$107
Natural Gas	\$3.63300	5.0 MBtu		\$18	25.514	\$464
Energy Subtotal		5.2 MBtu		\$23		\$572
Water Subtotal		0.0 Mgal		\$0		\$0
Total				\$23		\$572

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
Non-Annually Recurring Subtotal	\$0			\$0
Total	\$0			\$0

4. First year savings \$23
5. Simple Payback Period (in years) 197.57 (total investment/first-year savings)
6. Total Discounted Operational Savings \$572
7. Savings to Investment Ratio (SIR) 0.13 (total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR) -3.85% $(1+d) * SIR^{(1/n)} - 1$; d=discount rate, n=years in study period

Figure 78. Economics without Installation Costs.

8.3.5 Secondary Scenario Cost Analysis

A cost analysis for the secondary scenario (no original wall insulation) was conducted. This analysis used the energy consumption values listed in Table 26.

Table 26. Secondary Scenario Energy Consumption Analysis.

	Baseline	Retrofit	Savings	% Difference
Total electric (kWh)	11,233	10,693	540	-5%
Natural gas (kBtu)	77,700	43,970	33,729	-43%
Total (kBtu)	116,029	80,456	35,573	-31%

8.3.5.1 Cost Analysis – Secondary Scenario – with Installation

A cost analysis was conducted for the secondary scenario using the same natural gas and electricity rates described earlier.

As seen in Figure 79, the simple payback of 108 years and SIR of 0.21 is better than the original scenario with a simple payback of 769 years and SIR of 0.03.

8.3.5.2 Cost Analysis – Secondary Scenario – without Installation

Figure 80 shows the BLCC cost analysis without installation costs.

Without installation costs, the secondary scenario simple payback of 28 years and SIR of 0.82 is better than the simple payback of 198 years and SIR of 0.12.

Based on these cost analyses, it is clear that the existing cavity insulation in the facility impacts the system economics significantly. In facilities with no or very little insulation, the MAI is more promising. The relatively low cost of Fort Drum utilities also negatively impacts the economics. Additional work is underway to significantly reduce installation costs, which should help improve the cost economics further.

8.4 Applicability to Federal Building Portfolio

Within DOD, this technology is applicable to facilities where insulation is a requirement. Specifically, cold climates where continuous insulation is recommended (per ASHRAE 90.1 – 2013 standards), MAI can be used. Because of the large building portfolio, and the lack of detailed construction data in a centralized repository, it is difficult to estimate the full market potential of this technology within DOD. However, by looking at a subset of facilities, it is possible to develop a cursory estimate of its applicability.

For this study, the team analyzed data from the Army Headquarters Installation Information System (HQIIS). A subset of Army facilities from Installation Management Command (IMCOM) were analyzed. These included facilities categorized as Defense Logistics Agency (DLA), Europe, Pacific, Sustainment and Training.

NIST BLCC 5.3-17: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2017.

Location: New York Discount Rate: 3%

Project Title: Ft. Drum MAI With Installation Analyst:

Base Date: April 1, 2017 Preparation Date: Wed Nov 01 14:08:41 CDT 2017

BOD: April 1, 2017 Economic Life: 30 years 0 months

File Name:

1. Investment

Construction Cost	\$15,099
SIOH	\$905
Design Cost	\$1,510
Total Cost	\$17,514
Salvage Value of Existing Equipment	\$0
Public Utility Company	\$0
Total Investment	\$17,514

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage	Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	\$21.42350	1.8 MBtu		\$39	22.967	\$907
Natural Gas	\$3.63300	33.7 MBtu		\$123	23.008	\$2,819
Energy Subtotal		35.6 MBtu		\$162		\$3,726
Water Subtotal		0.0 Mgal		\$0		\$0
Total				\$162		\$3,726

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
Non-Annually Recurring Subtotal	\$0			\$0
Total	\$0			\$0

4. First year savings	\$162
5. Simple Payback Period (in years)	108.09 (total investment/first-year savings)
6. Total Discounted Operational Savings	\$3,726

Savings

7. Savings to Investment Ratio (SIR)	0.21 (total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	-2.18% $(1+d)^n \cdot SIR^{(1/n)} - 1$; d=discount rate, n=years in study period

Figure 79. Secondary Scenario with Installation Costs.

NIST BLCC 5.3-17: ECIP Report

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

The LCC calculations are based on the FEMP discount rates and energy price escalation rates updated on April 1, 2017.

Location: New York Discount Rate: 3%

Project Title: Ft. Drum MRI With Installation Analyst:

Base Date: April 1, 2017 Preparation Date: Wed Nov 01 14:10:25 CDT 2017

BOD: April 1, 2017 Economic Life: 30 years 0 months

File Name:

1. Investment

Construction Cost	\$3,879
SIOH	\$233
Design Cost	\$388
Total Cost	\$4,500
Salvage Value of Existing Equipment	\$0
Public Utility Company	\$0
Total Investment	\$4,500

2. Energy and Water Savings (+) or Cost (-)

Base Date Savings, unit costs, & discounted savings

Item	Unit Cost	Usage	Savings	Annual Savings	Discount Factor	Discounted Savings
Electricity	\$21.42350	1.8 MBtu		\$39	22.967	\$907
Natural Gas	\$3.63300	33.7 MBtu		\$123	23.008	\$2,819
Energy Subtotal		35.6 MBtu		\$162		\$3,726
Water Subtotal		0.0 Mgal		\$0		\$0
Total				\$162		\$3,726

3. Non-Energy Savings (+) or Cost (-)

Item	Savings/Cost	Occurrence	Discount Factor	Discounted Savings/Cost
Non-Annually Recurring				
Non-Annually Recurring Subtotal	\$0			\$0
Total	\$0			\$0

4. First year savings	\$162
5. Simple Payback Period (in years)	27.77 (total investment/first-year savings)
6. Total Discounted Operational Savings	\$3,726

Savings

7. Savings to Investment Ratio (SIR)	0.83 (total discounted operational savings/total investment)
8. Adjusted Internal Rate of Return (AIRR)	2.35% $(1+d)^*SIR^{(1/n)}-1$; d=discount rate, n=years in study period

Figure 80. Secondary Scenario without Installation Costs.

For this analysis, only permanent, active facilities were considered. Other temporary or semi-permanent facilities were not considered because of the long-term payback for envelope technologies. Non-relevant facilities such as fuel storage tanks, bus stops, lift stations, open areas, etc. were not considered in this analysis. After filtering for these non-relevant facilities, the number of facilities listed in Table 27 were analyzed.

Table 27. Total Number of IMCOM Facilities.

Facility Type	Total Number of Facilities in HQIS	Number of Analyzed Facilities	% of facilities in HQIS
DLA	465	315	68%
Europe	18160	8600	47%
Pacific	18726	7825	42%
Readiness	57702	37656	65%
Sustainment	14915	9707	65%
Training	28699	19602	68%
Total	138,667	83,705	60%

At a high level, approximately 60% of IMCOM facilities are good candidates for study. Once the technology becomes more mature (and cost effective), these subsets of facilities can be analyzed to determine potential candidates. Currently, very few facility retrofits are viable because most buildings already have insulation. As discussed in previous sections, MAI provides increased R-value for colder climates. Therefore, DOD sites in colder climates should be considered as early adopters for this technology. This 60% applicability will vary across the services and within various departments.

In addition to climate, further analysis can be done on a site by site level. After applying filters to remove non-relevant facilities, facilities could be ranked by energy consumption. Assuming audit data are available, high energy consumers should be studied to determine if envelope-related losses can be mitigated using this technology.

The Sustainment Management Suite (SMS) BUILDER tool is being implemented across DOD to manage inventory. Although each service is making progress towards entering data within SMS, the inventory database are not complete. Therefore, any analysis is subject to change as additional facilities are added to BUILDER.

The BUILDER software was used to filter the facilities and components. The following components were selected for analysis:

- System Component – B201001 Exterior Enclosure
- Component – B2010 Exterior Walls
- CompType – Metal Siding, Metal Panel, Pre-Engineer Steel Wall and Panel, Vinyl Siding, Wood Cladding w/Stud Backup.

These components provide the best insight regarding facilities that could potentially use the MAI technology. For 18 Active Army Installations, as classified within BUILDER, applying the above filters yields approximately 2,835 buildings/subsections with approximately 6.6M sq ft of wall area. Further information for various services and/or sites can be obtained through BUILDER.

9.0 IMPLEMENTATION ISSUES

Minor issues and lessons learned are discussed here for end-user consideration:

1. Replacing J-channels and siding around doors/windows: The MAI and polyiso add 1 in. of thickness to the entire envelope. Therefore, provisions to increase the thickness of J-channels around doors and windows is necessary. This usually involves purchasing deeper channels and or fabricating custom channels if necessary.
2. Due to the increase in envelope thickness, facilities with soffit vents will need additional modifications. At Fort Drum, the soffit vents all needed to be trimmed by 1 in. This was accomplished using a table saw. However, it is recommended that new soffit vents (cut to the correct size) be ordered. This avoids significant work in trimming, replacing, and adjusting soffit vents.
3. After removing the exterior metal siding, commercial glue was used to glue the MAI panels to the Tyvek-type wrap. However, after some experimentation, the team determined that the glue was not necessary. If the polyiso foam is placed correctly, the MAI panels can be held in place between two rows of foam.
4. After the MAI and polyiso was installed, the team re-fastened the exterior metal siding to the building. The team had to take great care in ensuring that all fastener holes were lined up with the polyiso strips to avoid damaging the panels. Due to lighting conditions, it was difficult to ensure that the fasteners were being placed into the foam. The team recommends applying red tape to the polyiso before attaching the exterior siding. This red tape is easier to see and will help to make sure that fastener holes are lined up with the foam.

9.1 Failure Rate of MAI/VIP

The failure rate of MAI and VIPs is of concern for the longevity of insulation. Leakage of air across the VIP/MAI membrane will result in degradation of the insulation R-value. For building envelope applications, the primary risk of failure of VIPs is during handling and installation. Installers and manufacturers must take care to ensure that VIP panels are not damaged. Some products attempt to mitigate this risk by encapsulating the MAI within a more resilient material (e.g., foam, drywall).

There are few studies on real building or actual installations, especially in North America, to get meaningful data related to failure rates. Although this demonstration did not evaluate the long-term effects of the insulation, some previous studies have attempted to gain some insight into the issue.

Mukhopadhyaya et al. (2014) reported the installation and monitoring of VIPs used to retrofit a masonry wall in Yukon, located in Northern Canada. Experience gained from the construction process and available thermal performance data over a period of 3 years provide encouraging indicators for the constructability and long-term thermal performance of VIPs in the subarctic Canadian weather. According to the authors, experience with installation of the VIPs was more positive than originally anticipated. Only one minor installation problem was encountered, and it was related to the use of anchors in masonry walls rather than installation of the VIPs. To the authors' knowledge, no VIPs were damaged during construction. An infrared image taken 3 years

after the installation of the VIPs did not show any damaged VIPs. The monitored temperatures were analyzed and also did not reveal any significant performance degradation.

Brunner and Wakili (2014) reported conductivity measurements of VIPs installed on a roof in Zurich. The conductivity measurements were performed before installation and after 8.8 years of installation. The initial conductivity was about 0.0045 W/mK and increased to 0.0066–0.007 W/mK. The increase in conductivity was attributed to natural aging of the VIPs due to diffusion of atmospheric gases and vapors through the barrier films and accumulation of moisture in the core material.

The risk of damage during handling and installation can be reduced by encapsulating the VIPs in foam insulation. A couple of recent DOE funded projects have evaluated foam-VIP composites (Childs et al. 2013; Biswas et al. 2015).

9.2 Application of MAI for New Facilities

MAI can be used to supplement or replace traditional insulation in new construction. Although the application process will differ depending on the type of construction, ASHRAE 90.1 guidelines and cost data can be used during the design process to determine if and how much MAI to use for a particular building.

For examples from Climate Zones 3 and 5, see the R-values for wood-framed walls (highlighted in Tables 28 and 29), where “c.i.” represents exterior continuous insulation and the other (R13/R19/R20) represents the cavity insulation. Thus, there are different combinations that can meet the overall U-value requirement of the assembly.

Table 28. ASHRAE Building envelope Requirements for Climate Zone 3.

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
<i>Roofs</i>						
Insulation Entirely above Deck	U-0.039	R-25 c.i.	U-0.039	R-25 c.i.	U-0.119	R-7.6 c.i.
Metal Building ^a	U-0.041	R-10 + R-19 FC	U-0.041	R-10 + R-19 FC	U-0.096	R-16
Attic and Other	U-0.027	R-38	U-0.027	R-38	U-0.053	R-19
<i>Walls, above Grade</i>						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal Building	U-0.094	R-0 + R-9.8 c.i.	U-0.072	R-0 + R-13 c.i.	U-0.162	R-13
Steel Framed	U-0.077	R-13 + R-5 c.i.	U-0.064	R-13 + R-7.5 c.i.	U-0.124	R-13
Wood Framed and Other	U-0.089	R-13	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.089	R-13

Table 29. ASHRAE Building envelope Requirements for Climate Zone 5.

Opaque Elements	Nonresidential		Residential		Semiheated	
	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value	Assembly Maximum	Insulation Min. R-Value
<i>Roofs</i>						
Insulation Entirely above Deck	U-0.032	R-30 c.i.	U-0.032	R-30 c.i.	U-0.063	R-15 c.i.
Metal Building ^a	U-0.037	R-19 + R-11 Ls or R-25 + R-8 Ls	U-0.037	R-19 + R-11 Ls or R-25 + R-8 Ls	U-0.082	R-19
Attic and Other	U-0.021	R-49	U-0.021	R-49	U-0.034	R-30
<i>Walls, above Grade</i>						
Mass	U-0.090	R-11.4 c.i.	U-0.080	R-13.3 c.i.	U-0.151 ^b	R-5.7 c.i. ^b
Metal Building	U-0.050	R-0 + R-19 c.i.	U-0.050	R-0 + R-19 c.i.	U-0.094	R-0 + R-9.8 c.i.
Steel Framed	U-0.055	R-13 + R-10 c.i.	U-0.055	R-13 + R-10 c.i.	U-0.084	R-13+R-3.8 c.i.
Wood Framed and Other	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.051	R-13 + R-7.5 c.i. or R-19 + R-5 c.i.	U-0.089	R-13

10.0 REFERENCES

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11.0 APPENDICES

APPENDIX A: POINTS OF CONTACT

Table A1. Points of Contact.

Point of Contact	Organization	Phone & E-mail	Role in Project
Mr. Tapan Patel	U.S. Army Engineer Research and Development Center- Construction Engineering Research Laboratory (ERDC-CERL) 2902 Newmark Dr. Champaign, IL 61826	217.373.3457, tapan.c.patel@usace.army.mil	Project Manager
Mr. Nicholas Josefik	ERDC-CERL	217.373.4436, nicholas.m.josefik@usace.army.mil	Technical assistant
Mr. Lake Lattimore	ERDC-CERL	217.373.6770, jeffrey.l.lattimore@usace.army.mil	Technical assistant
Dr. Kaushik Biswas	Oak Ridge National Laboratory (ORNL) PO Box 2008, MS6070 Oak Ridge, TN 37831-6070	865-241-0917 (F) 865-574-9354 biswaks@ornl.gov	Research; Lead on Data analysis
Som Shrestha	ORNL	865-241-8772 shresthass@ornl.gov	Researcher, Data Modeling
Mr. Stephen Rowley	Fort Drum Energy Manager 85 First St West Public Works Fort Drum New York 13602	315-772-5433 Stephen.e.rowley3.civ@mail.mil	POC at Fort Drum
Mr. Doug Smith	NanoPore Inc. 2525 Alamo Ave. SE Albuquerque, NM 87106	505-224-9373 smith@nanopore.com	Technology provider

APPENDIX B: ENERGYPLUS MODELING

Table B1 summarizes all collected data. The table highlights how the data were used in the modeling process and includes any assumptions or estimates that were made.

Table B1. Data Collection Summary.

Data Collected	Data Collection Method	Relevance To Energy Model	Assumptions or Estimates
Building construction data (wall/roof assembly type, insulation, fenestration type, infiltration rate)	Floor plans, physical measurements, construction drawings, walkthrough audit of building), blower door testing	Input construction information to develop baseline building model	None
Internal lighting and plug loads	Walkthrough Survey to include lighting type and usage, plug loads and estimated usage	Input information to model determine heat gain from internal loads	Estimate lighting and plug load usage based on occupancy ¹
Occupancy	Assumed occupancy due to lack of occupancy information.	Input information into model to determine heat gain from occupants	Assume DOE recommended occupancy. Estimate any periods of partial occupancy ²
Heat Flux and temperature, Location of sensors	Thermocouples, heat flux sensors, physical measurements	Determine heat flow through walls. The actual heat flux and temperature data will be used to calibrate the models. The location of the sensors will be defined in the model.	None
HVAC type, capacity, electric and natural gas usage of HVAC system	Nameplate information, meter data of HVAC system	Calibrate the electric and natural gas usage of the HVAC system against the model	None
Temperature Setpoints	Interior air temperature thermocouples	Input information into model. Setpoints will determine how much heating/cooling is needed within the model	None
Overall building energy consumption	Electric meter, natural gas meter	Used to calibrate energy model to actual building energy usage	None
Weather (wind speed, direction, temperature)/Solar (long wave and short wave solar radiation, Direct Normal Incidence (DNI), Broadband Solar Irradiance)	Vaisala instrumentation suite for weather data, Solar data via Pyrgeometer, Pyranometer, Pyrheliometer, and a Global Secondary Standard Pyranometer. Solar data from nearby Air Field station was used due to faulty solar station.	Weather and solar information	None
1 Since both buildings are classrooms, occupancy is assumed to have a direct correlation with lighting and plug loads. Based on preliminary discussions with the Safety Office, plug loads are expected to be minimal. 2 Periods of partial occupancy (i.e., non-class related occupancy) are expected to be minimal since both spaces are primarily used as classroom-only space.			

E+ models of both the retrofit and baseline buildings were created. The objective was that, once calibrated and validated, the models can provide accurate estimates of energy consumption of both buildings under identical operating conditions. This allowed an energy savings analysis to show the effects of adding MAI panels to the test building for this particular climate zone.

The building geometry and orientation, local weather data and other characteristics like occupancy, interior loads, etc. were used as inputs to building models. Both buildings were monitored for a period of 12 months, side-by-side, to ensure that the effects of seasonal variations were captured. The measurements were used to determine the heat transfer through the walls and ceiling, and

energy consumption of the buildings with and without the MAI panels, and for comparison with the model output. Data collected from the buildings include: heat flux, temperature/RH on the interior and exterior walls on each face, internal temperature setpoints, weather, and overall electric and natural gas consumption. Occupancy and plug loads were assumed. All of this information was used to create and calibrate/validate the E+ models. The models were calibrated to the actual heat flux and electric/gas consumption.

Finally, the calibrated building models were simulated under identical building, weather, and assumed operating conditions, except the addition of MAI panels in the test building, to precisely estimate the energy savings due to addition of the MAI panels. These models are referred to as the normalized models. Figure B1 below shows a flow diagram of the modeling process:

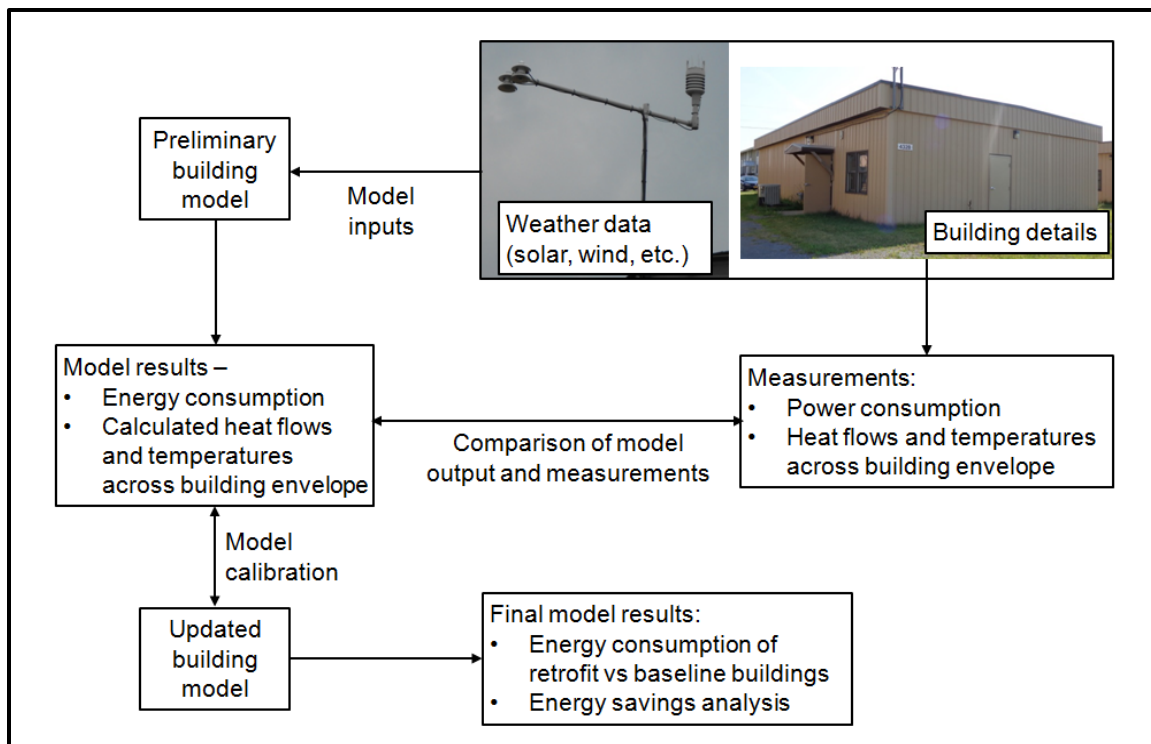


Figure B1. Information Flow for Modeling.

EnergyPlus Modeling

The E+ program is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. It does this by simulating the building and associated energy systems when they are exposed to different environmental and operating conditions. The core of the simulation is a model of the building that is based on fundamental heat balance principles. Figure B2 SHOWS a diagram showing a basic overview of the integration of these important elements of a building energy simulation.

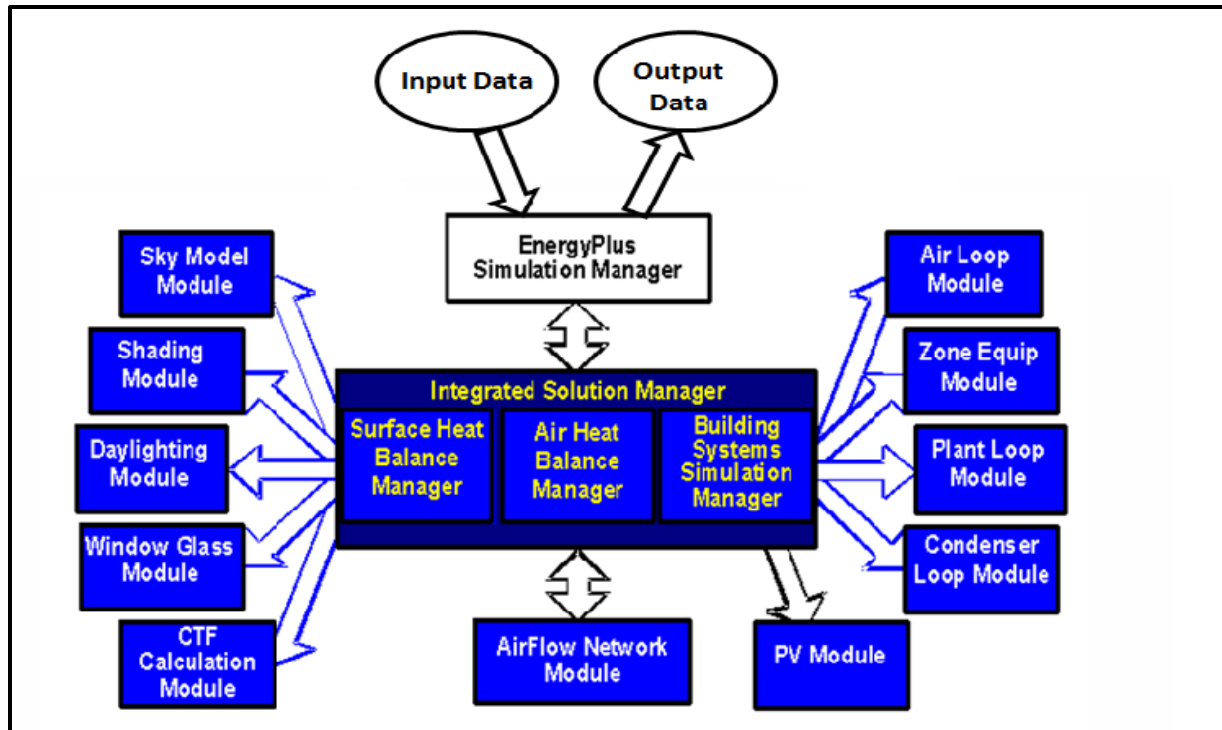


Figure B2. E+ Data Flow and Operation Diagram.

Temperature based R-value dependency

One additional consideration for the E+ modeling includes the temperature dependency of the MAI panels and polyiso. The differing nominal thermal resistance of the polyiso and MAI panels along with their differing temperature dependent R-value need to be incorporated. For example, the R-value of MAI increases with lower temperature, whereas polyiso R value decreases. Using the CAD drawings of the MAI/polyiso layout, and any on-site modifications, the team was able to replicate the overall R-value of the envelope. Using known temperature values, the R-value of the envelope can be determined as a function of time. These temperature dependent R-values were entered into the model. Only the MAI was modeled as a function of temperature because data on the foam were not available. E+ is capable of using temperature-dependent thermal resistance (or thermal conductivity) as model inputs. Any impacts (positive or negative) of using polyiso will be discussed in the final report.

Heat Balance Algorithm. The Heat Balance Algorithm object provides a way to select what type of heat and moisture transfer algorithms was used across the building construction calculations, the choices being Conduction Transfer Function (CTF) and Conduction Finite Difference (CondFD).

Conduction Transfer Function Module. The most basic time series solution is the response factor equation, which relates the flux at one surface of an element to an infinite series of temperature histories at both sides.

Conduction Finite Difference Solution Algorithm. E+ models generally follow fundamental heat balance principles very closely. To accommodate MAI into energy analysis, a conduction

finite difference (CondFD) solution algorithm has been incorporated. This algorithm compliments the CTF functions for cases where the user needs to simulate MAI materials or variable thermal conductivity. It is also possible to use the finite difference algorithm for zone time steps as short as 1 minute.

Other Features. Many of the simulation characteristics have been inherited from the legacy programs of Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2. Some of the features of E+ are:

- **Integrated, simultaneous solution, in** which the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- **Sub-hourly, user-definable time steps** for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability).
- **American Standard Code for Information Interchange (ASCII) text based weather, input, and output files** that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively.
- **Heat balance based solution** technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both the interior and exterior surface during each time step
- **Transient heat conduction** through building elements such as walls, roofs, floors, etc. using conduction transfer functions
- **Improved ground heat transfer modeling** through links to three-dimensional finite difference ground models and simplified analytical techniques
- **Combined heat and mass transfer** model that accounts for moisture
- **Adsorption/desorption** either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD)
- **Thermal comfort models** based on activity, inside dry bulb, humidity, etc.
- **Anisotropic sky model** for improved calculation of diffuse solar on tilted surfaces
- **Advanced fenestration calculations** including controllable window blinds, electrochromic glazings, and layer-by-layer heat balances that allow proper assignment of solar energy absorbed by window panes, and a performance library for numerous commercially available windows
- **Loop based configurable HVAC systems** (conventional and radiant) that allow users to model typical systems and slightly modified systems without recompiling the program source code. No program is able to handle every simulation situation. However, it is the intent of E+ to handle as many building and HVAC design options as possible, either directly or indirectly

through links to other programs to calculate thermal loads and/or energy consumption for a design day or an extended period of time (up to, including, and beyond a year).

E+ has been subjected to a lengthy and rigorous testing plan by an outside agency as well as numerous beta testers. This level of effort and collaboration is unprecedented in the history of energy analysis and thermal load calculation programs and has resulted in a higher level of confidence in the results.

APPENDIX C: BUILDING FASTENERS AND PLANNED MAI PANEL LAYOUT

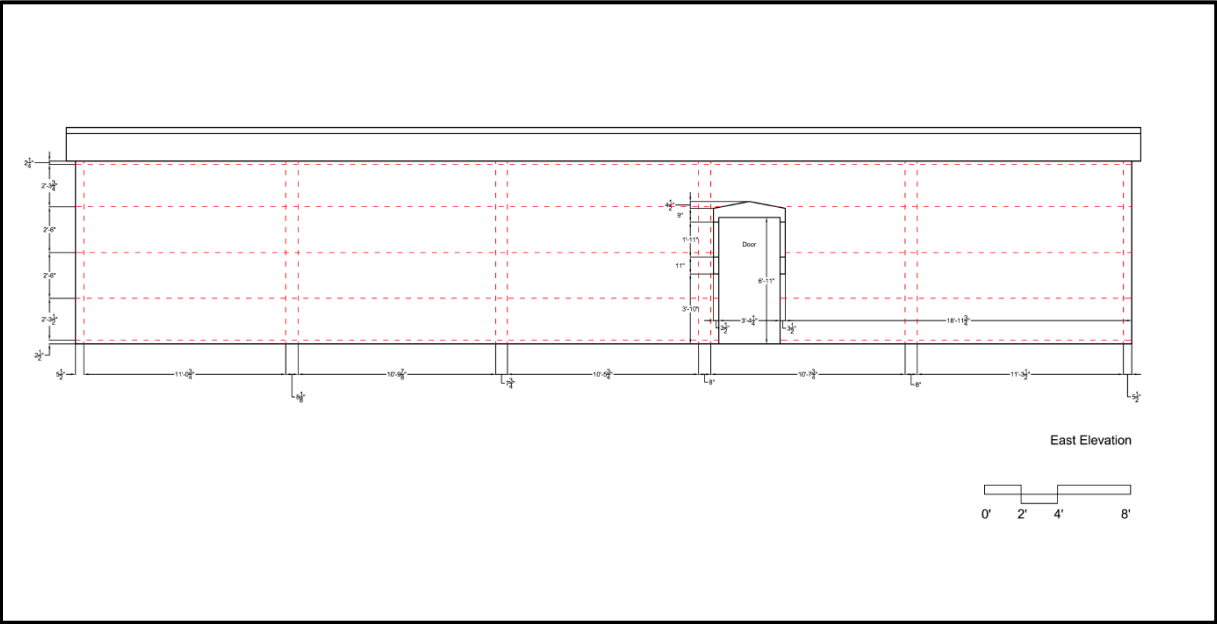


Figure C1. East Elevation.

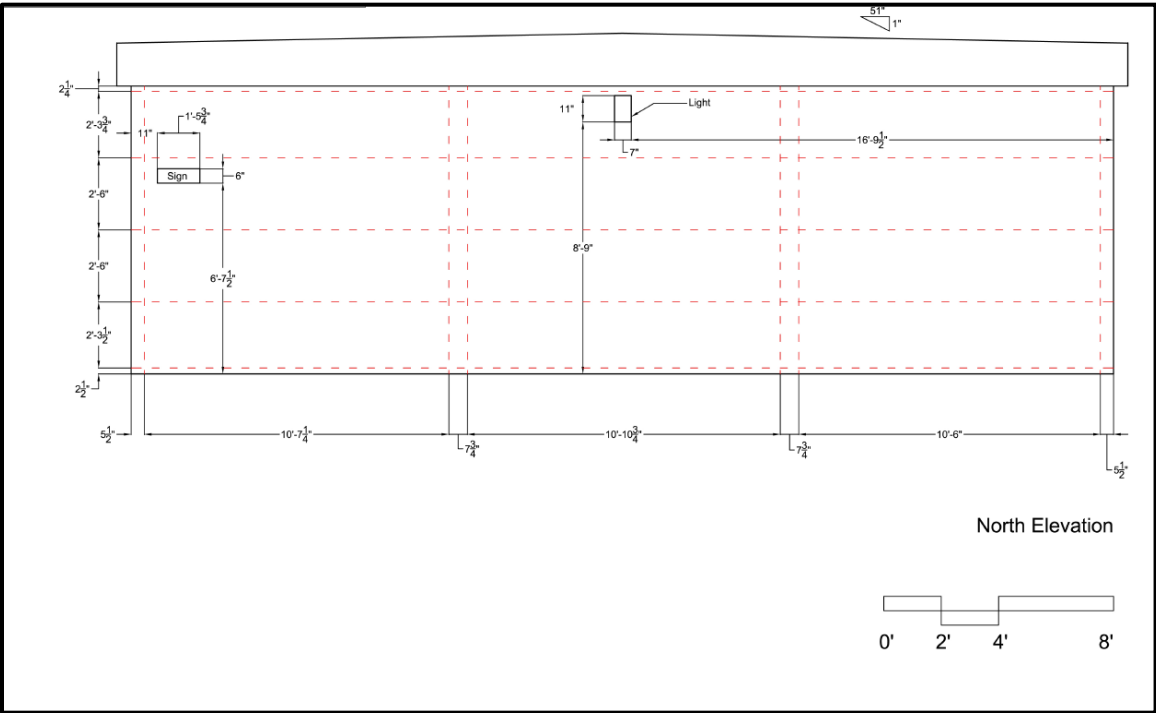


Figure C2. North Elevation.

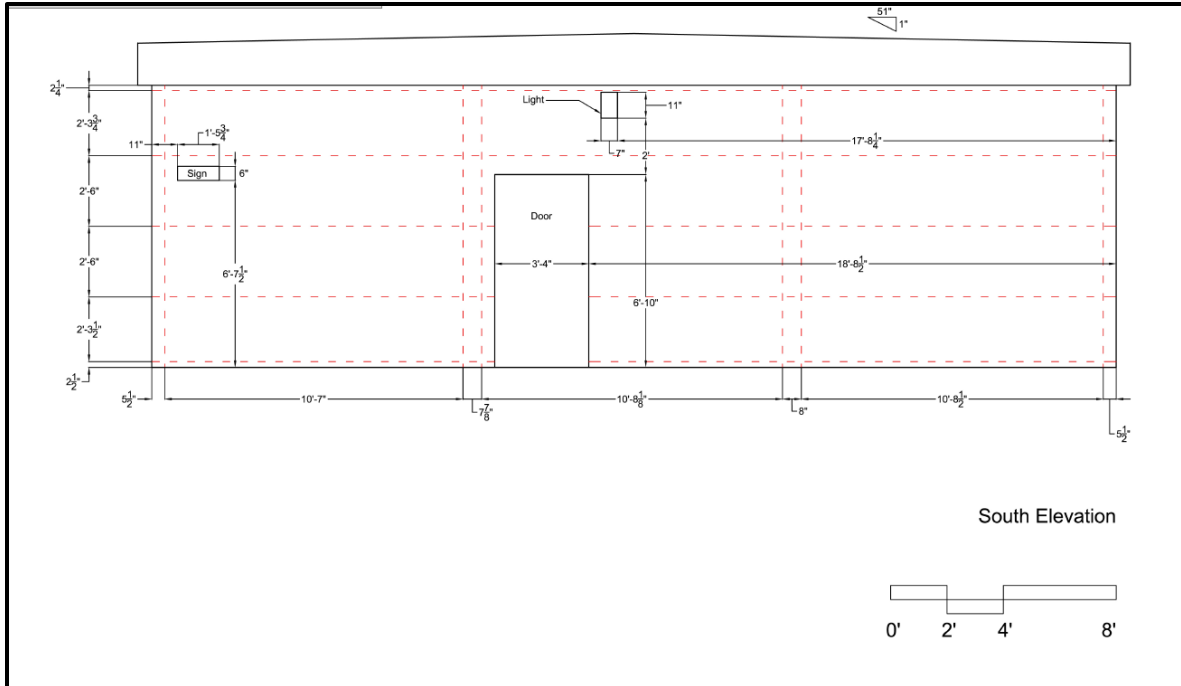


Figure C3. South Elevation.

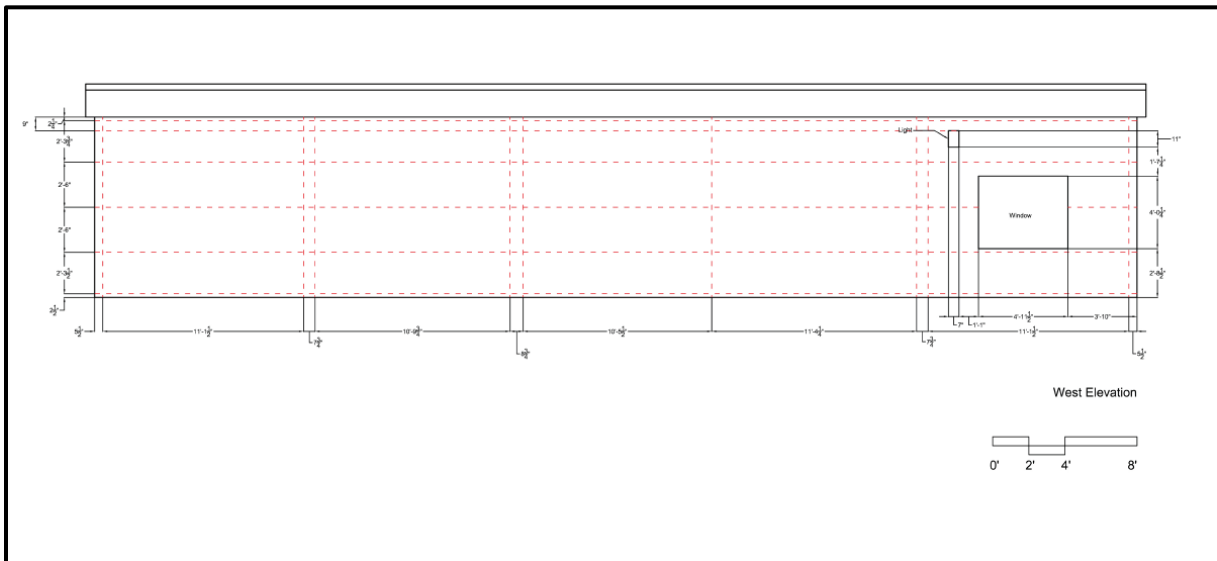


Figure C4. West Elevation.

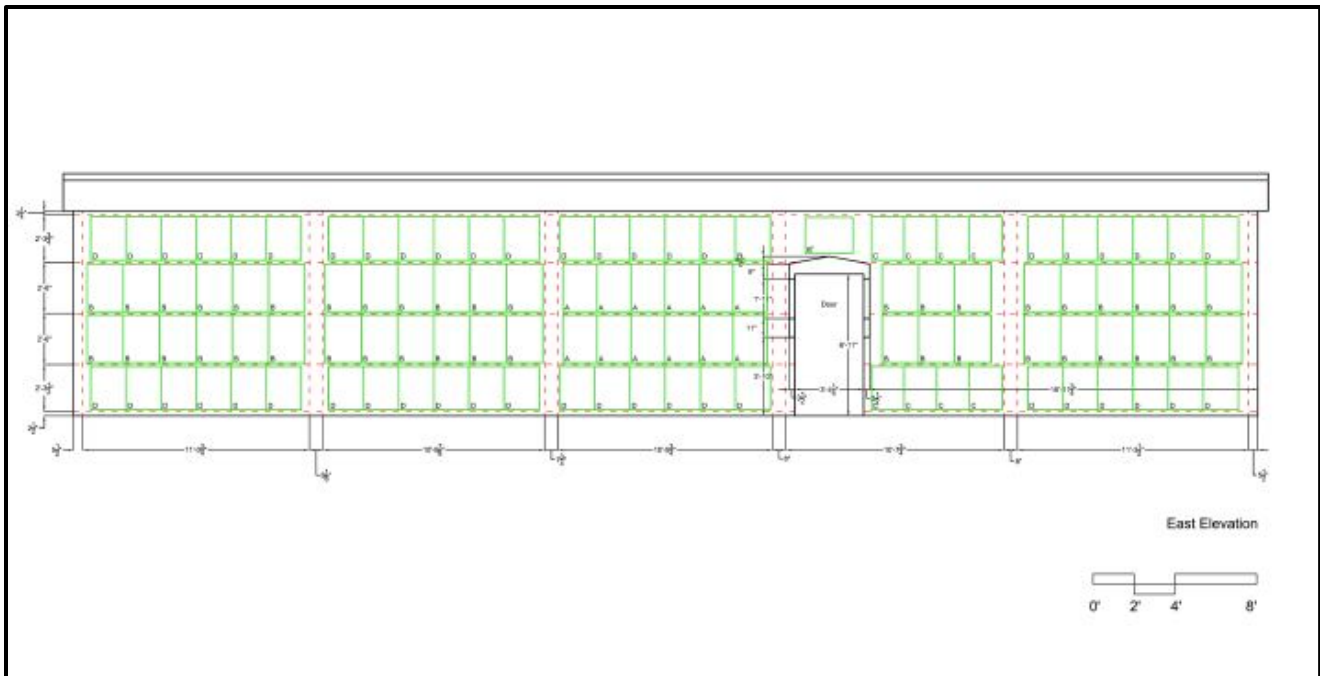


Figure C5. East Elevation with MAI panels.

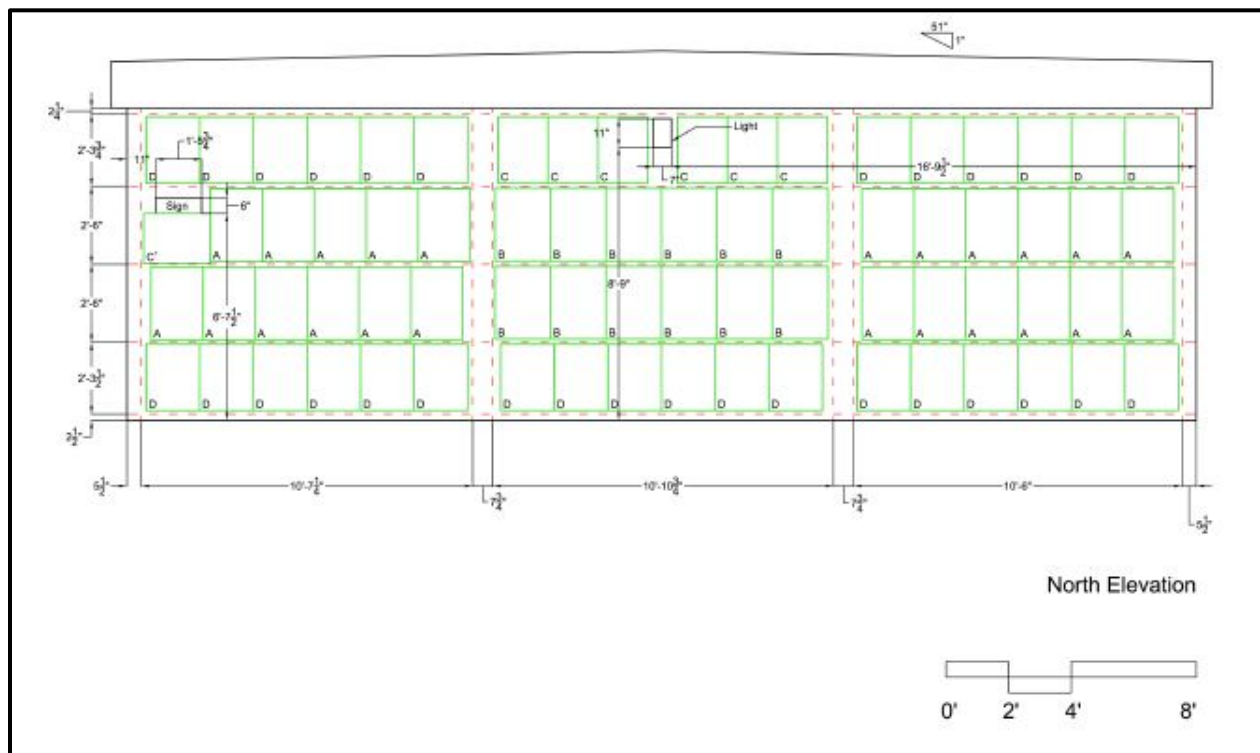


Figure C6. North Elevation with MAI panels.

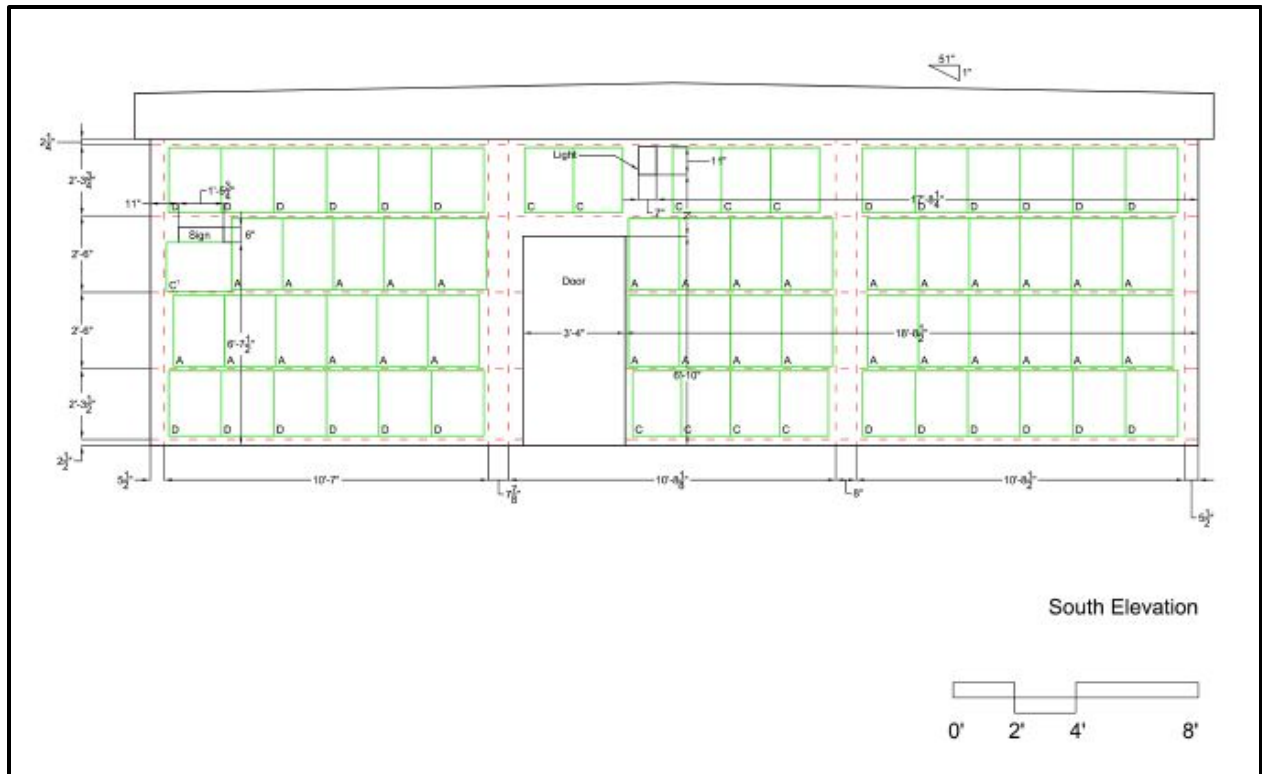


Figure C7. South Elevation with MAI panels.

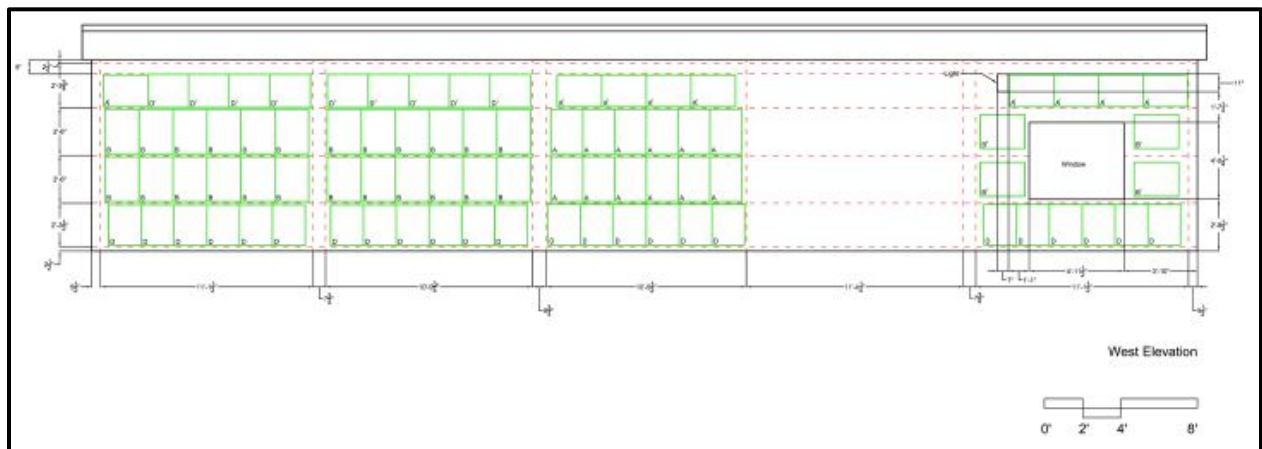


Figure C8. West Elevation with MAI panels.

APPENDIX D: LIKERT QUESTIONNAIRE FOR INSTALLERS

		Strongly disagree	Disagree	Neutral	Agree	Strongly Agree	N/A
	Questions						
1	The retrofit process was simple and straightforward				X		
2	I would participate in and support future retrofits using MAI panels				X		
3	I would support using this insulation for retrofit applications instead of traditional batt or foam insulation					X	
4	I would consider adding this type of insulation to my residence if it was cost effective					X	
6	The retrofit process was simpler than other insulation retrofits			X			
7	This retrofit takes less time than other insulation retrofits			X			
8	The adhesive chosen is an effective means of attaching MAI panels				X		
9	Reinstalling the siding required minimal effort				X		
10	Structural changes required to accommodate the insulation retrofit were minimal					X	

Comments or recommendations:

- Were there technical issues that were not foreseen with the installation, in areas including (but not limited) MAI attachment, sealing of gaps, complete coverage of the walls with insulation, etc.?
 - Soffit had to be trimmed in order to accommodate insulation.
 - Had to obtain a table saw because one was not available onsite.
 - The door areas with overhangs required a much greater deal of effort to retrofit due to the construction.
 - Ran out of ZipTape (less than a roll short), had to use duct tape and roofing tape for a small section.
 - Ran short of the ordered ISO, was able to obtain that from Lowe's

Figure D1. Likert Questionnaire 2.

		Strongly disagree	Disagree	Neutral	Agree	Strongly Agree	N/A	Comments
	Questions							
1	The retrofit process was simple and straightforward				X			For a first attempt
2	I would participate in and support future retrofits using MAI panels					X		
3	I would support using this insulation for retrofit applications instead of traditional batt or foam insulation				X			All about cost/performance
4	I would consider adding this type of insulation to my residence if it was cost effective					X		
6	The retrofit process was simpler than other insulation retrofits			X				
7	This retrofit takes less time than other insulation retrofits			X				
8	The adhesive chosen is an effective means of attaching MAI panels				X			Not clear if this is actually required if used in conjunction with the poly-iso strips
9	Reinstalling the siding required minimal effort					X		
10	Structural changes required to accommodate the insulation retrofit were minimal					X		
Comments or recommendations: • Were there technical issues that were not foreseen with the installation, in areas including (but not limited) MAI attachment, sealing of gaps, complete coverage of the walls with insulation, etc.? No.								

Figure D2. Likert Questionnaire 3.

		Strongly disagree	Disagree	Neutral	Agree	Strongly Agree	N/A
	Questions						
1	The retrofit process was simple and straightforward			X			
2	I would participate in and support future retrofits using MAI panels				X		
3	I would support using this insulation for retrofit applications instead of traditional batt or foam insulation				X		
4	I would consider adding this type of insulation to my residence if it was cost effective				X		
6	The retrofit process was simpler than other insulation retrofits			X			
7	This retrofit takes less time than other insulation retrofits			X			
8	The adhesive chosen is an effective means of attaching MAI panels					X	
9	Reinstalling the siding required minimal effort					X	
10	Structural changes required to accommodate the insulation retrofit were minimal					X	

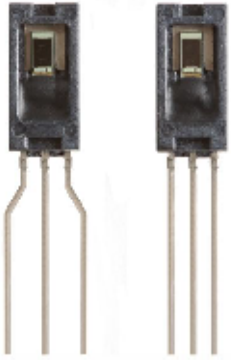
Comments or recommendations:

- Were there technical issues that were not foreseen with the installation, in areas including (but not limited) MAI attachment, sealing of gaps, complete coverage of the walls with insulation, etc.?

Rework around the soffit vents was an unforeseen issue as was work around the door awnings.

Figure D3. Likert Questionnaire 1.

Honeywell



HIH-4000 Series

Humidity Sensors

DESCRIPTION

The HIH-4000 Series Humidity Sensors are designed specifically for high volume OEM (Original Equipment Manufacturer) users.

Direct input to a controller or other device is made possible by this sensor's near linear voltage output. With a typical current draw of only 200 μ A, the HIH-4000 Series is often ideally suited for low drain, battery operated systems.

Tight sensor interchangeability reduces or eliminates OEM production calibration costs. Individual sensor calibration data is available.

THE HIH-4000 Series delivers instrumentation-quality RH (Relative Humidity) sensing performance in a competitively priced, solderable SIP (Single In-line Package).

Available in two lead spacing configurations, the RH sensor is a laser trimmed, thermoset polymer capacitive sensing element with on-chip integrated signal conditioning.

The sensing element's multilayer construction provides excellent resistance to most application hazards such as wetting, dust, dirt, oils and common environmental chemicals.

FEATURES

- Molded thermoset plastic housing
- Near linear voltage output vs % RH
- Laser trimmed interchangeability
- Low power design
- Enhanced accuracy
- Fast response time
- Stable, low drift performance
- Chemically resistant

POTENTIAL APPLICATIONS

- Refrigeration equipment
- HVAC (Heating, Ventilation and Air Conditioning) equipment
- Medical equipment
- Drying
- Metrology
- Battery-powered systems
- OEM assemblies

Figure E1. HH-4000 Humidity Sensor Cut Sheet.

Product certificate

Pages: 1
Release date: 07-05-2015

Product code **SR20-T2**
Product identification **serial number 3747**
Product type **pyranometer**
Measurand **hemispherical solar radiation**
Classification **secondary standard (ISO 9060), high quality (WMO-No. 8)**

Calibration result

Sensitivity **$S = 11.54 \times 10^{-6} \text{ V/(W/m}^2\text{)}$**
Calibration uncertainty **$\pm 0.11 \times 10^{-6} \text{ V/(W/m}^2\text{)}$**

the number following the $\pm$ symbol is the expanded uncertainty with a coverage factor $k = 2$, and defines an interval estimated to have a level of confidence of 95 percent

Measurement function **$E = U/S$**
with E irradiance in $[\text{W/m}^2]$, U voltage output in $[\text{V}]$

Product specifications and conformity

1:	ISO 9060 secondary standard	verified
2:	resistance	67.0 Ω
3:	insulation resistance	$> 100 \times 10^6 \Omega$
4:	response time (95 %)	4.4 s
5:	temperature response*	verified
6:	directional response	verified

*see separate certificate; result may be used to improve measurement quality

Table 0.1 Connections

PIN	WIRE	
2	Red	10 k Ω thermistor [H]
3	Pink	10 k Ω thermistor [+]
6	Blue	10 k Ω thermistor [-]
8	Grey	10 k Ω thermistor [-]
1	Brown	heater
4	Yellow	heater
9	Black	ground
7	White	signal [H]
5	Green	signal [-]

The 10 k Ω thermistor is a single four-wire thermistor measuring instrument body temperature.

Calibration procedure according to ISO 9817. Traceability of calibration is to the WRR (World Radiometric Reference) maintained at the World Radiation Center in Davos, Switzerland.

Please consult the user manual for set-up, operation and maintenance instructions, and information on measurement uncertainty during actual use.

Person authorising acceptance and release of product:
G.J. Halve

Date:
07-05-2015

SR20-T2 product certificate

page 1/4

Figure E2. SR20-T2 Calibration Sheet.

Product certificate

Pages: 1
Release date: 15-01-2015

Product code: **NR01-05**
Product identification: **serial number 2390**
Product type: **4-component net-radiation sensor**
Measurand: **net-radiation**

Product specifications

1: functional test **passed**
2: cable length **5 m**

Person authorising acceptance and release of product: **W.J.B. Fokke**
Date: **15-01-2015**

Calibration results

Component	SR01 ↓	SR01 ↑	IR01 ↓	IR01 ↑
Position	1	2	3	4
Serial number	3962	3963	3909	3910
Sensitivity	15.97×10^{-6}	20.36×10^{-6}	13.21×10^{-6}	14.22×10^{-6}
Uncertainty*	$\pm 0.19 \times 10^{-6}$	$\pm 0.25 \times 10^{-6}$	$\pm 0.70 \times 10^{-6}$	$\pm 0.75 \times 10^{-6}$
Calibration date	17-12-2014	12-12-2014	30-12-2014	30-12-2014
Resistance	63.7	68.0	197.8	217.4

With Sensitivity in $V/(W/m^2)$, Uncertainty in $V/(W/m^2)$, Resistance in Ω

* The number following the $\pm$ symbol is the expanded uncertainty with a coverage factor $k = 2$, and defines an interval estimated to have a level of confidence of 95 percent.

Table 0.1 connections **Cable 1**

PCB04	WIRE	
1	Blue	SR01 ↓ [-]
2	Red	SR01 ↑ [+]
3	Yellow	IR01 ↓ [-]
4	Brown	IR01 ↑ [+]
5	Grey	IR01 ↓ [-]
6	Pink	IR01 ↑ [+]
7	Green	SR01 ↓ [-]
8	White	SR01 ↑ [+]
11	Black	shield

Table 0.2 connections **Cable 2**

PCB03	WIRE	
1	Brown	heater
2	Red	Pt100 [-]
3	White	Pt100 [-]
4	Blue	Pt100 [-]
5	Green	Pt100 [-]
6	Yellow	heater
	Pink	not connected
	Grey	not connected
10	Black	shield

The IRT100 is a single four-wire resistance temperature detector measuring instrument body temperature.

SR01 calibration procedure according to ISO 9812. Traceability of calibration is to the WRR (World Radiometric Reference) maintained at the World Radiation Center in Davos, Switzerland.

IR01 calibration procedure according to Hukseflux IRC02. Traceability of calibration is to the WISG (World Infrared Standard Group) operated at the Infrared Radiometry Section of the World Radiation Center in Davos, Switzerland.

Please consult the user manual for detailed measurement functions and product set up, operation and maintenance instructions.

Figure E3. NR01-05 Calibration Sheet.

Product certificate

Pages: 1
Release date: 24-04-2015

Product code: **DR02-T1-05**
Product identification: **serial number 9207**
Product type: pyrheliometer
Measurand: direct solar radiation
Classification: first class (ISO 9060), good quality (WMO-No. 8)

Calibration result

Sensitivity: **$S = 11.16 \times 10^{-8} \text{ V/(W/m}^2\text{)}$**
Calibration uncertainty: **$\pm 0.09 \times 10^{-8} \text{ V/(W/m}^2\text{)}$**

the number following the $\pm$ symbol is the expanded uncertainty with a coverage factor $k = 2$, and defines an interval estimated to have a level of confidence of 95 percent

Measurement function: **$E = U/S$**
with E irradiance in $[\text{W/m}^2]$, U voltage output in $[\text{V}]$

Product specifications

1:	ISO 9060 first class	verified
2:	resistance	206,7 Ω
3:	insulation resistance	$> 100 \times 10^9 \Omega$
4:	response time (95 %)	2,0 s
5:	cable length	5 m

Table 0.1 connections

Connector	WIRE	
1	Red	Pt100 (+)
2	Brown	Pt100 (-)
3	Yellow	Pt100 (-)
4	Blue	Pt100 (-)
5	Pink	heater
6	Grey	heater
7	Green	signal (-)
8	White	signal (+)
9	Black	ground

The Pt100 is single four-wire resistance temperature detector measuring instrument body temperature.

Calibration procedure according to Hukseflux DR002. Traceability of calibration is to the WRR (World Radiometric Reference) maintained at the World Radiation Center in Davos, Switzerland.

Please consult the user manual for information on measurement uncertainty during actual use and for product set up, operation and maintenance instructions.

Calibration performed by: G.J. Halve Date: 24-04-2015

Person authorising acceptance and release of product: W.J.B. Hokke Date: 24-04-2015

DR02-T1 product certificate

page 1/2

Figure E4. DR02-T1-05 Calibration Sheet.